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Proceedings of the American Solar Energy Society National Conference

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Editors

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Preface

We are living in a world where the impact of climate change is felt in our everyday lives with ever-increasing extreme weather events. What used to be a 100-year event will soon be annual occurrences. We at the American Solar Energy Society (ASES) believe that with the right policy and strategic persuasion through education, campaigning, legislation, and finally execution, we can avert damage from reaching/crossing the point of no return. This complex societal issue can only be solved by intense planning by key stakeholders in our community to explore interests of shared values, identify contentious issues in energy transitioning toward 100% renewables, and to deliberate on finding solutions and ultimately making a positive difference in communities around the world. After a great deal of deliberation, we came up with the theme for this year's conference: "Energy Transition with Economic Justice". To elevate public, institutional, and governmental awareness of the important role energy transition is playing in the USA, a large number of Bills dealing with energy transitioning were passed all across the USA. The challenge we will all face in days to come is how well energy transitioning will be happening with inclusive engagement, which is often left out during the crucial planning stage.

Since defining the conference theme, a large number of individuals worked tirelessly to give a shape to this theme. This complex topic is broken down into seven tracks: Energy Transformation, Economic Justice, Energy Policy, Grid Integration and PV Advances, Buildings Innovations, Clean Transportation, and Education. More than 200 abstracts were submitted by solar enthusiasts all across this nation and some from abroad. A technical review committee was formed with 14 members including scientists, engineers, architects, building designers, university faculty, community leaders, writers, policy experts, publishers, program managers, graduate students, consultants, high-tech entrepreneurs, strategists, and business founders. Abstracts were reviewed followed by critical discussion resulting in accepting around 120 abstracts for presentation under three different modes during the conference. During the review process, review committee members also felt the need for bringing out a conference proceedings, partnering with Springer Nature, one of the best publishing houses in the world.

In order for participants to have a fulfilling time networking and sharing ideas with others, the proceedings will be made available to authors before the start of the conference. This will be a positive step toward empowering each other in our common aspiration of serving all stakeholders judiciously.

These proceedings are a collection of 32 papers, authored by members of our community with the objective to provide a glimpse of issues related to energy transition efforts. One such effort, the implementation of electric vehicle technology, that has revolutionized the auto manufacturing industry as marketable high-tech, and is now beginning to prove its viability and acceptance for long-term, everyday use, into the greater auto manufacturing industry. Scientists and engineers are making efforts to develop recyclable solar modules that will impact how we use and dispose of them for a sustainable future. Various groups all across the USA are currently working to develop financing models for community solar that will not need any grants and subsidies.

On behalf of the American Solar Energy Association, we appreciate the opportunity to serve as editors of this esteemed group of scholarly articles contributed by a diverse group of solar enthusiasts in the USA and abroad. We hope you will find these articles informative.

Ashok Kumar Ghosh
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Marlene Brown retired from a long career at Sandia National Labs. She has 2 Engineering Masters degrees and over 30 years of working with photovoltaics (solar electricity), including testing, monitoring, consulting, teaching, and training. Marlene is currently teaching photovoltaics at Central New Mexico Community College (CNM) in Albuquerque to the future photovoltaic workforce. Along with teaching hands-on classes, she also consults with homeowners in her community to make them more aware and better consumers when purchasing PV for their homes and businesses. When Marlene is not working or playing with solar, she likes to African dance, bike, play with bees, hike in the mountains and ski. She raced with the corporate downhill ski team for Sandia for over 10 years and still sings with the Sandia Singers group.

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Contents

Energy Transformation

Community Energy Trading in Texas: Potential Revenue Streams for Helping Make Community Solar Sustainable

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Abstract. One critical component of a sustainable "Community Solar" * model in Texas is making it attractive enough to customers that projects can be developed without subsidies or grants. To address energy poverty issues, TRCSS' goal is to generate enough revenue that a portion of each project group can be offered to local Low to Moderate Income residents with reduced cost participation options. TRCSS was awarded a National Community Solar Partnership Technical Assistance grant in 2020 and has continued to investigate the potential for adapting energy trading concepts to Community Solar at three levels: 1) Wholesale markets: Smaller projects aggregated to sufficient size that power can be sold through the ERCOT real time, day ahead, and long term markets using tools and practices already in use for some large merchant projects; 2) Commercial and industrial retail (C&I) markets: Smaller projects and some large single site installations might be managed using tools and practices already in use by energy managers and Sustainable Energy as a Service contractors or directly by Retail Electric Providers, Municipal Utilities, and Cooperative Electric Utilities; 3) Smaller C&I projects might use emerging tools and practices leveraging "Blockchain Transactive Energy" standards. * "Community Solar" has a component of ownership by the local community.

Keywords: Community solar · ERCOT market · Energy broker · Blockchain transactive energy · Low to moderate income

1 Introduction

Trinity River Community Solar Systems (TRCSS) is an early-stage start-up non-profit Texas corporation developing & designing Community Solar projects with local community participation in the North Central Texas region. This paper shares TRCSS' ongoing efforts to develop a model for developing Community Solar in the Electric Reliability Council Of Texas (ERCOT) competitive energy market. This territory includes most of the state of Texas, and has a unique structure with participants including generation companies, Retail Electric Providers (REPs), & Transmission & Distribution (T&D) Utilities. There are several Community Solar programs operated by Municipal Utilities such as Austin Electric, and Electric Cooperatives such as Pedernales Electric Cooperative (PEC), but arguably none that are "local" in the ERCOT deregulated/competitive

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areas at this time. Developing a model to expand local Community Solar to this territory is necessary to address important issues in Texas including emissions reductions and energy equity. The following subsections describe "where we are" as an introduction to where we are trying to go.

1.1 Distributed Solar in Dallas

TRCSS has been tracking the amount of distributed solar in the City of Dallas ("Dallas" or "City") reviewing permit data posted monthly by the City [1]. This approach leaves some gaps, but is useful in looking at relative trends and can be compared to other sources (see Sect. 1.2 following). The following charts show data as of March 2022 and include a projection to relate those values to the 2050 goals presented in the City's Comprehensive Environmental and Climate Action (CECAP) Plan (see Sect. 1.7 following) (Chart 1 and 2).

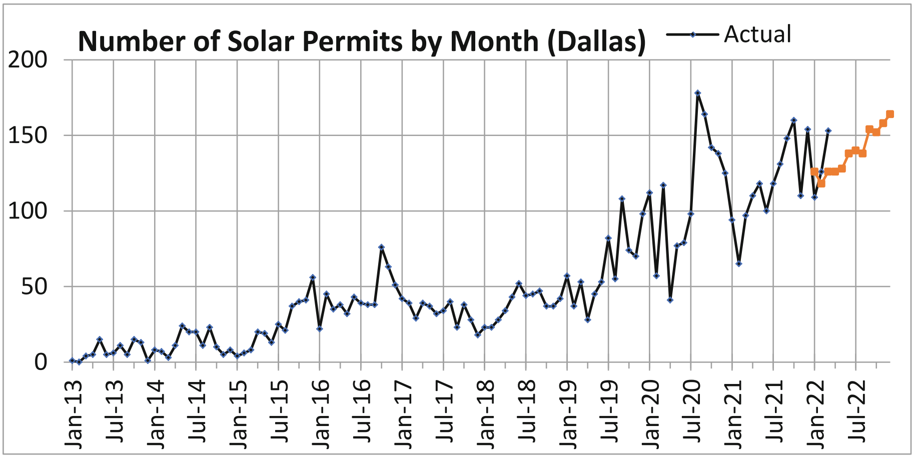

Chart 1. Solar permits by month in the City of Dallas. Source: TRCSS internal analysis of City posted data [1].

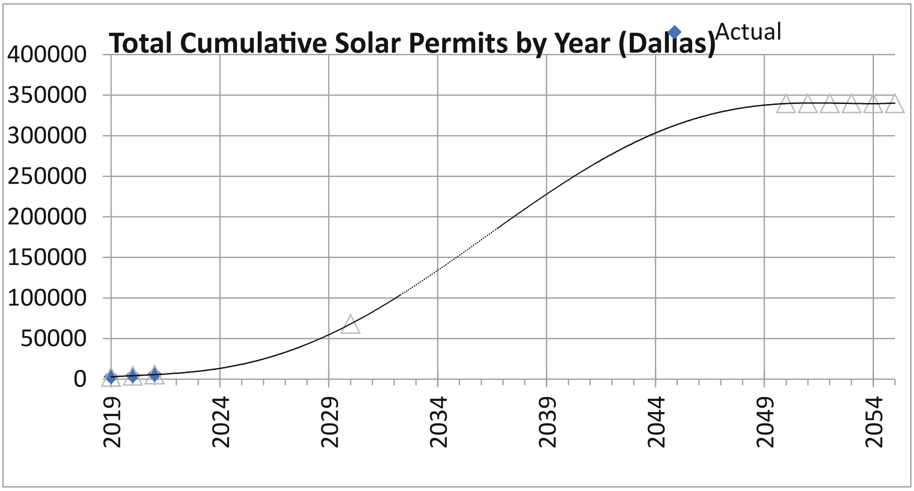

Chart 2. Total cumulative solar permits by year in the City of Dallas with projection to CECAP goal in 2050. Source: TRCSS internal analysis of City posted data [1].

1.2 Distributed Solar in Texas

The Public Utilities Commission of Texas requires T&D Utilities in the ERCOT region to submit an annual report presenting distributed generation sources in their territories. Oncor serves most of the North Central Texas region, and for the last several years has included a summary by city [2, 3]. TRCSS is working on charting these summaries for Dallas and other cities in North Central Texas. Note that 2021 data was recently published in March, 2022.

TRCSS also plans to research data from the other T&D Utilities as time and resources permit.

1.3 Community Solar in Texas

The National Renewable Energy Lab (NREL) publishes periodic updates presenting a list of "Community Solar" in the USA by state [4]. Since the ERCOT electrical grid is essentially isolated from the rest of the country, the NREL recent report includes several large utility scale solar installations in Texas which are considered local in the sense that they are on the ERCOT grid and located relatively close to population centers compared to earlier utility scale systems located in West Texas. Note that these "local" utility scale systems are becoming more common due to increasing transmission congestion charges incurred by far West Texas systems attempting to serve loads in distant large population centers including the DFW Metroplex, Austin, San Antonio and Houston.

1.4 Community Solar in the USA

TRCSS is a member of the National Community Solar Partnership (NCSP - a DOE/NREL partnership to support development of community solar). They recently set a goal (which TRCSS supports) of powering the equivalent of 5 million households with community solar by 2025, realizing a potential for $1 billion in energy bill savings for subscribers [5].

The NREL report [4] includes breakdowns of Community Solar in each of the other US states, as well as for Texas.

One specific use case that TRCSS is interested in demonstrating is the potential for shade structures on parking lots to use solar photovoltaic modules. An example of an analysis that TRCSS would like to see in regions like Texas was conducted for Connecticut [6] using data from an existing University of Connecticut study.

1.5 Community Energy Trading in Australia and Europe

Other regions of the world with high penetrations of distributed renewable energy systems have regulatory systems more easily adapted to the Energy Trading platform that TRCSS would be utilized for Community. Examples of viable programs and companies are available for those with the funds to provide access. Market research firms such as Guidehouse Insights provide reports on these activities. For those without the funds to procure the detailed reports, Executive Summaries provide useful lists of resources [7].

1.6 Transactive Energy in the USA

Two examples where TRCSS relies on research in the field of Transactive Energy in the USA will be the upcoming Institute of Electrical and Electronics Engineers (IEEE) Integrative Smart Grid Technologies (ISGT) Conference [8] and the IEEE Transactive Energy Systems Conference (TESC) [9].

1.7 Examples: Opportunities in Dallas

An obvious partner in developing pilot Community Solar projects in Dallas is the City itself, as part of achieving the goals set forth in its Comprehensive Environmental & Climate Action Plan (CECAP) [10].

A specific opportunity is the recently announced Fair Park Community Park project [11]. Opportunites that TRCSS is interested in developing include installing bifacial solar modules on shade structures inside the park and solar parking canopies for the new parking lot.

A major long-term development opportunity in Dallas is the Hensley Field Planned Urban Development on the site of a decommissioned Naval Air Station [12].

Another development concept opportunity is solar for multifamily housing. A new project was recently announced by a major developer with multiple planned locations throughout North Central Texas [13].

Finally, a smaller but noteworthy potential Community Solar site is the planned reclamation project Floral Farms (former Shingle Mountain site) Community Park [14].

2 Wholesale Markets in ERCOT

3 Commercial, Industrial, and Municipal Markets: Energy Brokers

Sections 2 and 3 above are important markets for adding to the value stack for Community Solar in Texas and TRCSS will continue to investigate.

4 Small Projects and Blockchain Transactive Energy

For commercial and small industrial solar PV installations, TRCSS is investigating paradigms for energy trading including but not limited to peer-to-peer (P2P) transactions.

4.1 Institute of Electrical and Electronic Engineers (IEEE)

TRCSS has been participating in the IEEE P2418.5 Blockchain In Energy Proposed Standard Working Group and Use Cases Task Force as part of TRCSS' efforts to stay current with developments in standardization [15].

TRCSS is also interested in presentations at the upcoming ISGT 2022 Conference (mentioned in Sect. 1.6 earlier) on Blockchain in Energy As A Venue for Electricity Grid Modernization (panel session, 4/21/22).

The IEEE Blockchain Initiative has an Energy Focus section that TRCSS is also following [16].

4.2 Existing Blockchain Transactive Energy (BCTE) Organizations

Examples of leaders in BCTE available in executive summaries such as the Guidehouse Report [7] include:

- Powerledger [17]
- LO3 Energy [18]
- Electron [19]
- Energy Web [20]
- WePower [21]

4.3 Decentralized and Web 3.0 Organizations

TRCSS research discovered "non-traditional" Blockchain software vendors such as:

- ConsenSys [22].
- Ocean Protocol [23].

4.4 Texas Implementation Strategies

The unique market structure in the ERCOT deregulated operating region provides unique implementation opportunities for community solar that TRCSS is just beginning to explore. Many of them are already in use at utility scale projects. The challenge for TRCSS is how to develop and implement local Community Solar projects without the overhead expenses becoming prohibitively costly. For example, it is relatively easy to register as a Retail Electric Provider (REP) in Texas and then be able to buy electricity from generation entities and sell that power at competitive rates it to residential, Commercial & Industrial (C&I), & municipal customers.

4.5 Other Technologies

Cloud Computing is an approach to managing energy data that may compete with Blockchain and Web 3.0 applications. This was discussed by Astrid Atkinson, CEO & co-founder, Camus Energy, who presented this approach at a recent Energy Systems Integration Group (ESIG) presentation on DER Modeling & Distribution Systems Operations [24].

5 Conclusion

5.1 Summary

Section 1 of this paper provided background on (a) the current state of distributed solar in the City of Dallas and in the State of Texas; (b) Community Solar in Texas, the USA, and elsewhere; (c) Transactive Energy in the USA; and (d) examples of opportunities for Community Solar in Dallas.

Sections 2 and 3 remain research in progress for TRCSS.

Section 4 provided some details about possible paradigms for Energy Trading at the small project level and for using Blockchain Transactive Energy.

5.2 Next Steps and Plans

TRCSS plans to continue its research into Community Energy Trading systems at the wholesale market level, as well as through Energy Brokers for commercial, industrial, & municipal entities in the deregulated ERCOT energy market of north Texas.

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Addressing Regulatory Challenges to Tribal Solar Deployment

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Abstract. Although Tribal land represents more than 5% of the solar photovoltaic technical potential in the United States, this resource is largely untapped due to a range of barriers, including complex project economics, Tribal technical and human resource capacity, project funding and financing obstacles, and regulatory challenges.

To identify and better understand the regulatory barriers, the National Renewable Energy Laboratory (NREL) and the Midwest Tribal Energy Resources Association (MTERA) engaged Tribes, utilities, and regulators. Funded by the U.S. Department of Energy, the 3-year effort seeks to address regulatory challenges or barriers that affect Tribal solar projects differently—specifically or disproportionately because they are located on Tribal lands.

This paper, largely excerpted from a comprehensive (draft) guidebook released by NREL and MTERA, provides an overview of 13 key regulatory barriers identified through this research, as well as potential short- and long-term solutions. In addition, the paper points to potential pathways for addressing key barriers through case studies highlighting successful Tribal solar projects along with considerations for stakeholders working with Tribes. These resources can support stakeholders in creating meaningful relationships and pursuing workable solar projects.

Keywords: Tribal solar development · Tribal sovereignty · Tribal energy resources

1 Introduction: Project Overview and Goals

Tribal land in the United States represents approximately 2% of the country's total landmass and holds more than 5% of solar photovoltaic (PV) potential (Doris et al. 2013). This resource is largely untapped. Many Tribes are actively seeking to engage in solar development. A review of 35 Tribal strategic energy plans in 2019 revealed 32 of 35 Tribes were exploring solar options for their communities. Many Tribes also cited regulatory hurdles to achieving these goals.

In 2020, the Midwest Tribal Energy Resources Association (MTERA) and the National Renewable Energy Laboratory (NREL) launched a joint effort to unlock some

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of this potential by bringing regulatory, utility, and other stakeholders together to articulate key barriers to Tribal solar adoption and develop replicable solutions. Funded by the U.S. Department of Energy's Solar Energy Technologies Office, the 3-year project seeks to help expand an emerging market by increasing institutional capacity and developing frameworks, trainings, and a technical document repository for regulatory bodies, utilities, and Tribes.

The goal was to address regulatory challenges or barriers that affect Tribal solar projects differently—specifically or disproportionately because they are located on Tribal land

These effects can be due to Tribal sovereignty[1] and associated legal and jurisdictional differences between these projects and non-Tribal projects off Tribal land. They can be due to land management, permitting, or ownership differences between Tribal and non-Tribal land. They can also be related to common Tribal circumstances that affect Tribes' abilities to pursue policy change.

This paper highlights the 13 significant regulatory challenges and associated solutions identified through this project and documented in the resulting (draft) guidebook, *Addressing Regulatory Challenges to Tribal Solar Deployment* (Beshilas et al. forthcoming).

In addition to offering a high-level summary of proposed solutions to common challenges outlined in the guidebook, this paper aims to improve stakeholders' understanding of unique aspects of developing solar on Tribal land, and to help stakeholders work together on future policy solutions.

2 Regulatory Dimensions

This project considers regulatory barriers from various dimensions, including project scale and jurisdictional level (Table 1).

Table 1. Regulatory jurisdiction at various levels.

Jurisdictional level	Organization	Regulatory jurisdiction
Tribal	Tribal government	Develops and enforces all Tribal codes, regulations, and policies on Tribal trust land. Note: Tribal utilities have different governing structures and may or may not be regulated by the Tribe, a separate governing board, or a Tribal utility commission

(*continued*)

[1] Tribal sovereignty refers to the legal right of Tribes to govern themselves and regulate their internal affairs. Some Tribes or Tribal members may understand sovereignty to include energy independence or the ability of a Tribe to control all aspects of their energy use and supply.

Table 1. (*continued*)

Jurisdictional level	Organization	Regulatory jurisdiction
Local utility	Cooperative local utility (or similar) governing board	Some electric cooperatives are not regulated by the state utility commission; for these, the board of directors or similar body is the jurisdictional authority. Note: State-regulated utilities develop and implement processes such as interconnection procedures in response to a state regulator or governing board
Local	County	Develops and enforces building codes, including electrical codes, that local electric utilities may default to for interconnection
State	State public utility commission	Regulates the programs, rates, rules, policies, and services of certain electric utilities (often investor-owned utilities [IOUs]; sometimes cooperatives or other)
Regional	Independent system operator/ regional transmission operator	Has governing structures and jurisdiction over processes for interconnection or with participating utilities; ultimately regulated by the Federal Energy Regulatory Commission (FERC)
Federal	FERC	Regulates the transmission and wholesale of electricity and natural gas in interstate commerce; regulates the interconnection process for connections to the bulk (interstate) power system

2.1 Options for Tribes to Engage in the Regulatory Process

Regulatory challenges are largely relevant at the outset of the solar project development process, but addressing them proactively can avoid additional unforeseen obstacles. Options for Tribes to engage in the regulatory process include:

- Participating in utility or regulatory workshops or planning processes, submitting comments into processes, or serving on an advisory group or board
- Meeting one-on-one with representatives of the regulatory body or utility to discuss policy and Tribal priorities
- Codifying intentions, Tribal authority, and clear development parameters and processes in Tribal policy (e.g., engage in strategic energy planning; develop Tribal codes regulating electricity standards, rights-of-way, rates)
- Working with a national association or other organization to develop model policy language; working with relevant governing body to implement
- Intervening in a regulatory proceeding
- Petitioning the state to open a new matter for hearing.

In addition to the approaches above, Tribes can form electric utilities to establish an entity with a long-term mission to participate in the regional electric market and associated policy discussions that affect the Tribe.

There are also different types of policy solutions: short-term options or workarounds and options that require more time, resources, and commitment.

3 Regulatory Challenges and Solutions for Tribal Solar Development

Through a series of Tribal listening sessions and stakeholder engagements, NREL and MTERA researchers identified the following 13 regulatory barriers to Tribal solar development, along with potential solutions.

Barrier 1: Lack of Tribal Representation in Utility, State, or Federal Energy Policy Decision-Making Processes. This barrier applies at all scales and jurisdictions. Short-term regulatory solutions may include:

- Outreach from Tribal staff or leadership to elected and appointed officials with information about Tribal perspectives or priorities
- Tribal liaison positions.

Long-term regulatory solutions could include:

- Tribal members run for or get appointed to office
- Generic dockets (Table 2).

Table 2. Comparison of stakeholder perspectives contributing to Barrier 1.

Tribal	Regulator	Utility
Tribes are often left out of the process, or do not have staff time or expertise, or financial resources, to engage with the process	Regulators must engage Tribes in the same way they engage with all other parties	Tribes may not be interested in participating in the utility planning processes
When Tribes do engage, they feel that their concerns are not considered	Regulators must engage all parties in a narrowly prescribed manner inside the confines of specific regulatory proceedings	Tribal and utility goals are different

Barrier 2: Tribal Government or Enterprise Leadership and Staff Energy-Related Technical Capacity. This barrier applies at all scales and involves Tribal government or enterprise jurisdiction. The short-term solution is securing support from Tribal leadership (resolutions) for solar work. Long-term solutions can include:

- Undertaking long-term planning initiatives
- Prioritizing energy by fully or partially funding an energy-related Tribal government position (Table 3).

Table 3. Comparison of stakeholder perspectives contributing to Barrier 2.

Tribal	Regulator	Utility
Tribes are often understaffed and under-resourced, and may not have relevant prior technical experience, making it difficult to engage in solar project development	Regulatory bodies may believe that it would be helpful if Tribes had energy experts with time and resources to devote to energy projects and decision-making process engagement	Utility staff may believe that it would be helpful if Tribes had energy experts with time and resources to devote to energy projects and decision-making process engagement

Case Study: Eastern Band of Cherokee Indians
Long-Term Stepwise Strategy Alleviates Tribal Capacity Challenges

The Eastern Band of Cherokee Indians (EBCI) Tribal Council passed a resolution in 2006 promoting a healthy, sustainable natural environment, setting a long-term energy vision, and enabling a project team to apply for a U.S. Department of Energy grant to move forward with strategic energy planning.

In 2007, EBCI established an Energy Committee, and in 2009 it completed a strategic energy plan and invested in a long-term energy coordinator position within the Tribal government. These actions addressed the Tribe's significant capacity challenges, enabling sustained effort and providing project and policy continuity. After completing an energy efficiency retrofit of nine buildings, which cut consumption by more than 30%, EBCI set its sights on solar.

This stepwise, deliberate process, with engagement of key decision makers across government and economic operations, was critical to the smooth execution of a 700-kW solar array at EBCI's Cherokee Valley River Casino, which offsets nearly 10% of electricity usage across the casino, hotel, and two administrative buildings.

"The commissioning and dedication of the Tribe's 705-kW solar PV system was a monumental achievement for the Tribe, as it was the first utility-scale system deployed on EBCI lands," said Joey Owle, Secretary of Agriculture and Natural Resources. "We demonstrated our ability to partner, plan, design, construct, and manage a solar PV system that is achieving the Tribe's previously targeted goals."

Barrier 3: Tribes Served by Multiple Utilities. This barrier applies at the distributed, facility, and behind-the-meter scales and involves local utility jurisdiction. The short-term solution is early engagement with utilities during project development. Long-term solutions can include:

- Forming a Tribal utility
- Developing Tribal utility codes (Table 4).

Table 4. Comparison of stakeholder perspectives contributing to Barrier 3.

Tribal	Regulator	Utility
It is challenging to manage government budgets and logistics for implementing projects when a Tribe is served by more than one utility with different sets of rules	Regulators or states manage the charters for utilities, as well as any additions or changes to a utility's service territory. The regulator does not direct changes in the territory	The utility's service territory is typically dictated by the state or is historical. Serving part of a Tribal territory is likely not an issue that concerns the utility

Barrier 4: Net Metering Limits or Lack of a Net-Metering Policy. This barrier applies at the distributed, facility, and behind-the-meter scales (often referred to as "rooftop" solar) and involves the jurisdiction of the local utility, governed by the state or the utility's board of director (if a cooperative or a municipal utility). The short-term solution may be to split projects into smaller sizes to meet size caps. The long-term solution can be to work with utility or state rulemaking proceedings to modify or establish net-metering rules (Table 5).

Table 5. Comparison of stakeholder perspectives contributing to Barrier 4.

Tribal	Regulator	Utility
Net-metering rules that provide a time-guaranteed high dollar value per kilowatt-hour produced provide strong economic support for developing behind-the-meter solar	Net-metering rules need to be in place so utilities, consumers, and the companies installing behind-the-meter solar have a structure in which to operate and a stable set of fiscal conditions to use in calculating the project's economic impacts	Net metering has historically been an incentive for consumers to build solar. The effective price utilities compensate net-metered consumers is higher compared to the price of utility-scale generating facilities (or utility-owned facilities). As more consumers take advantage of a net-metering program, the incumbent utility's revenue decreases, making it harder for the utility to pay for the fixed costs of building and maintaining electric infrastructure
Weak net-metering rules (low dollar value, "avoided cost," or no time guarantee) make the projects harder to make sense economically		
Lack of net-metering rules, net-metering project size caps, or lack of virtual net-metering mean that a solar array must be sized so that all of the generation is used on-site to capture its value		

Barrier 5: Limit of Third-Party Ownerships. This barrier applies at the distributed, facility, and behind-the-meter scales and involves the jurisdiction of the state regulator. Short-term solutions can include:

- Early engagement with utility during project development

- Cooperative group of investors.

Long-term solutions can include:

- State legislature creates policy ownership
- Judicial ruling
- Regulatory change (Table 6).

Table 6. Comparison of stakeholder perspectives contributing to Barrier 5.

Tribal	Regulator	Utility
Because Tribes cannot take advantage of tax credits, a third-party ownership arrangement can help make projects more cost-effective. Therefore, Tribes may want to use a third-party arrangement	The state regulator may consider a third-party owner a "utility."	When the definition of third party is unclear, the utility can choose to prevent third-party ownership
Tribes could be considered a third party		

Barrier 6: Distributed Generation Interconnection Requirements. This barrier applies at the distributed scale and involves the jurisdiction of the of the local utility regulatory board or state. The short-term solution is to work with the utility to determine project-specific solutions. The long-term solution may be to establish Tribal laws and regulations for interconnection rules and procedures (Table 7).

Table 7. Comparison of stakeholder perspectives contributing to Barrier 6.

Tribal	Regulator	Utility
Unclear interconnection policies and processes can prevent or delay projects	Utilities need to deliver affordable electricity to all customers, and any policies developed are typically meant to be equally applied across all customers in a particular customer class	Policies that have not been needed in the past may be time-consuming to develop or may disadvantage the utility and transfer costs to other customers, which the utility may be legally prohibited from doing

Barrier 7: Tribal Utility Formation Desire Conflicts with Existing Net-Metering Agreements. This barrier applies at the distributed scale and involves the jurisdiction of the utility and Tribe. Short-term solutions can include:

- Honoring arrangements for specific installations
- Evaluating project economics based on timing of system takeover.

The long-term solution may be for the Tribal utility to take over the electrical system (Table 8).

Table 8. Comparison of stakeholder perspectives contributing to Barrier 7.

Tribal consumer	Regulator	Utility
If an existing Tribal solar energy project has negotiated favorable net-metering arrangements, the Tribe may seek to keep the arrangement if the Tribe takes over the electric utility to continue generating as much revenue from the project as possible	The Tribal enterprise would be governed by a Tribal Utility Board or Tribal Council, outside the jurisdiction of state and/or federal regulators	Utilities would typically resist customer departure. However, in the case of a Tribe with several robust net-metering arrangements, the utility may be willing to negotiate a streamlined exit

Barrier 8: Tribes Served by Cooperative Utilities That Are Not State Regulated. This barrier applies at all scales (although it is more relevant at the distributed scale) and involves the jurisdiction of the incumbent cooperative utility. Short-term solutions can include:

- Connecting with National Rural Electric Cooperative Association experts
- Working with cooperatives to form mutually beneficial arrangements.

No applicable long-term solutions were identified (Table 9).

Barrier 9: Distributed Solar Program Incompatibility with Tribal Facility Circumstances. This barrier applies at the distributed, facility, and behind-the-meter scales and involves the jurisdiction of the local utility. Short-term solutions can include:

- Submitting comments on rulemaking to FERC
- Submitting comments to regional organizations

A long-term solution can be to create Tribal building codes so buildings are "solar-ready" (Table 10).

Table 9. Comparison of stakeholder perspectives contributing to Barrier 8.

Tribal	Regulator	Utility
When a co-op utility is not state-regulated, the Tribe may have little ability to participate in or influence decision processes and co-op planning without going to FERC	The co-op regulatory board is responsible for rulemaking to self-regulate the co-op	The co-op utility is regulated by a board, and decisions are made at that level
		Many co-ops have very limited staff and financial resources and face financial constraints to enabling noncooperative electricity generation projects

Table 10. Comparison of stakeholder perspectives contributing to Barrier 9.

Tribal	Regulator	Utility
Grid-delivered electricity can be expensive for Tribes in both absolute and relative terms, as many Tribal residents are remotely located. Residential, rooftop solar can be desirable from a personal standpoint in addition to the technology's alignment with common Tribal goals of energy independence and environmental protection	Regulatory perspective does not apply for this barrier as regulatory commissions are not usually involved in rooftop solar rules, but local regulations do matter	Tribal rooftop solar is another manifestation of a larger trend: increased distributed generation. As the entity responsible for maintaining the stability and integrity of the grid, utilities are primarily concerned with the ripple effects of rooftop solar on electrical infrastructure, especially the distribution system

Barrier 10: Nontaxability of Tribes and Investment Tax Credit Rules. This barrier applies at all scales and involves federal jurisdiction via federal tax laws. Short-term solutions could include:

- Developing taxable entities
- Forming tax partnerships.

Long-term solutions could involve federal legislation (Table 11).

Barrier 11: Lack of Options for Selling Utility-Scale Output (Without Being Connected to the Market). This barrier applies at the utility scale and involves utility, state, and federal jurisdiction. The short-term solution may be to work with state regulators or utility for near- or mid-term opportunities. Long-term solutions can include:

Table 11. Comparison of stakeholder perspectives contributing to Barrier 10.

Tribal	Regulator	Utility
Tribal governments do not pay federal taxes so cannot take advantage of the federal solar investment tax credit (ITC), making solar installations functionally more expensive	Not applicable	Not applicable
A cash grant in lieu of a tax credit enables Tribal governments to leverage federal solar incentives		

- Participating in utility resource planning and advocating for Tribally sited projects
- Effecting changes in federal legislation (Table 12).

Table 12. Comparison of stakeholder perspectives contributing to Barrier 11.

Tribal	Regulator	Utility
It can be challenging for projects on Tribal land to compete with projects off Tribal land due to additional permitting, the National Environmental Protection Act process, and other steps	The regulatory role is to support utility buildout of resources that will provide the greatest reliability at the least cost. Other factors and values can also be considered, but their influence on the decision process must go through a customary regulatory proceeding	Projects typically have to be proven to the state regulator or utility board to be cost-competitive. This does not typically consider values like local economic development or historically disadvantaged communities. Utilities may have an interest in supporting Tribal solar projects for Tribes whose land they cross with rights-of-way or they have a legal and material interest in

Case Study: Saginaw Chippewa Indian Tribe of Michigan
Tribe Leverages Its Sovereignty To Produce and Market Energy

When the Saginaw Chippewa Indian Tribe of Michigan started planning a casino and hotel expansion in 2012, it discovered the increased electricity usage would require a network upgrade to the electrical distribution facilities owned by its local utility.

The Tribe's land is adjacent to the Midcontinent Independent System Operator (MISO) bulk power transmission network, so in 2013, the Tribal Council decided to build its own substation and join MISO as a market participant. It also passed an ordinance creating the Saginaw Chippewa Indian Tribe of Michigan Tribal Electric Authority, which purchases wholesale electricity in the MISO footprint. Under the ordinance, the Tribal utility is authorized to sell power to non-Tribal retail customers as well as the Tribal hotel and casino.

Despite the incumbent utility's initial pushback, the Michigan Public Service Commission had no jurisdiction over the Saginaw Chippewa Indian Tribe of Michigan, a federally recognized Tribe and a sovereign entity. FERC approved the Tribe's interconnection request, paving the way for the Tribe to join MISO.

With its own substation, the Tribe was able to invest in its own infrastructure, exercise its right as a sovereign nation, and can now deliver safe, reliable electricity to Tribal and non-Tribal businesses within the Saganing Community's Tribal Trust Land near Standish, Michigan.

Because it is not regulated by the state, if the Tribe elects to sell power to non-Tribal businesses within Tribal trust land, it can build its own rate structure and offer more transparency and hedging options in electric service pricing. Its power could potentially be cheaper than incumbent utility pricing, but it would be exposed to real-time power price volatility.

As a market participant of MISO, the Tribe has access to virtual power trading that can be used to help large customers hedge the costs of their electric service. This level of transparency is typically only available to corporations with the largest electric usage, but the Tribal Electric Authority's efficiency makes these potential cost savings available to any business that operates within the Tribe's borders.

Other Tribes could learn from Saginaw Chippewa's experience and replicate the Tribe's model for their own financial gain, said Kevin Blaser, Energy Specialist for the Migizi Economic Development Company (the economic development arm of the Saginaw Chippewa, tasked with diversity and managing the Tribe's nongaming revenue sources)—especially as the electric grid becomes more distributed.

"Unlike gaming, Tribal nations can all participate in energy," he said, pointing out that while there is a limited market for gaming patrons across any given state, there is a lot of demand for energy services that can be provided by energy storage and other market products related to energy.

Barrier 12: Property Taxation Jurisdiction Questions Cause Double Taxation. This barrier applies at the utility scale and involves state and Tribal jurisdiction. The short-term solution can be to negotiate a tax-sharing agreement (Table 13).

Table 13. Comparison of stakeholder perspectives contributing to Barrier 12.

Tribal	Regulator	Utility
Tribes need to be able to recover tax revenue in the same way that counties and states do to fund services like public safety, road maintenance, and fire prevention, all of which benefit utility-scale renewable energy project owners. Allowing the county/state to tax the project as well results in double taxation	Federal (Bureau of Indian Affairs [BIA]): in 2013, the BIA issued a federal regulation (25 CFR § 162.017) prohibiting local jurisdictions or states from imposing property taxes on projects on Tribal land and Tribal member-owned land on a reservation	If a solar project is taxed by both the Tribe and the state/county, the cost of energy may be prohibitively high or uncompetitive with a project on non-Tribal land that is not double-taxed

Barrier 13: Lack of Tribal Land Use Planning or Land Entitlement Procedures. This barrier applies at the utility and distributed scales and involves Tribal and local jurisdictions. The short-term solution may be making ad-hoc decisions about land use. The long-term solution could be to establish land policy to make land-use planning more streamlined (Table 14).

Table 14. Comparison of stakeholder perspectives contributing to Barrier 13.

Tribal	Regulator	Utility
It is challenging for a Tribe to complete a solar project if land use planning is difficult or unclear	No relevant perspective from state regulatory authority	A utility may be impacted by this barrier if the utility is working with a Tribe on a solar project
		Projects built on Tribal land may be more expensive if land use is difficult to navigate, making them less cost-competitive in utility requests for proposals

4 Conclusion

This paper is based on a forthcoming guidebook that NREL and MTERA wrote detailing 13 key regulatory barriers as well as potential short- and long-term solutions. The *Addressing Regulatory Challenges to Tribal Solar Development* guidebook also points to potential pathways for addressing key barriers through case studies highlighting successful Tribal solar projects along with considerations for stakeholders working with

Tribes. The final section of the guidebook presents issue briefs that provide insight into certain topics and introduce stakeholders to important concepts related to Tribal solar development.

By increasing understanding of issues that are important to Tribes, this information can support all stakeholders in creating meaningful relationships and pursuing workable solar projects.

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Advances in Solar Powered Water Pumping: Providing for Energy Resiliency and Social Equity

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Abstract. Solar water pumping (SWP) is a mature and reliable solution for irrigation, livestock, and community water supply for human consumption and hygiene. Low cost of photovoltaic (PV) modules, combined with advances in pump, motor and control and communication technologies, are transforming the way we pump water globally. Traditionally, solar pumps have served off-grid locations by simply filling a storage tank, but applications are expanding to include integration and power-sharing with battery-based and grid-tied systems.

Access to affordable water is often a matter of social equity, where over a billion low and middle income (LMI) people around the world do not have access to a clean and safe water supply. SWPs are cost competitive as compared to diesel pumps or electric pumps powered by the grid. Water supply is a great consumer of energy worldwide. SWPs are an alternative to grid expansion, diesel generators, traditional windmills and water hauling. This paper introduces SWP for a range of applications. Economic and social equity benefits are presented, using examples from around the globe.

This paper includes highlights from the authors' upcoming The Solar Water Pumping Handbook (to be published by CRC Press by 2023), which combines their decades of worldwide experience with recent research, as well as worldwide case studies. This paper discusses new SWP technology, sizing and system configurations, remote connectivity, economics, financing models.

Keywords: Photovoltaics · Solar water pumps · Water supply · Irrigation

1 Introduction

Solar water pumping reduces the demands for fuel-consumption and power grid extension. It supplies the most water when it is needed the most, with the fewest moving parts. There is an excellent match between seasonal solar resource and seasonal water needs. A wide range of needs can be met by SWP, from livestock and community water supply to small and even large-scale irrigation. The field has benefited from price drops in

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photovoltaics (PV) and other technologies, and is poised for major growth. SWP system costs have declined significantly, from over US$25 per peak watt over 25 years ago to total system costs under US$3 a peak watt today [1].

1.1 Scope of SWP Applications

The following figure illustrates the global range of SWP techniques and applications (Fig. 1).

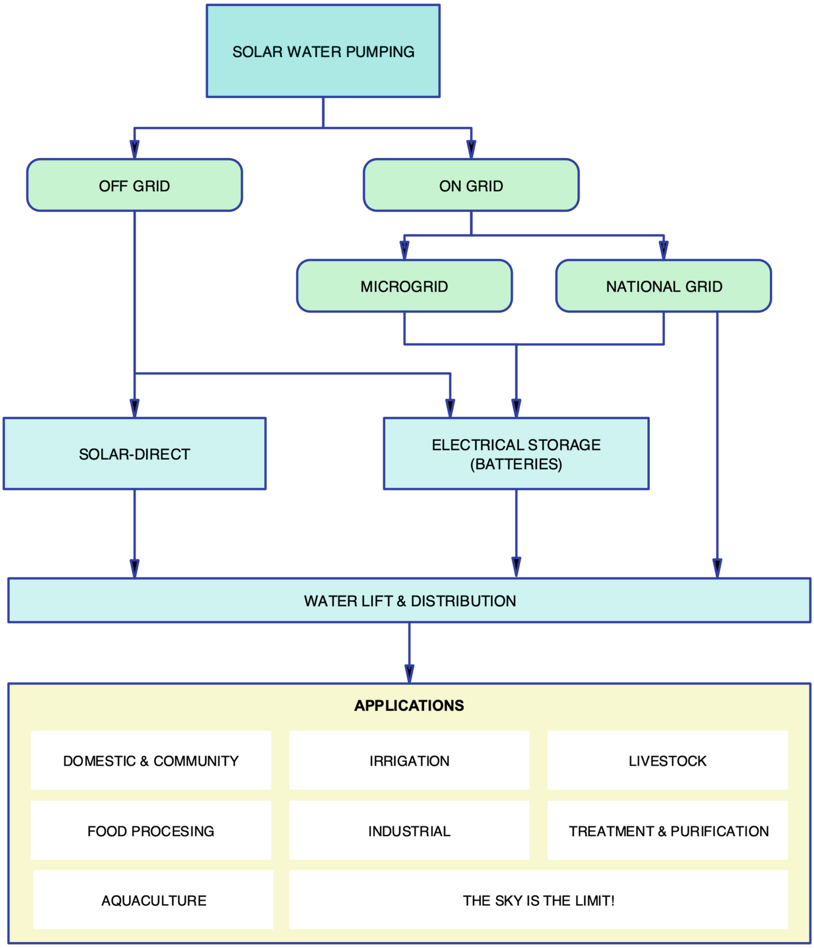


Fig. 1. Graphic overview of solar pump techniques and applications [1].

1.2 Typical Stand-Alone SWP

A SWP system resembles other electric pumping systems, except that the power source is solar energy. SWP systems have, as a minimum, a PV array, a motor, a pump, and normally a water storage tank. Alternating current and direct current motors are used with either centrifugal or displacement pumps. Water is typically stored in a tank or pond, but electro-chemical battery storage is also viable in some cases. Pump motors are most-often direct-driven from the PV array using a power-matching controller, thus eliminating batteries, decreasing costs, and increasing reliability. SWP schematic and size categories are shown below.

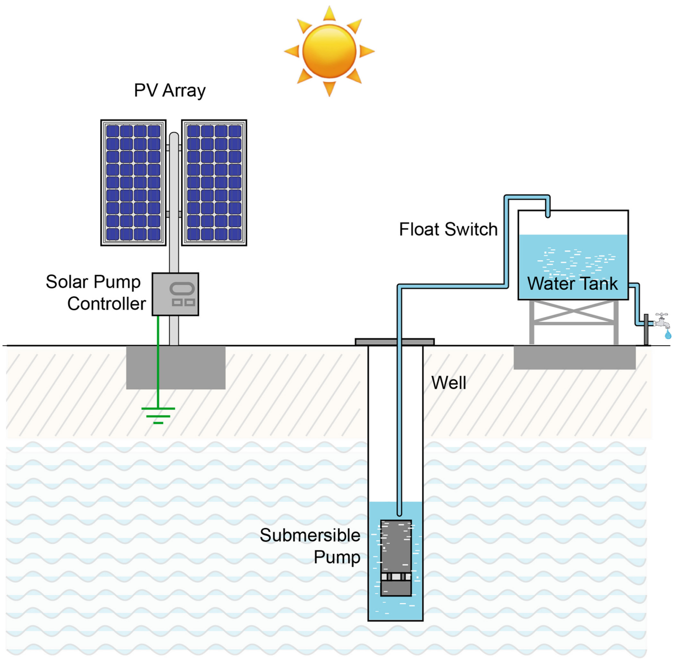
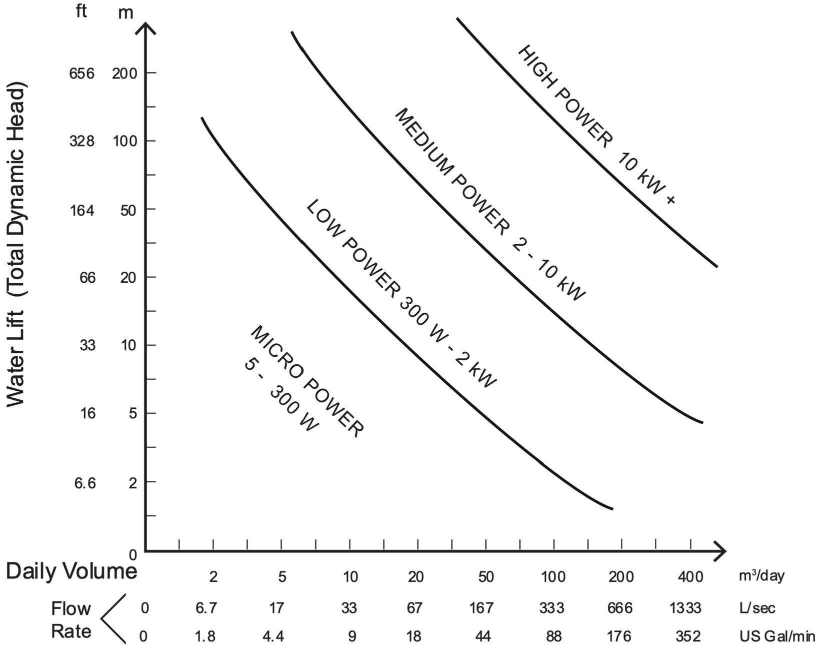


Fig. 2. Typical stand-alone PV-direct SWP system [1].

2 Defining Power Ranges

The authors have defined four ranges of power, micro, low, medium and high. SWP products are commercially available in all these ranges, from 5 watts to over 100 kW. The following figure illustrates these four power ranges plotted against vertical lift and water flow. This graph also provides a way to roughly estimate the power requirement for pumping water for any situation in which the lift (total dynamic head) and the water demand are known. A rough power estimate is a first step in determining the economic feasibility of a proposed system (Fig. 3).

Micro-power and low-power systems can provide affordable water for even poor, smallholder farmers, by pumping throughout the entire day. The smallest SWPs have the longest history for commercial application, and show the most technology diversity, often using displacement pumps and DC motors. The low-power range brings in greater use of



NOTE: Figure based on wire-to-water efficiency of 40% for the micro range, 45% for low range, 55% for medium range, and 70% for high range. Daily Volume is based on average 6 peak sun hours per day, typical of a semi-arid climate. 1 m^3= 1 cubic meter = 1000 liters = 264 US gallons

Fig. 3. SWP power ranges related to vertical lift and flow [1].

centrifugal pumps and AC motors. The medium and high-power ranges use conventional centrifugal pumps with AC motors.

3 Technical Advances in SWP

Significant advances of the past 25 years include simpler, more efficient pump mechanisms, brushless DC motors, AC solar motor controllers (pump inverters) for conventional pumps and retrofits, improved batteries, grid integration with energy management, and remote connectivity for monitoring and managing pumps from a distance.

3.1 Pumping Mechanisms

One major commercial pump development of the past 20 years is the *helical rotor* submersible pump. It is a *displacement pump*, in contrast to conventional *centrifugal* pump mechanisms. Its efficiency is superior for high lift and for low and variable pumping rates. It takes the place of piston and diaphragm pumps, using just one moving part and eliminating most maintenance. The figure below shows one example (Fig. 4).

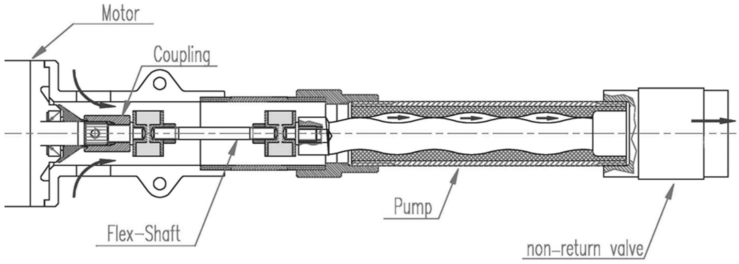


Fig. 4. Helical rotor pump, cutaway view, shown horizontally Source: Bernt Lorentz GmbH.

The following figure summarizes how the various SWP mechanisms fit the full range of water lift and flow that is found around the world (Fig. 5).

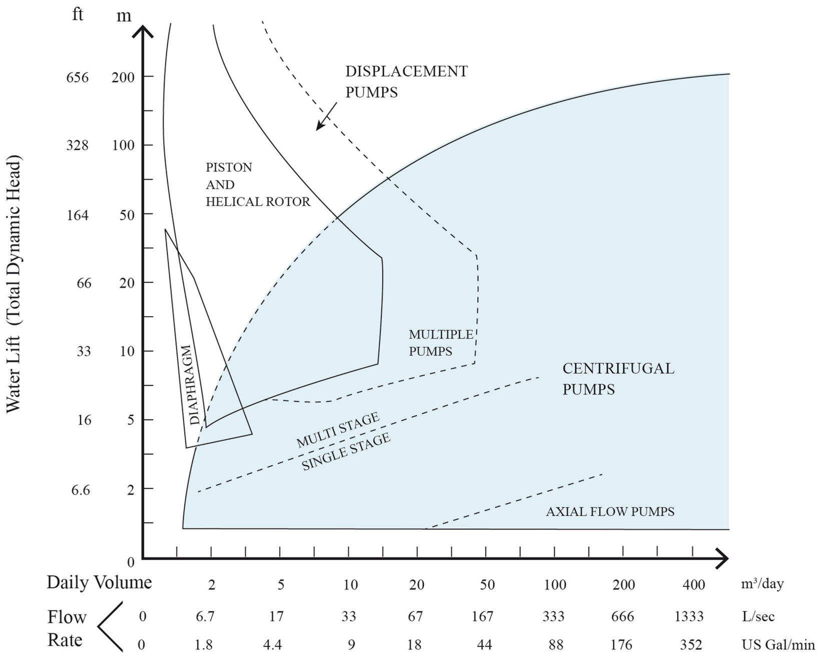


Fig. 5. Pump mechanisms in relation to vertical lift and water requirements [1]

3.2 Motors and Controls

Major advancements include high-efficiency variable-speed motors, and the electronic controllers that enable them. Pumps start earlier in the day, and resist stalling as clouds pass by. A different family of controllers enables conventional electric pumps to run from PV power; called *AC pump controllers* or *pump inverters.*

3.3 System Configurations

SWP systems follow a variety of configurations besides the traditional PV-direct, non-battery pump. Some use storage batteries, and some are integrated with a power grid. The following figure illustrates these choices, in the form of a decision tree (Fig. 6).

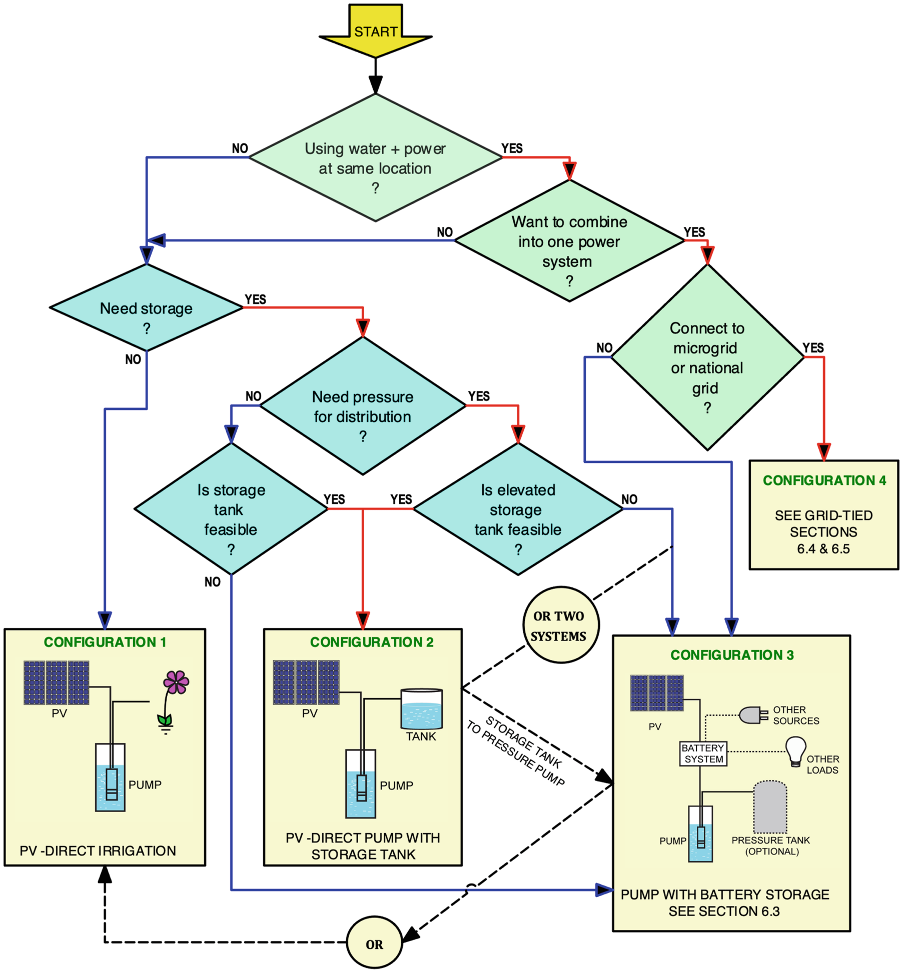


Fig. 6. Selection guide to SWP system configurations [1]

Traditionally, for simplicity and economy, SWPs have been PV-direct, meaning there is no battery or connection to any other power system. This is indicated as Configurations 1 and 2, and illustrated in Fig. 2. Pumping occurs only when the sun shines. Water is stored in a tank or pond, or applied directly to farmland. Other configurations now open the field to a greater range of possibilities. Advancements in batteries make energy storage safer and more economical than it was in the past. Battery storage is most beneficial in these cases:

- where a large water tank is not practical or economical
- for pressure, where the elevation of a tank is not practical or economical
- for irrigation that requires steady flow for uniform water distribution
- for portable and emergency pumping, to provide water on demand
- for centrifugal pumps that work poorly at reduced speeds
- for slow-recharge water sources, where water must be pumped at night too
- for water treatment and other processes that require steady pressure
- where a battery-based system is needed for other electrical applications

In a PV-battery system that serves a home, school, clinic or workshop, a small water pump is often integrated, as simply one more electrical load. This can be a simple and economical approach to SWP. When less pumping is needed (winter or wet season) the PV resource is available for lighting and other needs. On a farm, when irrigation isn't needed, power can be applied to refrigeration or crop processing. This concept also applies when power systems are networked to form *solar micro-grids*.

If a water source is located near a national power grid, typical grid-tied PV arrays may be considered. They can connect at any suitable location on the grid, while existing pumps can remain in place. When pumping is not needed, excess solar power may be sold to the utility, to meet the demands of other consumers. If pumping is needed when solar power is low, power may be purchased back from the grid.

3.4 Energy Management

Energy management is a core concept of grid integrated SWP. Pumping can be synchronized with solar availability, to minimize the dependence on stored energy. The concept applies to power-sharing systems of all sizes, from off-grid homes to village micro-grids to national power grids. This expands the definition of "solar water pumping" to systems on every scale.

3.5 Remote Connectivity

SWP systems in the most remote locations can now be monitored and controlled from any distance, by remote connectivity. No longer does a ranch hand need to drive a truck for many miles to check on pump operations. Many SWP products have connectivity features built-in so it can be easily enabled through cellular or satellite or internet connection. Pump owners and managers can monitor water flow, tank levels and more, and be alerted if a failure occurs or if maintenance is due. These systems make pumps user-friendly in ways that were never dreamed of in the past. Pumps can be switched on or off at a distance. Payment schemes (pay-as-you-go) can be coordinated, all without personal visits to pump sites. Connectivity also enables energy management in micro-grids and in public grid-tied systems, where pumping power is synchronized with solar power, even at great distances.

4 SWP Economic Models

Private-sector SWP adoption occurs as a result of successful pilot projects. The local population must understand the technology and what it can provide; quality products and services must be available locally; and the ability to pay for the technology must exist. For the latter, access to applicable financing mechanisms is key. Initial capital investment can be prohibitive for many rural farmers and ranchers in less developed regions, despite the fact that the levelized life-cycle costs of SWPs are highly competitive. Standard approaches used to purchase of SWPs are:

- Cash sales
- Financed sales
- Pay-as-you-Go (PAYGO) for water service
- Leasing
- Direct Subsidies

Market-based financing and leasing approaches for SWPs have the greatest potential for expanding the access of rural households to this technology. Renewable energy for water pumping also offers the potential to generate new and important business activity in rural areas by creating jobs through local retail sales and services (Fig. 7).

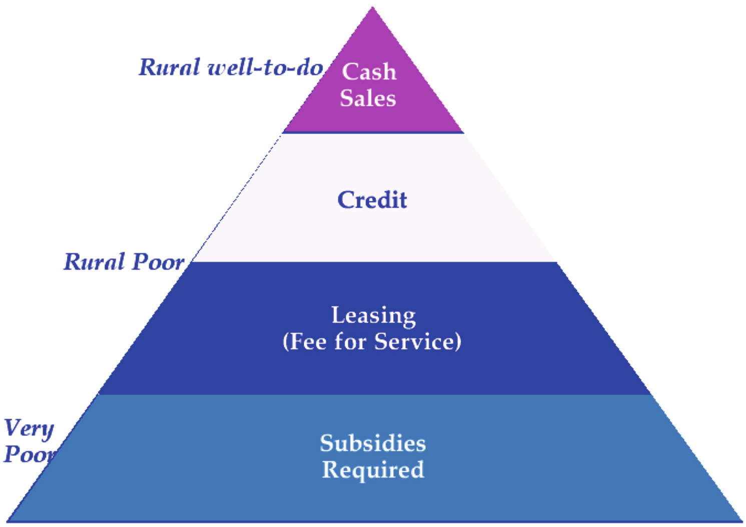


Fig. 7. Institutional SWP sales pyramid [2].

Sales of SWPs in rural regions of less developed countries occur at four different levels, as exemplified by the sales approach pyramid shown above. At the top of the pyramid are the few direct cash sales to relatively well to do rural households that can afford the high initial capital costs. Following this, are many more consumers who can afford to purchase a system if reasonable credit terms are provided, including Pay-as-you-Go options. There are still more people who could afford to simply pay a small service fee by leasing a SWP. Finally, there are the poorest households who may even live outside of a cash economy and are simply trying to survive. They may be have no access to SWPs unless it is directly subsidized [2].

4.1 SWP Economic Models and Equity Impacts Case Studies

4.1.1 Kenya: Solar irrigation in Homa Bay

Ms. Lilian Akinyi rents a farm in Homa Bay County near Luala Kambuya village. She was using a diesel pump to transfer water from a canal which is fed by the Sondu Miriu River. She hired the diesel pump one day a week for US $5.50, which included petrol and transport. She irrigated 0.75 acre of tomatoes with the diesel pump and 0.25 acre of kale with a watering can. In September 2016 Ms. Akinyi purchased a Futurepump solar pump powered by a 80 W_p solar module and a 12m pipe through Futurepump's Pay-As-You-Go program. She paid US $236 down, and made monthly loan payments of US $20 for 22 months. She stopped using the diesel pump after the SWP purchase (Fig. 8).

Fig. 8. Smallholder Kenyan farmer Lilian Akinyi with her 0.75 acre solar irrigated maize crop.

Ms. Akinyi eliminated diesel pump rental, fuel and transport costs, has increased her irrigated area from 1 to 1.25 acres, has added a maize crop, and is irrigating more frequently than before. We assume she will increase to 1.5 acres by the second season after purchasing the solar pump. Using conservative estimates, her gross profit is projected to increase by 186% by her second season after purchasing the solar pump. A profit and loss analysis for Ms. Akinyi is shown in Table 1 [3].

Table 1. Kenya SWP of Lilian Akinyi profit and loss analysis [3].

	Year 1 Actual		Year 2 Actual	Year 3 Projected
Lilian Akinyi Farm	**Season 1 (Pre-SWP)**	**Season 2 (Post-SWP)**	**Season 1**	**Season 2 (Post Loan)**
Farmer Profit and Loss Statement				
Acreage Planted	Tomatoes: 0.75; Kale 0.5	Tomatoes: 0.25; Kale 0.25; Maize 0.25	Tomatoes: 0.5; Kale 0.5; Maize: 0.5	Tomatoes: 0.5; Kale 0.5; Maize: 0.5
Total Yield (kg)	2,517	3,683	6,300	6,900
Yield change, %		*46%*	*71%*	*10%*
Total Revenues	**99,200**	**144,890**	**250,600**	**282,800**
Revenue growth %		*46%*	*73%*	*13%*
Operating Costs	29,530	38,063	50,246	52,700
Pump Fuel and its Transport	2,500	1,000	-	-
Pump Hire and Maintenance	3,000	3,700	1,500	1,800
Total Operating Costs	**35,030**	**42,763**	**51,746**	**54,500**
Gross Profit	**64,170**	**102,127**	**198,854**	**228,300**
Gross Profit Margin, %	*65%*	*70%*	*79%*	*81%*
Loan + interest payment (6 months)	-	15,000	15,000	-
Earnings Before Taxes (EBIT)	**64,170**	**87,127**	**183,854**	**228,300**
Debt Coverage and Investment Returns				
SWP Total Upfront Investment	78,600	5 Yr Return on Investment (ROI)		18.14
financed by own savings	23,600	5 Yr Internal Rate of Return (IRR)		197%
financed by Vendor Loan (10%, 2 yrs)	55,000	Incremental Gross Profit/Initial Investment		2.56x
Loan Principal and Interest due in 2yrs	65,000	Cash Flow/Total Debt Coverage		10.63x
vs Cash flows generated in 2 years	691,011			

4.1.2 Nepal: Empowering Women and Improving Livelihoods

"I can now earn enough to invest on the education of my children and I feel empowered" - Ms. Dila Gurung.

Ms. Dila Gurung, 35 years old from the off-grid Taule village in Surkhet District, was in a difficult economic situation before acquiring a SWP. Even though she has holding 5 Ropani (0.62 acres) of land, she was dependent on intermittent rain with no prospects for irrigation to increase crop productivity. The money provided by her husband who works in Qatar was inadequate to provide and educate their four children. She was in debt with no hope of loan repayment. WI approached her about the potential to extend her ability to grow crops during the dry season through solar powered irrigation that would help transport 10,000 L of water per day uphill from the nearby river to her fields.

Her land is now green with high value commercial vegetables made possible with a SWP in collaboration with the Sitaram Agricultural Group. Financing was made accessible through the Small Farmer Saving and Credit Cooperative. Technical support was from Winrock International from the USAID AC-PVWP project in collaboration with the Veri-Ganga municipality and USAID KISAN project.

The 1,260 W_p SWP installed at Taule-10 is primarily used for vegetable farming. The system includes 9 PV modules (140 Wp each) from Ningbo Komaes Solar Technology. The system is community-based, benefiting 11 active farmers. It is designed to pump 10,000 L per day of water at a total dynamic head of 60 m. The SWP system was installed at a total cost of US$4,766 using a Grundfos 1.26 kW SQF-3A10 helical rotor pump. KISAN arranged a cost-sharing agreement in which eight farmers took out a loan of $3,000 from a local farmers' cooperative, paid back by additional income from vegetable sales. Winrock, KISAN and the local Veri Ganga Municipal government contributed grants totaling $2,200. With labor supplied by the farmers and technical expertise from Winrock. The system was installed in May of 2015 [4] (Fig. 9).

Fig. 9. SWP array rated at 1.26 kW_p used for irrigation by the Taule village farmers.

Consistent access to water has greatly increased the amount of vegetables Gurung and his fellow farmers can grow. "*After the solar pump, the production has increased 70 or 80 percent*" says Gurung. Household incomes have also risen between $300 and $2,750 annually, allowing the farmers to pay off the loan for the SWP.

The SWP has completely changed Mrs. Gurung's lifestyle. She appreciates the low maintenance and running costs, and quiet operation. Her traditional subsistence farm has become a profitable enterprise. She harvests high value commercial vegetables and has seen a five-fold increase in her annual income. She grows cauliflower, cabbage, and red chilies and sells to the local markets. She is financially empowered and earned US$1,9145 in the first year. She has improved self-esteem, and new technical skills from KISAN farmer trainings. "*I feel socially, financially and technically empowered after commercial vegetable farming. I shared my journey of transition and boundless* *opportunities brought by the solar pump to Haree village to inspire women to switch to commercial vegetable farming*" [4].

4.1.3 Bangladesh Rural Electrification Board (BREB)

Bangladesh's agriculture sector faces increasing challenges with water access as a constraint for farmers with irrigation required for ~6 months/year. A majority of the country's farmers depend on inefficient flood irrigation systems powered by over 1.27 million diesel pumps, as well as 270,000 subsidized on-grid electric pumps [5].

The Bangladesh Rural Electrification Board (BREB) is addressing these challenges by implementing a SWP program with the Asian Development Bank by installing 2,000 SWPs, focusing on replacing diesel pumps ranging in pump size up to 20 kW. The farmer pays half of the investment costs; partly through an installment with remaining monthly payments, or for on-grid systems via credits through power sold back to the grid, especially for the half year when irrigation is not needed [5] (Fig. 10).

Fig. 10. Bangladesh BREB SPPAI 7.5 kW SWP installed in Dinajpur in December, 2021.

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Our Path to 24/7 Renewable Energy by 2025

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Abstract. Peninsula Clean Energy, the official power provider for California's San Mateo County, has an unprecedented goal in the utility sector of providing all of our customers with 24/7 renewable electricity by 2025. This white paper is the first in a two-part series and outlines our 24/7 renewable energy vision, why it is critical to tackling climate change, our progress to date and how we are planning to achieve this trendsetting goal reliably and cost-effectively. Accomplishing this goal would be one of the most consequential actions we can take to mitigate our rapidly changing climate. This can provide affordable, reliable and clean power to customers throughout our incredibly diverse service territory - which stretches from industrial and blue-collar South San Francisco and East Palo Alto, affluent and influential Menlo Park and Atherton, senior communities in coastal Half Moon Bay and, starting in 2022, the city of Los Banos in central California's Merced County. Just as important, it can serve as a model for others to more broadly implement 24/7 renewable power, especially as part of efforts to shut down fossil-fuel power plants in disadvantaged communities and convert to pollution-free renewable alternatives.

Keywords: Renewable energy · Time-coincident · 24/7 · Decarbonize · Carbon-free

1 Why we are Pursuing 24/7 Renewable Power

Since our inception, Peninsula Clean Energy has pushed the boundaries in clean energy procurement and deployment to significantly reduce greenhouse gas (GHG) emissions. In 2016, we set an unprecedented goal for a California load serving entity at the time: to procure 100% renewable energy. However, we knew this goal in and of itself was not sufficient to drive the long-run transformation needed to achieve a fully decarbonized grid. So, we decided to push the boundaries even further. In 2017, we adopted a goal to deliver 100% renewable energy on a 24/7 basis by 2025, matching our renewable energy supply with our load every hour of every day to reduce our demand signal for fossil fuels from the grid [1].

From the beginning, we also committed to affordable pricing and have maintained prices consistently below those of Pacific Gas & Electric (PG&E). We believe this is important for widespread consumer adoption of clean energy. This is because, even though research indicates that nearly half of Americans say they are willing to pay more

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for clean electricity, we have found that only a very small percentage of our customers choose to do so [2].

Peninsula Clean Energy was already delivering 50% renewable energy to our first customers in 2016, 14 years ahead of California's goal of 50% renewable by 2030. In 2021, we procured 100% renewable or carbon-free power for all our nearly 300,000 customers. We have done this while building a financially strong organization, with two investment grade credit ratings, and providing this cleaner electricity at a consistently lower price than what our customers would pay at PG&E rates, savings our customers over $90 million to date, and demonstrating that we can reduce GHG emissions and save consumers money at the same time.

This is the cornerstone of the challenge we set for ourselves: How to cost-effectively deliver 100% renewable energy on a 24/7 basis by 2025. Because our load profile is similar in shape to the system-wide load profile in the state, we believe that achieving this goal would demonstrate that this approach is scalable state-wide. If we can achieve this goal, we can provide a model for other load serving entities to follow and accelerate further reductions of GHG emissions in the electricity supply.

The need to do this is urgent, a fact recognized by many since we set our goal in 2017. The following year, Google described its vision of a 24/7 carbon-free goal for their data centers and campuses, and in 2020 set a goal to achieve this by 2030 [3, 4]. Cities such as Los Angeles, Sacramento, and Des Moines have now set similar goals, and researchers at RMI (formerly Rocky Mountain Institute) and Princeton have begun studying the trend [5–9]. Earlier this year, the United Nations started building a global coalition for 24/7 carbon-free energy [10]. Our goal still remains the most ambitious in terms of its timeline and commitment to renewable energy.

This white paper introduces Peninsula Clean Energy's vision for 24/7 renewable energy, our progress to date, and at a high level how we are planning to achieve it by 2025. This paper will be followed in the next few months with a report containing the results of our modeling, including details about the expected costs and resource mix required to achieve this unprecedented goal.

2 Renewable Energy vs. Carbon-Free Energy

Renewable energy is produced from resources that are naturally replenished as they are used, while carbon-free energy is produced from resources that do not emit greenhouse gases into the atmosphere. Many resources are both renewable and carbon-free (such as wind and solar), some resources are renewable but not carbon-free (such as biomass), and others are carbon-free but not renewable (such as nuclear). In our case, when we talk about renewable energy, we are using the definitions set by California's Renewables Portfolio Standard [11]. As we develop our mix of resources to meet our goal, we will consider renewable baseload resources such as geothermal and biogas, which may emit small amounts of carbon but generate electricity on a continuous basis in all hours of the day (Table 1).

Table 1. Comparison of resources to meet 24/7 renewable goal

Supply resource	Renewable	Carbon-free	Baseload	Median emissions factor[a] ($lbCO_2e/MWh$)
Solar PV	X	X		0
Wind (Onshore and Offshore)	X	X		0
Geothermal	X	Certain types	X	126
Small Hydroelectric (<30 MW)	X	X		0
Biogas	X		X	8
Wave/Tidal	X	X		0
Biomass	X		X	52
Large Hydroelectric		X	X	0
Nuclear		X	X	0

[a]Peninsula Clean Energy's currently contracted geothermal resource has an emissions factor of 79 lbCO2e/MWh

3 What is 24/7 Procurement and Why is it Important?

To better understand what it means for Peninsula Clean Energy to deliver renewable energy to our customers, it is first necessary to explain generally how the electric grid works. In physical terms, the electric grid is a system of wires that transmits and distributes electricity throughout the state, connecting our customers with the renewable energy generators under contract with us. As an analogy, it can be helpful to think of the electricity grid as a river. Just as streams and tributaries add their water flow to larger rivers, power plants throughout California add their energy to the electricity grid. Just as downstream customers can draw water from the river to use in their homes and businesses, our customers consume energy from the grid. The key point of this analogy is that just as it is impossible to track the source of a single molecule of water drawn from a river, it is similarly impossible to track exactly where each electron you consume comes from.

The electricity that we deliver to customers is therefore tracked based on contractual terms, rather than physical terms. We know how much metered energy our contracted generators deliver to the grid, and we make sure that it is the same amount of metered energy that our customers use. While in contractual terms we currently deliver a specific mix of renewable and carbon-free electricity to our consumers, the physics of the power grid means that everyone consumes a mix of electrons from both the carbon-free and fossil-based resources that deliver energy to the grid.

In addition, the timescale that we use to track our contractual renewable energy deliveries matters. California's current regulatory standards for procuring and reporting clean electricity, such as the Renewables Portfolio Standard and Power Source Disclosure program [12], are tracked on an annual basis. We count how many megawatt-hours

(MWh) of electricity our contracted generators produce in a year and match that to the number of MWh that our customers consume in a year. This annual accounting framework is how we are required to report our procurement to the state and report in our Power Content Label sent to our customers [13].

However, this annual accounting standard ignores whether our contracted generators produce electricity at the same time our customers use it. At certain hours, our contracts generate less clean energy than our customers are using. During those times, we must rely on generic grid electricity (most of which in California comes from methane gas[1] power plants) to make up the difference. In other hours, our contracts generate more clean energy than our customers use. Under the current standards, we can "credit" this excess clean generation to the hours when we rely on fossil-based grid energy and net out our grid energy use on an annual basis. While the excess renewable generation we contribute to the grid in some hours generally displaces fossil generation, we continue to send a demand signal for fossil-based energy in those hours when our clean energy contracts do not match the timing of our customers' energy demand (Fig. 1).

This is why a 24/7 renewable energy approach, which matches renewable energy supply with demand on an hour-by-hour basis, is so important for the success of our state and global decarbonization goals. It enables us to help eliminate the demand signal for fossil-based electricity from the grid that our customers' electricity consumption presently provides at the times when our contracted renewable generation does not match our load. Reducing demand for this fossil-based electricity generation means that these generators run less frequently and become less economic to operate, ultimately helping to expedite the retirement of these resources. The 24/7 procurement approach also helps address the state's grid reliability needs, helping to ensure that there is enough renewable capacity on the grid at the times when it is needed, and helping to address the state's renewable integration challenges characterized by the "duck curve" [14].

Although Peninsula Clean Energy is just a small part of the California grid, if we can demonstrate that 24/7 procurement can be achieved practically and cost-effectively, it will create a blueprint for others to follow. If scaled, this collective action to achieve 24/7 goals can ultimately lead to a carbon-free electricity supply for the whole state and beyond.

4 Our Progress to Date

As of 2020, based on the annual accounting standard, Peninsula Clean Energy delivered 52% renewable energy and 47% large hydro to our customers [13]. Our delivered electricity had a GHG emissions intensity of 12 lbCO2e/MWh, compared to the California utility average of 466 lbCO2e/MWh[2].

[1] Methane gas is also marketed as "natural gas".

[2] 12 lb/MWh is a load-weighted average of our "ECOplus" product with a GHG intensity of 13 lb/MWh, and our "ECO100" product, which had a GHG intensity of 0 lb/MWh. The non-zero emission footprint of our portfolio on an annual basis is related to small emissions associated with geothermal and biomass energy sources.

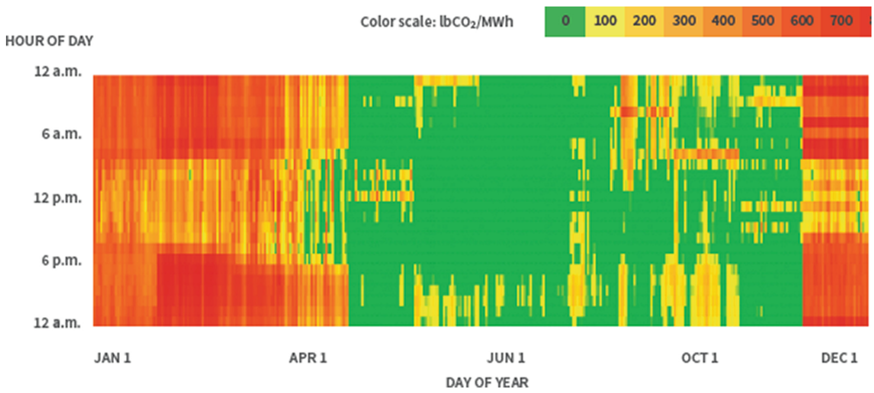

Fig. 1. Hour-by-hour emissions intensity for 2020

This heatmap shows the estimated carbon intensity of Peninsula Clean Energy's delivered electricity for every hour of the year in 2020, considering the emissions intensity from our renewable energy and greenhouse gas-free contracts as well as the use of generic (fossil-based) grid energy. When available, we used the actual hourly generation data from our contracts to develop this heatmap, otherwise, we used the CPUC Clean System Power Calculator to estimate the hourly generation.

Also as of 2020, 47% of our hourly load was matched by contracted renewable energy generated in the same hour. That is slightly lower than our annual renewable percentage (52%) because in some hours our contracted generators produced more renewable energy than we consumed, which we do not count toward meeting our goal. This excess renewable energy is still delivered to the grid. However, although the excess renewable energy offsets emissions from the grid as a whole, it is not being used to offset the emissions from generic grid energy that our customers consume in those hours when consumption exceeds what our contracted renewables produce. Using an hourly, time-coincident accounting method, we estimate that the GHG emission intensity of our delivered electricity was closer to 187 lbCO2/MWh[3] (Table 2).

Table 2. Calculations based on different accounting methods

	Renewable percentage	GHG emissions intensity
Annual accounting method	52%	12 lb CO2e/MWh
Time-coincident accounting method	*47%*	187 lb CO2/MWh

[3] We assigned grid mix electricity a residual mix emissions factor, which we estimated to include a mix of all non- renewable and non-carbon free system CO_2 emissions in each hour as reported by CAISO's "Today's Outlook" dashboard.

Based on contracts signed to date, we are currently on track to be 64% renewable on a time-coincident basis in 2025, and we are actively working to plan and procure the remaining 36% by that year (Fig. 2).

Fig. 2. Seasonal load profile and contracted resources for 2025. For each season of the year 2025, this plot shows the average hourly match between our forecasted load and currently contracted resources, as well as hypothetical energy storage dispatch. This puts us on track to be 64% renewable on a time-coincident basis in 2025 if we were to take no further actions.

Starting in 2020, we began developing a novel 24/7 portfolio planning model to identify the most cost-effective portfolio of renewable energy and energy storage resources that can meet our goal. The results of this modeling will be shared in the second part of this white paper, to be published in early 2022. We have also convened an advisory group of external experts from industry and academia, with whom we meet regularly to review our approach.

5 Overview of 24/7 Strategies

Meeting our 24/7 renewable energy target will require a combination of supply-side and demand-side strategies that together can help match supply and demand around the clock. On the supply side, we plan to procure a diverse portfolio of resources that most closely match our load and utilize energy storage to shift excess generation to the times when we need it.

On the demand side, we can use load shaping and load shifting to better match the timing of our energy demand to the times when renewables are more available. By evaluating these strategies together, we can design a portfolio that most cost-effectively allows us to meet this goal.

5.1 Diversify Our Generation Portfolio

The first strategy is to procure energy from a diverse set of generation resources. Each type of resource—wind, solar, geothermal, or small hydro—produces energy at different times of day and in different seasons. We will also pursue geographic diversity. Wind resources have different power production profiles depending on location. Emerging technologies, such as offshore wind, may have distinct generation profiles that fill a gap left by existing, proven resources and technologies. The challenge of this strategy is finding the right combination of resources that together can generate electricity at the times when we need it and at the lowest cost. Even with a diverse portfolio, it would be nearly impossible to exactly match our generation with our load in every hour of the year. There will be some hours or seasons when we will have more supply than we need, and other hours or times of years when we may fall short. This is why this first strategy is only part of the solution to achieving a 24/7 match (Fig. 3).

5.2 Use Storage to Fill the Gaps

The second strategy is to leverage energy storage to help shift excess renewable generation to the times when there is not enough generation to meet our load. In California, most storage is charged midday and stored energy is discharged in the evenings as solar production decreases and power is most needed (Fig. 4). As resources and load profiles change over time, storage systems provide significant flexibility to charge and discharge at times when it is most needed.

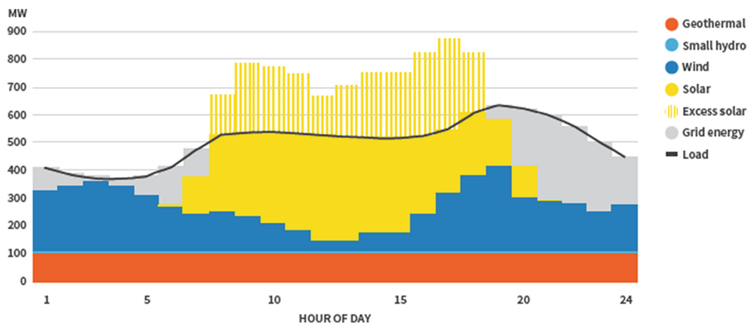

Fig. 3. Diversify renewable portfolio. A hypothetical day demonstrating a mix of renewable resources being used to try and match hourly load. In some hours, there is excess solar generation, and in other hours, this example load is still relying on generic grid energy.

Most storage today is capable of shifting energy between hours of a day or days in a week. As part of our storage strategy, we are evaluating both short duration and long-duration energy storage that is capable of filling unexpected renewable production gaps in our portfolio.

Our specific storage dispatch strategy will involve responding not only to matching our net load, but also to wholesale electricity price signals. This ensures that our energy storage will not only be working to meet Peninsula Clean Energy's needs, but also

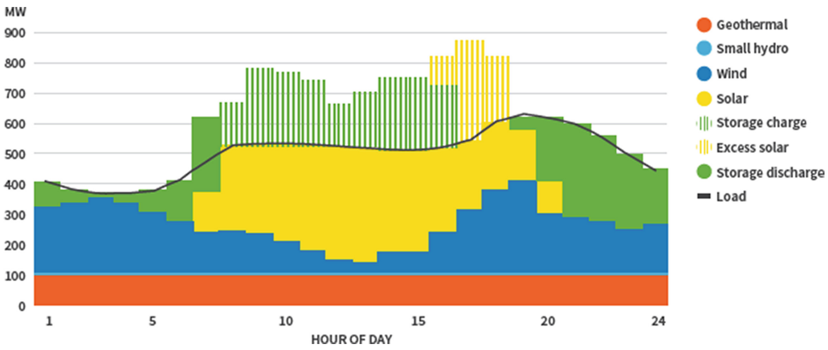

Fig. 4. Use storage to shift renewable energy timing. By adding storage to the hypothetical example, some of the excess solar generation in the middle of the day can be stored and discharged in the evening and early morning to reduce reliance on generic grid energy.

the needs of the broader electric grid. This strategy also helps maximize the economic benefits of energy storage, keeping costs low for our customers.

5.3 Shape and Shift Load

The final strategy involves approaching the challenge from the opposite direction: If it is challenging to match supply to load, how can we better match our load to the available supply of renewable energy? This demand-side approach involves both shaping and shifting our load (Fig. 5).

Load shaping refers to actions that permanently modify the shape of our load profile, such as transportation and building electrification, energy efficiency, and time-of-use electricity rates. For example, setting high commercial rates during the peak hours of the day will lead businesses to modify their energy use to minimize their energy bill.

Load shifting, in contrast, refers to shifting load between hours of a single day in response to specific signals, and may be useful to help respond to shorter-term intermittency of renewable resources. For example, customers with smart thermostats could shift their heating and cooling to match the availability of renewable resources each day.

The challenge of this strategy is these demand-side resources are often distributed, take time to develop, and represent a relatively small portion of our overall load. As opposed to signing a contract for a single 200 MW solar farm, which may help match up to half of our midday load, demand-side resources may only affect single-digit percentages of our load. The largest opportunities for load shaping may come from strategically shaping the charging of the increasing number of electric vehicles on the road (for example, through encouraging mid-day workplace charging rather than overnight at-home charging), as well as the electrification of our homes and buildings as we transition away from methane gas.

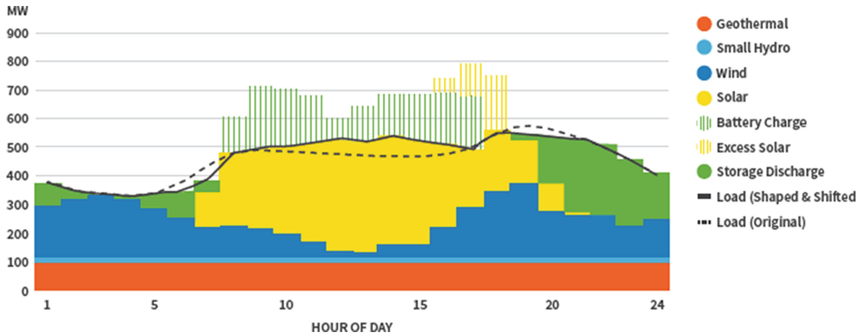

Fig. 5. Shape and shift load to match renewable availability. Using demand-side resources can help further align load with the timing of renewables to reduce the need for as much storage.

6 Challenges in Meeting 24/7 Renewable Energy

As we blaze a trail toward achieving 24/7 renewable energy, we have uncovered both technical and policy barriers that require creativity and innovation to overcome. While these make the process more challenging, we are confident we can address these and help reduce these barriers for others who follow.

6.1 Technical Challenges

Seasonal Mismatches Between Renewable Energy and Load. Even with all three of our strategies working in tandem, there are likely to be mismatches in supply and demand at certain times. The largest mismatches between renewable supply and demand are likely seasonal in nature. For example, because solar energy is more available in the summer, if we procure enough solar to match our wintertime demand, we would have a large amount of excess solar generation in the summer.

We can partially address this challenge by procuring non-solar resources such as wind and geothermal. We could also sell the excess solar to another entity that has a need for more summer resources. Storage may also be able to help address this in the future, however at this time, most seasonal storage technologies are immature or not widely available.

Implications of Forecasting Limitations. There are also likely to be mismatches between load and supply due to errors in our forecasts. Peninsula Clean Energy prepares forecasts on an hourly basis for how much electricity our customers are likely to consume (plus any distribution losses that occur to deliver the electricity), as well as how much generation our resources are likely to produce.[4] However, our actual demand and generation in each hour of the year is often going to differ from our forecasts (Fig. 6).

[4] Our goal currently seeks to match our generation to our loss-adjusted load, which includes retail sales plus distribution losses, but not transmission system losses. We are interested in better understanding how we could consider dynamic and locational transmission losses in our approach.

Years ahead of when power is actually consumed, Peninsula Clean Energy produces a long-term forecast of our hourly load to try to match generation procurement with the anticipated need. Both our demand forecasts and generation forecasts are based on historical data, models, and future assumptions. Our estimates improve as we get closer to the real-time hour. However, climate change is making long-term forecasting even more difficult by introducing more extreme and unprecedented weather events, as well as worsening climate-driven disasters such as wildfires that introduce unpredictable factors affecting both our supply and load.

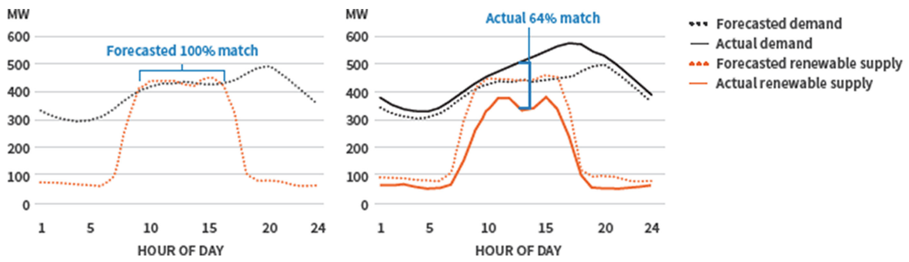

Fig. 6. Forecasted vs. actual supply and demand – October 2, 2020. An example showing how our actual renewable supply and demand on October 2, 2020, differed from our forecasts for that day.

Uncertainty Surrounding Demand-Side Resources. Making effective use of demand-side resources requires us to plan for and understand when and how these resources would perform, and how much it would cost to deploy them. At this time, we have limited information about these characteristics for load in our territory, which makes it challenging for us to model demand-side resources and understand how big a role they might play in our 24/7 strategy.

6.2 Policy Barriers and Solutions for Tracking and Reporting 24/7 Clean Energy

As mentioned previously, California requires procuring and reporting renewable energy on an annual rather than hourly basis. The Western Renewable Energy Generation Information System (WREGIS), the organization responsible for tracking renewable energy in California, currently issues monthly renewable energy certificates (RECs).[5] WREGIS has recently contracted with M-RETS, which has established a process for tracking renewable energy on an hourly basis which, once fully implemented by WREGIS, should allow us to communicate about our progress and report the time-coincident renewable content of electricity to our customers. Fortunately, these issues are also being actively discussed by policymakers in Sacramento [15].

5 A renewable energy certificate (REC) is issued by WREGIS for every megawatt-hour of metered renewable energy generated and reported into this system.

7 Phased Approach to Delivering 24/7 Renewable Energy

Peninsula Clean Energy plans to take a phased approach to meeting its 24/7 goal. The first phase, which aligns with our 2025 target, is to procure 24/7 renewable energy from proven technologies based on our forecasted hourly load and generation. This recognizes that in real time our actual renewable generation may not perfectly align with our actual load due to forecast errors. However, because we are part of a larger power system with a centralized balancing authority who can draw on systemwide resources to balance supply and demand, these relatively small mismatches due to forecast error may be more efficiently managed by the balancing authority than they would be by us.

Once we meet our 2025 goal of matching supply and demand on a forecasted basis, the second phase is to evaluate the costs and benefits of more closely matching our load and generation on a real-time basis. This will require improving our real-time data pipelines with PG&E, the California ISO, and our generation projects. We will need to develop more sophisticated portfolio management and dispatch tools. We will also need to continue to scale our demand-side flexibility resources and make room in our supply portfolio for emerging technologies that may better match our load shape than currently available resources.

8 Next Steps Toward Our Goal

Peninsula Clean Energy expects to complete a first round of modeling of our 24/7 portfolio in early 2022. We plan to release the results of this modeling in a follow-up white paper to be published mid-2022. This modeling will take a rigorous approach to exploring some of the more complex questions about our 24/7 procurement approach: How much will it cost to achieve? What types of resources will be needed to match our load? How can this approach help address grid reliability challenges? What are the short-run and long-run emission impacts of pursuing this goal? How should storage and demand flexibility be dispatched to balance grid needs, emission impacts, and 24/7 balancing?

After publishing the second part of our paper, we plan to release the modeling tool itself. Others can use it to evaluate their own 24/7 goals and hopefully join us in this journey to accelerate the decarbonization of the electric grid.

Appendix: About Peninsula Clean Energy

Peninsula Clean Energy is a Community Choice Aggregator (CCA) and the official electricity provider for San Mateo County and all twenty of its towns and cities, located just south of San Francisco, California. In April 2022, Peninsula Clean Energy has started providing electricity service to the city of Los Banos in California's Central Valley. Founded in 2016 with a mission to reduce greenhouse gas emissions, Peninsula Clean Energy now serves a population of approximately 800,000 people with annual retail load totaling approximately 3,500 GWh. As a community-led, not-for-profit agency, Peninsula Clean Energy makes significant investments in our communities to expand access to sustainable and affordable energy solutions.

As a CCA, Peninsula Clean Energy is responsible for planning for and securing commitments from a diverse portfolio of energy-generating resources to reliably serve the electric energy requirements of its customers over the near-, mid-, and long-term horizons. The energy which Peninsula Clean Energy procures is delivered on power lines and infrastructure managed by Pacific Gas & Electric, the investor-owned utility which serves much of Northern California. Peninsula Clean Energy is a locally controlled Joint Powers Authority and is governed by a Board of Directors consisting of elected officials from each of the jurisdictions to which we supply energy.

Appendix: Peninsula Clean Energy's 24/7 External Advisory Group

To date, Peninsula Clean Energy is engaging with the following individuals who have agreed to serve as part of our external advisory group for our 24/7 goal. We look forward to expanding this group and hearing from those who may be interested in joining us on this journey.

- Vince Battaglia, PhD, Lawrence Berkeley National Laboratory
- Mark Dyson, RMI
- Mike Della Penna, Google
- Ben Gerber, M-RETS
- Andy Satchwell, Lawrence Berkeley National Laboratory
- James Sweeney, PhD, Stanford University
- Christine Vangelatos, zGlobal.

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Solar Recycling: Transitioning from a Linear to Circular Economy

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Abstract. While solar technology provides a means for emission-free energy generation, little thought has been given to manufacturing impacts on the environment and waste management for end-of-life panels. The current system for solar panel manufacturing follows a linear economic model. Raw materials are mined from the earth and used in factories to manufacture modules. Once a module reaches its end-of-life, there is little consideration for recovery of precious or toxic materials. In a circular economic structure, all materials from solar modules would be recovered and reused in the manufacturing of new devices. Transitioning from a linear to circular economy is imperative for creating a sustainable and socially conscious solar industry.

Keywords: Recycling · Circular economy · Sustainability · E-waste

1 Introduction

The Intergovernmental Panel on Climate Change 2022 climate report highlights the alarming rate at which human-caused climate change is shaping our world. Drastic changes to global terrestrial, ocean, and freshwater ecosystems, along with impacts on human infrastructure and health, have all been linked to climate change [1]. This deleterious Anthropocene epoch is said to have started in the late eighteenth century [2]. Scientific data shows global temperatures have drastically increased since 1950 [3], and these temperatures will only increase as more greenhouse gases are pumped into the atmosphere. With global warming presently at 1.01 °C above 1880 levels [3], it is imperative the world takes action to reduce greenhouse gas emissions, invest in carbon-capture technologies, and decrease the human impact on the natural world.

One step towards decreasing human carbon emissions is to transition from fossil fuel power generation to renewable energy. As solar panels become ubiquitous energy devices, a deeper analysis into the sustainability of the solar industry is needed. Presently, solar panels follow a linear economic and manufacturing model. This model relies on the mining and refining of raw materials, which poses innumerable negative environmental and health impacts [4]. In order to be truly sustainable, a circular economic and manufacturing model must be implemented.

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2 Linear Economy

The term ‘linear economy’ is defined as an economic model in which raw materials are mined, transformed into goods, and disposed of at their end-of-life. Value is measured by how much product is sold, and money is made based on how much ‘stuff’ one can sell [5]. In this type of model, it can be concluded that the manufacturer should design products which satisfy only the bare minimum requirements for the product’s purpose, and that the products break down and are disposed of in a short time, in order to increase sales as much as possible.

2.1 Solar Example: Current Panel Manufacturing

Presently, solar panel manufacturing follows a linear model, as does the majority of products. Metals and sand are mined from the earth, passed through a series of refining processes, and used to manufacture solar modules in a factory. These panels are purchased by consumers, and once they reach their end-of-life, they are decommissioned. The main materials in solar panels are: glass, aluminum, polymer encapsulant, copper, lead, tin, silver, and silicon [6].

The most important material in crystalline solar modules is silicon. Silicon is a semiconductor material made from silica, a compound which makes up 59% of the Earth’s crust [7]. The process for refining silica and converting it into a solar cell involves tremendous energy inputs and dangerous chemicals. First, oxygen is removed from silica, resulting in metallurgical grade silicon. This process releases carbon dioxide and is conducted at high temperatures. Next, the metallurgical grade silicon is further refined through the Siemens process to produce electronic grade silicon. This process involves corrosive hydrochloric acid and large temperature gradients (31.8 °C to 1100 °C) [8, 9].

Because of the energy and materials costs for manufacturing silicon solar modules, their recycling is imperative for a sustainable future. A collaborative report by the International Renewable Energy Agency and the International Energy Agency Photovoltaic Power Systems Programme estimates there will be 78 million tonnes of solar waste globally by 2050 [10]. With the current linear economic model, tremendous quantities of raw materials could be wasted by landfilling solar modules. Incorporating end-of-life silicon cells back into silicon feedstock could help reduce energy losses by bypassing the energy-intensive silica-to-metallurgical grade silicon step. Although the linear model has worked up to this point for solar panel manufacturing, it is not the sustainable option for future energy production.

2.2 Impacts of Mining

Mined materials are omnipresent in modern life [4]. Gold is used in electronics and jewelry. Lead is used in solder for electronics. Lithium has become a popular choice for modern-day batteries. However, the global impacts of the mining industry are numerous, and often results are interconnected and complex. This section will highlight a few ‘case-studies’ which help demonstrate how mining is damaging to local communities, human health, and the environment.

Gold Mining in Ghana. In a comprehensive study by M. Rajaee et al., gold mining effects on human health and the environment in Ghana were analyzed. The group used an integrated assessment approach of reviewing studies and sample data to assess the socio-economic, health, and environmental impacts of the gold mining industry. Comprehensive tables documenting evidence of mercury, arsenic, cadmium, and lead contamination in soil, plants, sediment, and water are reported. Collectively, the group reports concerning levels of metal contamination, along with notable environmental damage.

Metal Contamination in Missouri, USA. J. Heiman et al. studied metal contamination in sediment and sycamore trees near The Big River in the Old Lead Belt in Missouri. They gathered samples from two test sites: one contaminated site, and one uncontaminated site. For the tree samples, the group analyzed four parts of the trees: bark, stem, leaf, and branch. The contaminated gravel sediment averaged 40 times higher lead levels and 10 times higher zinc levels compared to the uncontaminated samples. Contaminated sycamores had up to 58 times higher lead levels and 8 times higher zinc levels. Collectively, the sycamores had up to 70 times higher metal levels, with most metals accumulating in tree bark. Cadmium, cobalt, lead, and thallium were higher in contaminated trees compared to uncontaminated trees, with reported enrichment ratios of over 2 for all four parts of the tree tested. The measured levels of cadmium, uranium, and barium in the contaminated sycamore bark were higher than what the group found in literature. The measured levels of lithium and zirconium in sycamore leaves were at toxic levels compared to what the group found in literature. One concern this group and others highlight is the release of absorbed metals into the environment once the trees decompose or loose leaves.

Polymetallic Mining in South China. Z. Sun et al. analyzed local environmental pollution from a small mine in the Guangdong providence in south China. The group took samples of tailing, surface soil, and water. They report the mine tailings had elevated levels of heavy metals (for example, the average concentration of lead in the tailings was 3170 mg/kg). Water samples from local farmlands were considered toxic, most notably containing 1.5 times more cadmium than what was reported for normal. Farm soils were considered moderately to heavily polluted with copper, zinc, arsenic, cadmium, and lead. As an example, the lead concentration in soil samples was reported as being 427 mg/kg. This study also determined cadmium and lead were present in forms which are readily mobile through the environment, meaning these pollutants could have an even greater effect on the local community and ecosystem.

3 Circular Economy

A circular economy is paramount to a sustainable future. The term ‘circular economy’ is defined as a system in which goods and services follow the ‘Reduce, Reuse, and Recycle’ model. Consumption is limited to strictly necessary goods, and those goods are manufactured with longevity and ease of recycling in mind. Resources are recovered from defunct products and transformed into new products, creating circular pathways for raw materials. In the end, little to no waste is sent to landfills or burned [5, 14].

Although this economic model requires some engineering advancements, it will only be achievable through heavy action from policy makers and widespread support from the public. Without demand and support for a sustainable future and people's willingness to make lifestyle changes, a circular economy is not possible at the level which is needed for a green future.

3.1 Example: Solar Panel Recycling

Solar recycling has the potential to be the paradigm of a circular economy. With module installations on the rise around the globe (a projected 1600 GW of PV by 2030 [10]), the need for panel waste management is already less than a decade away (a projected cumulative waste of 1.7–8 million tonnes by 2030 [10]). Solar panels contain toxic metals such as lead, as well as high revenue generating materials such as silver, both of which make it imperative for panels to be recycled instead of landfilled [6]. The idea of recovering raw materials from panels and then feeding these materials back into the economy (such as in a sequential electrowinning process suggested by Huang et al.) supports the notion of a circular economy (Fig. 1). Solar already has a positive reputation for being a big part of the solution to green energy. Bringing a national recycling program up to speed would only boost solar's reputation and make it a truly green energy. In a struggling economy, a solar recycling industry could bring jobs to much-needed areas of the USA and help bolster the nation's transition towards a more sustainable future.

TG Companies, a solar recycling start up based out of Tucson, AZ, is spearheading the development of a sustainable solar recycling system. The company uses a two-step approach for recycling silicon solar modules:

1) Mechanical disassembly to extract silicon solar cells from modules and then burn off the encapsulant to expose the solar cells
2) Chemical recycling to recover materials from solar cells, such as silver, lead, tin, copper, and silicon in metallic form

Although still in the developmental phase, TG's technology shows promise to bolster a successful recycling industry not only for solar modules, but for other e-wastes as well. Its technology also focuses on circular chemistries and minimizing chemical waste by 80% over traditional recycling processes, while maximizing material recovery rates and profits. This balance between being environmentally/socially conscious and being profitable highlights the need for conscious e-waste recycling. This topic is expanded upon in the next section.

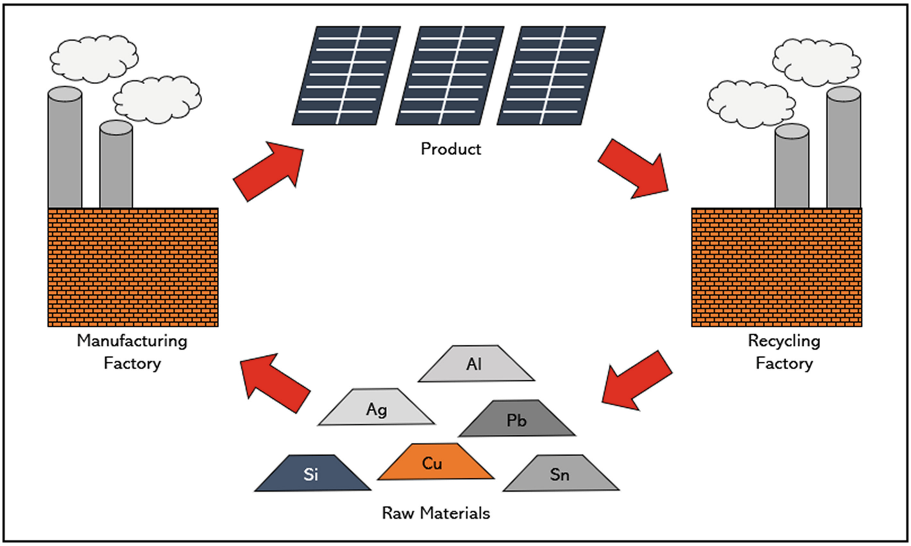

Fig. 1. Schematic for solar recycling in a circular economy

3.2 The Need for Conscious Recycling

A key component to establishing a circular economy is the implementation of recycling facilities, which prevent materials from ending up in the landfill. This is especially important for e-waste, such as solar. However, great care must be taken when integrating recycling facilities into a sustainable future. Electronics often contain hazardous heavy metals such as lead. Worker exposure, as well as the release of these metals into the environment, would counter the 'green' and 'safe' ideals of a more sustainable future.

One group (Lau et al.) studied metal contamination in five e-waste recycling facilities in Hong Kong. The group collected floor dust, air, and wiping samples from five facilities in Hong Kong and analyzed the samples for metal traces. They determined the blood lead level in some workers was significantly above CDC guidelines. Metal contamination in factory floor dust was also significantly high. This is just one example of the hazards associated with the e-waste industry [15]. In order to move towards a truly sustainable future, global e-waste needs to be recycled safely and responsibly. This is particularly important if the solar industry is going to be successful in leading the world towards a greener future. Public awareness and policy are necessary for ensuring this transformation happens in a manner which is beneficial to all, not just those who are socially and economically advantaged.

4 Conclusion

The present linear economy is damaging to the environment and local communities, and it is not sustainable for the perceivable future. The mining of raw materials, which form the feedstock for product manufacturing in a linear economy, is detrimental to local communities and the environment. Thus, a transition to a circular economy is needed.

This transition is coupled with the need for societies to shift from fossil-fuel power to carbon-free energy generation in order to combat climate change. Solar power is a leader in the energy transformation. However, little thought has been given to the life cycle of solar panels. Presently, solar is not as green as it's perceived to be because there is no universal recycling infrastructure for handling panel waste. The good news, though, is that with engineering advancements and public support, this can change. Solar can be the leader in supporting the development of a circular economy, and a prolific recycling industry could help curb the effects of mining and raise awareness to the destructive nature of the mining industry.

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Solar Parabolic Dish Concentrator Field Performance Evaluation

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Abstract. The field performance of the FOCUS, a near-parabolic dish concentrator developed by Solarflux Energy Technologies, Inc, (Solarflux) is reported. Parabolic dish concentrators are concentrating solar power (CSP) devices which focus Direct Normal Irradiance (DNI) on to a central receiver. The focused solar DNI is then collected as thermal energy which can be used to produce hot water or other fluid or steam for a variety of applications, including thermal uses and electricity generation. DNI was measured using a U.S. National Institute of Standards and Technology (NIST) referenced pyrheliometer attached to the FOCUS concentrator, and the data cross-referenced with other sources. Heat transfer fluid (HTF) temperature before and after the receiver was measured using thermocouples. The heat transfer fluid used was a 72/28 blend of DI water and propylene glycol. Flow rate was measured using a magnetic-induction digital flow meter. Where possible, sensor measurements were recorded and calculations were performed in accordance with American Society for Testing and Materials (ASTM) standards. The system response time was measured at 1 min 15 s, and the heat gain was calculated to be 72 W per 100 W/m^2 DNI, or 72%.

1 Introduction

The original impetus for the development of the FOCUS concentrator was a desire to find a viable sustainable energy solution for low-income rural populations in developing countries. According to the World Health Organization, around three billion people cook using polluting open fires or simple stoves fueled by kerosene, biomass (wood, animal dung and crop waste) and coal, and every year close to four million people die prematurely from illness attributable to household air pollution from inefficient cooking practices using polluting stoves paired with solid fuels and kerosene [1]. Furthermore, the unsustainable harvesting of fuel wood is major driver of forest degradation, adversely impacting more than 30 million hectares of forests in India alone [2]. In an effort to find a sustainable, low-cost, and resilient solution to this urgent problem, a thorough evaluation of available technologies was conducted.

A near-parabolic dish concentrator design was ultimately selected for ease of installation, flexible deployment capability, high efficiency, and potential for local manufacture and maintenance. Parabolic dish concentrators are acknowledged to be the most efficient CSP technology, in terms of both energy conversion and land-use. Historically, parabolic dish concentrators have been perceived as challenging to manufacture, due to the complex curvature of the dish as well as the additional moving parts required for two-axis

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vs. single-axis tracking. However, the approach adoption by Solarflux has been to focus heavily on the performance vs. cost tradeoff in all design decisions, and to utilize proven volume manufacturing methods and commercially available components to maximize reliability and minimize unit costs. The result is the FOCUS, a general-purpose parabolic dish concentrator suitable for a wide range of applications.

Several advanced prototypes of the FOCUS were installed at Penn State University's Berks Campus (PSU Berks) in Reading, Pennsylvania, USA, during 2016, as part of a solar energy related investment program funded by the Commonwealth of Pennsylvania. The FOCUS units installed included one smaller unit with 13.9 m^2 of reflective aperture, as well as three larger units, each with 42.4 m^2 of reflective aperture. The smaller FOCUS unit was devoted to providing heat to a greenhouse operated by the agriculture center at Penn State Berks, while the larger units were devoted to concentrated photovoltaic (CPV) research. The focus of this paper is on the field performance data from the smaller FOCUS unit (PSU Berks unit). Annual estimated DNI for this location in Pennsylvania is in the range 2.82–4.91 $kWh/m^2/day$.

In this work we test the performance of the FOCUS in two key areas, conforming closely to the ASTM E905-87 standard. According to ASTM E905-87, there are two tests to be performed by the manufacturer of a two-axis point concentrator: (1) Response Time and (2) Heat Gain. Response time is measured to establish the time required to achieve quasi-steady state conditions before and during each thermal performance test to assure valid test data. Heat gain (Q) is the product of the HTF mass flow rate (m), its specific heat (C_p), and the temperature difference between the input and output of the receiver (t_a).

There are many practical factors that contribute to the final heat gain product, with major contributors being reflectivity of the mirror, intercept factor, and overall efficiency of the absorber. Based on the index of refraction and extinction coefficient, the ideal first surface aluminum reflector would have an average reflectivity of 93%. Best geometric optics will predict an intercept factor of 99%, and based on a typical heat exchanger, the receiver will have a 90% heat transfer efficiency. Multiplying these factors predicts an 83% total solar-to-heat efficiency, representing the theoretical maximum heat gain achievable by the FOCUS.

Once heat gain is determined experimentally, $R(\Theta)$, the ratio of the rate of heat gain to the solar power incident on the aperture of the collector can be calculated. The experimental results will be compared to the theoretical maximum, any deviation will be discussed and possible improvements will be identified.

2 Concentrator Description

The FOCUS consists of five major sub-components, common to all parabolic dish concentrators. These are the collector, the receiver, the tracker assembly, the controller, and the mast. The mast is mounted on the ground or on a rooftop. The tracker assembly is then placed on the mast, and the collector is placed on top of the tracker assembly. The receiver is positioned on the optic axis at the waist point of the collector. The controller manages the tracker assembly to determine the orientation of the collector, ensuring its optimal positioning relative to the sun.

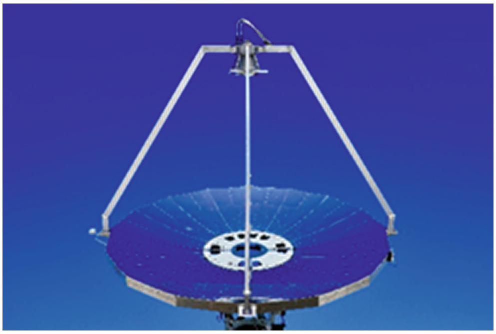


Fig. 1. FOCUS collector

The collector is made up of sixteen truncated sectors of a circle, forming petals. The petals are highly polished first surface aluminum mirrors consisting of 0.5 mm 1090 aluminum clad to a 1.5 mm, 3003 structural aluminum substrate. Each petal is self-supporting, not requiring a separate structure to either maintain mirror alignment to the optic axis, or provide the structural strength required for wind events. The petals have mechanical alignment features to ensure proper alignment to adjacent petals. Once attached to each other the petals form a self-supporting parabolic dish collector. Figure 1 shows the collector and receiver. The collector geometry is a segment of a spindle toroid. In the above configuration it has a total clear aperture of 13.94 m^2 and delivers a geometric concentration ratio greater than 2,000, verified using Zemax modeling. The collector's design is further described in the US patent 8680391, which covers several of the key features of the FOCUS.

The FOCUS collector demonstrates total solar weighted hemispherical reflectance of 89.6% [3]. The FOCUS collector's specular reflectance (the portion of the solar spectrum directed at the focal plane), a surface reflectance property, is measured at 85.6% [4]. Integrating the specular reflectance with ASTM G173–03, a reference for the terrestrial spectral distribution of solar irradiance, predicts an 83.8% solar-weighted specular reflectance for the collector. Prior to the installation of the collector at PSU Berks in 2016 the specular reflectance of the collector's surface aluminum averaged 84.1%, in the 400 nm and 1050 nm wavelength range [5]. In March 2021, the aluminum surface was cleaned for the first time since installation. Reflectance testing was then repeated over the same wavelengths and

Fig. 2. Thermal receiver

using the same instrument, with average specular reflectance measured at 83.5%. Comparing this measurement against the identical test performed on the same aluminum prior to installation five years earlier, we observe a modest 0.6% loss of specular reflectance after exposure to dust, birds, insects, aerosols and other atmospheric effects.

The thermal cavity receiver (see Fig. 2) is compact and light weight (~52 lbs/23.6 kg). It consists of four components: the absorber, housing, insulation, and a heat shield. The absorber is a trucated cone with a 300 mm diameter aperture that tapers down to 140 mm diameter and is 360 mm deep. It is fabricated using 0.5 in. diameter 0.035 wall thick copper tubing. The absorber is coated with a black body ceramic coating, with a 593 °C operating temperature, and emissivity greater than 0.9. The absorber is housed in an aluminum casting, with a 12 mm layer of ceramic insulation between the coil and the receiver housing. The heat shield is polished stainless steel and mounted at the entrance pupil of the receiver, protecting the aluminum housing from concentrated radiation.

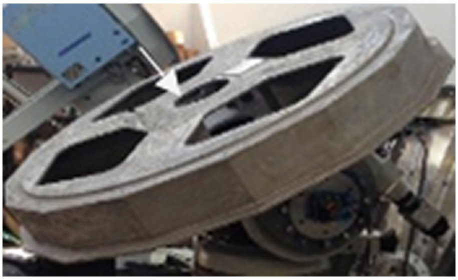


Fig. 3. Tracker assembly

The tracker assembly, shown in Fig. 3, is arranged in an azimuth and zenith configuration. It consists of a cast hub, slew drives, gearboxes, motors, encoders, and a controller. The azimuth has a range of motion of 360°, the Zenith 90°. The slew drives at each axis are hourglass worm drives that have a gear ratio of 85:1, with a precision of $\leq$0.09° and efficiency of 40%. Coupled to the input of the slew drive is a planetary gear box with a 256:1 gear ratio and efficiency of 89%. Drive power to each axis is supplied by a 400 step per revolution stepping motor. All components used in the assembly of the tracker are IP65 rated, providing robust environmental resilience. The assembled collector is slid onto the hub (like a split rim of a truck wheel). A retaining ring secures the collector to the hub while allowing it to freely expand and contract. The hub is connected to the slew drives by two custom castings.

Tracking control of the FOCUS concentrator is a hybrid between active feedback and open loop control. An optical sensor module is mounted on the collector and provides $\pm$0.05° feedback to the tracking controller. Additionally, encoders with a resolution of $\pm$0.01° are mounted on each axis to measure the true azimuth and zenith angles. At the beginning of each day and after the optical sensor module locks on to the sun the encoders are calibrated by comparing their readings to the National Renewable Energy Laboratory (NREL) solar position algorithm. During clear sky conditions active feedback from the optical module is used for tracking feedback, while broken skies and other weather events require the use of the encoders. The other function of the dish controller is safety and monitoring. Wet bulb thermocouples are attached to the input and output of the thermal receiver. If the temperature of the HTF exceeds preset limits, the controller will move the dish out of the sun. If the wind exceeds 30 mph (48 kph) the dish is moved into the wind safe position with the receiver pointing vertically up at the sky. Tracking is resumed once the wind has subsided. Failure mode analysis and field experience suggests that the FOCUS can withstand winds of at least 90 mph (144 kph) in safe mode.

The FOCUS concentrator is mounted on an 11 foot long mast consisting of sixteen-inch diameter galvanized Sch. 40 pipe, with a companion flange at each end. One end of the mast is bolted to the concrete foundation with the tracking mechanism bolted to the other.

3 Test Site and Instrumentation Overview

The PSU Berks unit was installed at Penn State University's Berks Campus. The concentrator is utilized to supply thermal energy to a greenhouse operated by the agriculture department at Penn State Berks. The GPS location of the PSU Berks FOCUS concentrator are 40° 21′ 51″ N and 75° 58′ 34″ W, with an elevation of 73 m [6]. Figure 4 shows the concentrator in the center of the image and the greenhouse to the East side. A utility shed (not shown) was subsequently built to the southeast of the greenhouse to host thermal loop related equipment.

Fig. 4. PSU Berks FOCUS concentrator installation location

Fig. 5. PSU Berks FOCUS concentrator

The PSU Berks FOCUS concentrator is shown in Fig. 5.

Figure 6 below provides an illustration of the system components, including placement of the thermocouples, at the Penn State Berks test site.

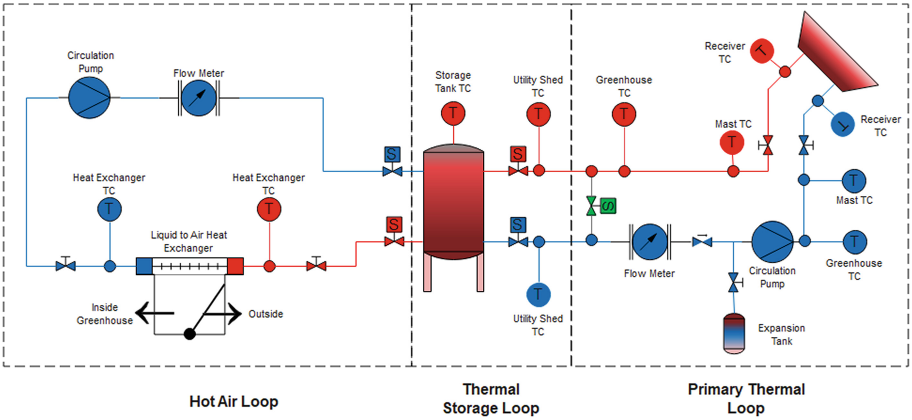
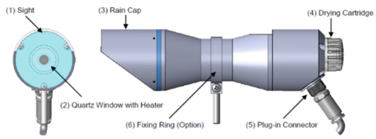
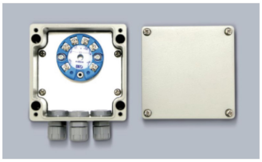
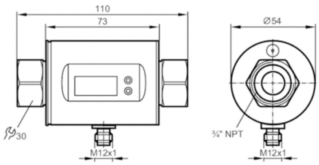


Fig. 6. PSU Berks FOCUS greenhouse system thermocouple placement

The system in Fig. 6 is divided into three thermal loops. At the beginning of each day HTF is circulated through the primary thermal loop. HTF is circulated from the receiver output to the greenhouse where it is diverted back to the input of the thermal receiver. This continues until the temperature of the HTF from the receiver exceeds that of the storage tank. Once the target temperature is achieved, a diverter valve opens to let the HTF circulate through the thermal storage loop and back out to the thermal receiver. This circulation continues until the storage tank reaches its maximum storage temperature or the greenhouse requires heat. When these conditions are met the hot air loop is opened, which circulates the HTF between the storage tank and the liquid to air heat exchanger. For the purposes of these tests all three thermal loops were manually opened, which dissipated heat produced by the collector and maintained the input temperature to the collector.

The instrumentation used is described in Table 1 below.

Table 1. Instrumentation

Instrument	Description	Image
Pyrheliometer (DNI Sensor)	• EKO, model no.: MS-57 • Field of view 5° • WRR scale • Operating temperature range: -40 - 80□ • Solar spectral range: 200 – 4000 nm • Solar irradiance range 0-1600 W/m^2 • Calibrated results: 8.297 $\mu V/W*m^2$ sensitivity with 0.36% uncertainty • Response time: 99% after 6 sec	
A-Box-I Signal converter	• Analogue interface (V) • 4-20 mA | 0-1600 W/m2 Irradiance • Correction for sensor temperature dependency and non-linearity • IP65 All-weather enclosure • Optional USB controller and EKO sense control software • Ingress protection: 65	
Weather station	• Davis model 6163 • Data updates every 2.5 seconds. • Outside temperature ±0.3°and humidity sensors ±2% • Wind speed ±5%, and direction ±3° • Rainfall • UV and GHI Solar radiation ±5% full scale, and range 0-1800w/m²	
Magnetic-inductive flow meter	• IFM • Model SM7604 • Measuring range: 0.2-50 l/min • Resolution: 0.1 l/min • Flow monitoring accuracy: ± (2% MW + 0.5% MEW) • Response time: 0.15 s	
Circulation pump	• Model: UPS 26-150 SF • Maximum flow: 11.81 m³/h • Pumped liquid: water/glycol • Liquid temperature range: 0 - 110 °C	
Optical sensor module	• FusioSeeker • Model DS-50-D6W • Accuracy ± 0.05°	
Absolute axis encoder	• Baumer • Model: GBA2W • Absolute accuracy ±0.01° • Single turn • 524288 / 19 bit steps per revolution	
Thermalcouple	• Type K thermal couple from Omega	

4 Test Setup

Pursuant to the ASTM E905-87 standard, we evaluated the performance of the FOCUS in the two key areas where testing is required for a two-axis point concentrator: (1) Response Time and (2) Heat Gain. Each test is considered in turn.

For the Response Time test, the following preparatory steps were taken prior to testing. The FOCUS collector was cleaned using ‘Simple Green’ all-purpose cleaner diluted 10:1 with filtered spring water. A microfiber cloth was then used to gently scrub the surface of the dish. A high-pressure washer (1,700 psi) used to rinse dish after cleaning, using filtered spring water. The DNI sensor lens was cleaned using clean dry microfiber cloth, and alignment with sun verified. The propylene glycol HTF concentration was measured using an ATC refractometer at 28% propylene glycol in 72% DI water. Circulation pumps were activated manually, all loops were opened and the heat exchanger blower was turned on one hour before testing to stabilize HTF input temperature at the receiver.

Mass balance for the HTF before and after the FOCUS concentrator was met, where the liquid mass flow entering the concentrator is the same as the liquid mass flow leaving the concentrator at any specific time. The HTF mass flow rate is calculated based on the instantaneous flow rate obtained by the magnetic-inductive flow meter and the heat transfer fluid density at the arithmetic mean temperature of the inlet and outlet of the FOCUS receiver. The flow meter measuring range is 0.2 to 50 L/m, while the maximum flow rate of the heat transfer fluid observed is around 8 L/m. Figure 7 shows the correlation between the heat transfer fluid density and its temperature.

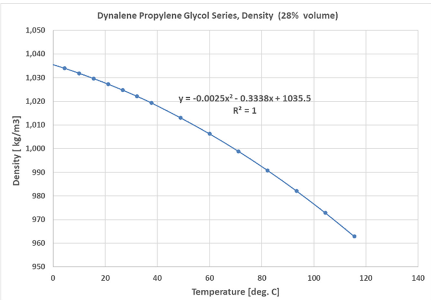


Fig. 7. Heat transfer fluid density vs. temperature

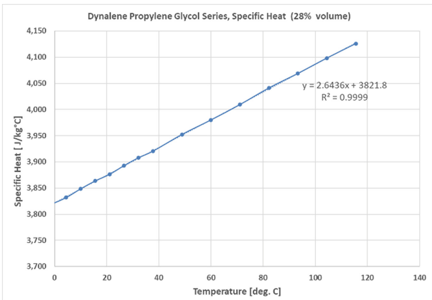


Fig. 8. Heat transfer fluid specific heat vs. temperature

For the area of interest, which is the heat transfer fluid between the FOCUS concentrator’s receiver inlet and outlet, the energy balance for the heat transfer fluid will neglect the potential and kinetic energies. Also, it was assumed that no external work has been applied to the heat transfer fluid, and no phase change occurred. Thus, the energy collected through the FOCUS concentrator will be transferred to the heat transfer fluid, minus any losses. The rate of heat/enthalpy gain (Q) is calculated from its defining relationship:

$$Q = \left(mC_p\right)\Delta t_a \tag{1}$$

where the product of mass flow rate and specific heat (mC_p) are determined using the plots shown in Figs. 7, and 8, at the mean value of inlet and outlet temperatures of the receiver, and (Δt_a) is the difference between the inlet temperature (t_{fi}) and output temperatures (t_{fe}) of the receiver

$$\Delta t_a = t_{fe} - t_{fi} \tag{2}$$

Conversion rate $R(\Theta)$ = the rate of heat gain (Q) divided by the product of the direct solar irradiance (DNI, $E_{s,DN}$) and the collector aperture (A_a) becomes:

$$R_\Theta = Q/E_{s,DN}A_a \tag{3}$$

5 Response Time Test Performance and Results

The response time test was conducted by Solarflux personnel led by Solarflux Chief Technology Officer and Principal Engineer John Fangman, in accordance with the guidelines outlined in ASTM E905-87, Sect. 21.1, and Procedure B. The test was conducted on June 6th, 2021.

At 11:10:57am the FOCUS collector was moved from its maintenance position to an azimuth angle of 116.41°, and zenith to 22.5°, as compared to the suns position at azimuth 118.39, and zenith 28.41. The collector remained in this position until the start of the test. The data shown in Table 2 were recorded every 15 seconds during the waiting period to establish steady state prior to the beginning of the test. The inlet temperature ($t_{f,I}$) varied ±0.2 °C, compared to maximum ±0.2 °C required for steady state. The temperature

Table 2. Data recorded during wait time prior to response time test

Parameter	Symbol	Average	Maximum	Minimum	±Range
Temperature of the HTF at the inlet of the Receiver	$t_{f,I}$	34.2	34.4	33.9	0.25
Mass flow of HTF	m	0.135	0.136	0.134	0.001
Energy associated with sensible heat of HTF	(mC_p)	0.524	0.527	0.521	0.003
Direct normal irradiance projected onto the collector	$E_{s,D}$	0.000	0.000	0.000	0.000
Global horizontal irradiance	$E_{s,2\pi}$	808.750	810.000	805.000	2.50
Temperature difference of HTF between receiver input and output	Δt_a	0.020	0.200	-0.100	0.15
Ambient air temperature	t_{amb}	29.919	30.000	29.778	0.11
Wind speed	m/sec	0.872	2.235	0.000	1.12

difference between the input and output (Δt_a) varied by ±0.1 °C compared to maximum ±0.4 °C required for steady state. Measured (mC_p) varied ±0.6% compared to maximum ±1.0% required for steady state. Direct irradiance ($E_{s,DN}$) measured at this position was 0.0 W/m^2 with 0.0% variation. Global irradiance ($Es_{,2\pi}$) varied ±0.3% compared to maximum ±4% required for steady state. Ambient temperature (t_{amb}) varied ±0.1 °C compared to maximum ±2.0 °C required for steady state. Maximum wind speed was 2.35 m/s compared to <4.5 m/s maximum for steady state.

At 11:16:57am the collector was placed in tracking mode, moving the collector from its waiting position to the collector aperture normal to the sun. At 11:17:42 the collector aperture completed its motion and aligned normal to the sun. At 11:23:42 the response time test was completed. Data were recorded every 15 s for the duration of the test, and plotted in Fig. 9.

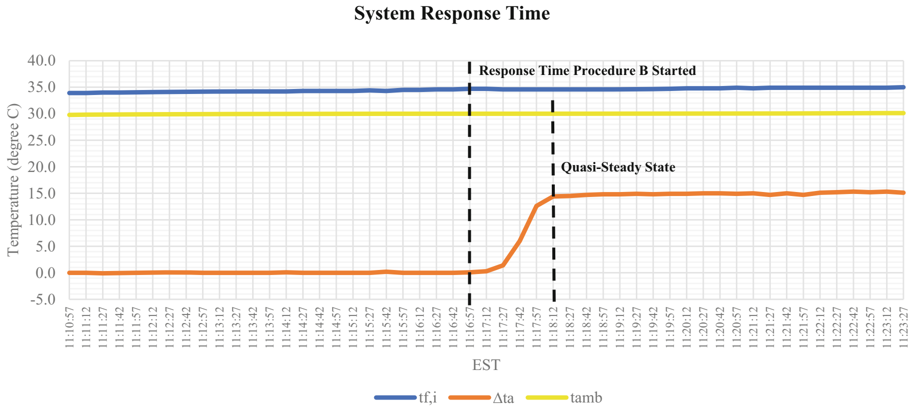


Fig. 9. Response time plot

In accordance with ASTM E905-87 Procedure B quasi-steady state is achieved when the equation below is satisfied:

$$\left(\Delta t_{a,f} - \Delta t_{a,T}\right)/\left(\Delta t_{a,f} - \Delta t_{a,i}\right) = 0.10 \tag{4}$$

where:

$\Delta t_{a,f}$ is the temperature difference across the receiver inlet and outlet at final quasi-steady state condition
$\Delta t_{a,i}$ is the temperature difference across the receiver inlet and outlet at the initial start condition
$\Delta t_{a,T}$ is the temperature difference across the receiver inlet and outlet at the start of the quasi-steady state condition.

Substituting measurements taken during testing, $\Delta t_{a,f} = 15.10$, and $\Delta t_{a,i} = 0.08$, and solving for ($\Delta t_{a,T}$), quasi-steady state is achieved when the temperature difference across the receiver reaches 13.59 °C. This was achieved at 11:18:12am. Compared to the start time of the test (11:16:57am), the response time is determined to be (1 m 15 s) one minute fifteen seconds.

A summary of the data between the onset of quasi-steady state and the completion of the test is shown in Table 3. The inlet temperature ($t_{f,I}$) varied ±0.2 °C, compared to maximum ±0.2 °C required for steady state. The temperature difference between the input and output (Δta) varied by ±0.3 °C compared to maximum ±0.4 °C required for steady state. Measured (mC_p) varied ±1.3% compared to maximum ± 1.0% required for steady state. Fluctuations in the circulation pump flow rate was the contributor to this variation, and appears to be in the normal range of this pump. Direct irradiance ($E_{s,DN}$) averaged 839.7 w/m^2 ±0.25%, compared to a maximum allowed variation of ±4%. Global irradiance ($Es_{,2\pi}$) varied ±0.3% compared to maximum ±4% required for steady state. Ambient temperature (t_{amb}) varied ±0.11 °C compared to maximum ±2.0 °C required for steady state. Maximum wind speed was 1.34m/sec compared to <4.5 m/s maximum for steady state.

Table 3. Taken over 5-min period after achieving steady state

Parameter	Symbol	Average	Maximum	Minimum	±Range
Temperature of the HTF at the inlet of the Receiver	$t_{f,I}$	34.8	35.0	34.6	0.20
Mass flow of HTF	m	0.135	0.137	0.133	0.00
Energy associated with sensible heat of HTF	(mC_p)	0.531	0.539	0.524	0.01
Direct normal irradiance projected onto the collector	$E_{s,D}$	839.638	842.022	837.138	2.44
Global horizontal irradiance	$Es_{,2\pi}$	819.619	824.000	817.000	3.50
Temperature difference of HTF between receiver input and output	Δt_a	14.971	15.300	14.700	0.30
Ambient air temperature	t_{amb}	30.045	30.111	30.000	0.06
Wind speed	m/sec	0.596	1.341	0.000	0.67

6 Rate of Heat Gain Test

The test procedure for "Rate of Heat Gain at Near Normal Incidence" is described in Sect. 13.5 of the ASTM E905-87 standard. The application of the PSU Berks concentrator is to provide space heating to the PSU Berks greenhouse. As such, the temperature is never to exceed 100 °C, which limits the range of input temperatures that can be evaluated. It is difficult to produce four equally spaced values of input temperatures, as specified in Sect. 13.5 for an application with such a narrow range. As such heat gain was evaluated at 42 °C, 52 °C, 66 °C, and 72 °C. The data sets used for this evaluation are consistent with the quasi-steady state condition, which for this system is one minute fifteen seconds. Also, per Sect. 10.1 of the ASTM the condition must exist for a period equal to two times the response time. Once these criteria are met the data may be used to calculate the rate of heat gain (Q) using Eqs. (1), and (2).

Values for mass flow (m), and specific heat (Cp) were determined by using the mean temperature between the input and output of the receiver (Δt_a) for each test and the expressions shown in Figs. 7 and 8. All heat gain tests were conducted on June 6th, 2021 between the hours of 11:30am to 4:47pm.

Table 4 is the summary data to validate that a quasi-steady state condition existed during the 42 °C inlet temperature testing. The data were taken over a five-minute period starting at 11:31am. Substituting values from Table 4 into Eq. (1) for calculating heat gain, average Q = 8.28 kW ± 0.07 kW. Further, substituting the value for Q into Eq. (3) where:

$E_{s,D}$ = direct normal incidence (w/m^2) on the collector from Table 3

A_a = the clear aperture of the collector, which is 13.94 m^2.

The ratio of the rate of heat gain (Q) to the solar power incident on the aperture can be calculated (R_Θ):

$$R_\Theta = 0.70, \text{ or } 70.0\% \text{ solar-to-thermal conversion}$$

Table 4. Quasi-steady state summary data 42 °C Inlet

Parameter	Symbol	Average	Maximum	Minimum	±Range
Temperature of the HTF at the inlet of the Receiver	$t_{f,I}$	34.6	42.4	0.0	21.20
Mass flow of HTF	m	3.217	3.932	0.000	1.97
Energy associated with sensible heat of HTF	(mC_p)	6.487	8.360	0.008	4.18
Direct normal irradiance projected onto the collector	$E_{s,D}$	549.854	852.399	0.005	426.20
Global horizontal irradiance	$E_{s,2\pi}$	691.212	846.000	0.002	423.00
Temperature difference of HTF between receiver input and output	Δt_a	12.679	15.600	0.006	7.80
Ambient air temperature	t_{amb}	27.346	30.444	0.056	15.19
Wind speed	m/sec	1.679	3.129	0.155	1.49

Table 5 is the summary data to validate quasi-steady state condition existed during 52 °C inlet temperature testing. The data was taken over a five-minute period starting at 12:38pm. Substituting values from Table 5 into Eq. (1) for calculating heat gain, average

Q = 8.49 kW ± 0.07 kW. Further, substituting the value for Q into Eq. (3), the ratio of the rate of heat gain (Q) to the solar power incident on the aperture (R_Θ) is calculated:

$$R_\Theta = 0.71, \text{ or } 71.0\% \text{ solar-to-thermal conversion}$$

Table 5. Quasi-steady state summary data 52 °C Inlet

Receiver Input Temperature 52°C					
Parameter	**Symbol**	**Average**	**Maximum**	**Minimum**	**±Range**
Temperature of the HTF at the inlet of the Receiver	$t_{f,I}$	52.6	52.7	52.3	0.20
Mass flow of HTF	m	0.113	0.114	0.113	0.001
Energy associated with sensible heat of HTF	(mC_p)	0.448	0.452	0.446	0.003
Direct normal irradiance projected onto the collector	$E_{s,D}$	855.676	858.808	852.399	3.20
Global horizontal irradiance	$E_{s,2\pi}$	904.474	911.000	902.000	4.50
Temperature difference of HTF between receiver input and output	Δt_a	18.937	19.100	18.800	0.15
Ambient air temperature	t_{amb}	31.576	31.611	31.500	0.06
Wind speed	m/sec	2.682	2.682	2.682	0.00

Table 6 is the summary data to validate quasi-steady state condition existed during 66 °C inlet temperature testing. The data was taken over a five-minute period starting at 3:16pm. Substituting values from Table 6 into Eq. (1) for calculating heat gain, average Q = 7.59 kW ± 0.16 kW. Further, substituting the value for Q into Eq. (3), the ratio of the rate of heat gain (Q) to the solar power incident on the aperture can be calculated (R_Θ).

$$R_\Theta = 0.72, \text{ or } 72.0\% \text{ solar-to-thermal conversion}$$

Table 7 is the summary data to validate quasi-steady state condition existed during 72 °C inlet temperature testing. The data was taken over a five-minute period starting at 4:41pm. Substituting values from Table 7 into Eq. (1) for calculating heat gain, average Q = 7.04 kW ± 0.16 kW. Further, substituting the value for Q into Eq. (3), the ratio of the rate of heat gain (Q) to the solar power incident on the aperture can be calculated (R_Θ).

$$R_\Theta = 0.72, \text{ or } 72.0\% \text{ solar-to-thermal conversion}$$

Table 6. Quasi-steady state summary data 66 °C Inlet

Receiver Input Temperature 66°C					
Parameter	**Symbol**	**Average**	**Maximum**	**Minimum**	**±Range**
Temperature of the HTF at the inlet of the Receiver	$t_{f,I}$	66.6	66.8	66.4	0.20
Mass flow of HTF	m	0.114	0.115	0.113	0.001
Energy associated with sensible heat of HTF	(mC_p)	0.457	0.459	0.453	0.003
Direct normal irradiance projected onto the collector	$E_{s,D}$	759.370	773.044	746.490	13.28
Global horizontal irradiance	$E_{s,2\pi}$	793.700	803.000	788.000	7.50
Temperature difference of HTF between receiver input and output	Δt_a	16.635	17.000	16.300	0.35
Ambient air temperature	t_{amb}	32.608	32.611	32.556	0.03
Wind speed	m/sec	5.812	5.812	5.812	0.00

Table 7. Quasi-steady state summary data 72 °C Inlet

Receiver Input Temperature 72°C					
Parameter	**Symbol**	**Average**	**Maximum**	**Minimum**	**±Range**
Temperature of the HTF at the inlet of the Receiver	$t_{f,I}$	72.0	72.2	71.9	0.15
Mass flow of HTF	m	0.114	0.115	0.113	0.001
Energy associated with sensible heat of HTF	(mC_p)	0.458	0.461	0.454	0.004
Direct normal irradiance projected onto the collector	$E_{s,D}$	700.204	710.475	683.311	13.58
Global horizontal irradiance	$E_{s,2\pi}$	617.130	624.000	601.000	11.50
Temperature difference of HTF between receiver input and output	Δt_a	15.365	15.600	15.100	0.25
Ambient air temperature	t_{amb}	32.937	32.944	32.889	0.03
Wind speed	m/sec	2.838	5.364	1.341	2.01

7 Test Results and Discussion

It should be noted that the FOCUS system used to conduct these tests is a developmental prototype intended to demonstrate the use of a Solarflux designed concentrator in a space heating application. Thus, other than the DNI sensor, all the instrumentation and hardware used such as the circulation pump, weather station, valves, storage tank etc., are typical of those used in any of our standard installations. The DNI sensor is a Class I device, as required by the ASTM standard. The DNI sensor is mounted on the receiver frame and not on its own independent tracker. Global solar irradiance measurements are also recorded by a Davis 6163 weather station located at the Penn State Berks site and measurements were verified to be consistent with historical DNI and GHI measurements taken from NREL, NASA, and NOAA databases at this location in early June.

The ‘response time’ is not a test but a characterization of the installed system. Only data recorded after the response time has elapsed can be considered valid results for subsequent tests. Since the tests were conducted on a two-axis tracking point concentrator, it had to be and was moved within a few degrees of tracking prior to the test. Subsequently, part of the response time includes the time required to move from the waiting position to optical alignment and tracking with the sun, and therefore the seventy-five second response of the system is a conservative measurement.

The heat gain tests were performed on the **same day, and immediately after the response time study**. Using quasi-steady state criteria, the enthalpy change (Q) as it relates to DNI and input temperature was ascertained. Substituting the value (Q) for each input temperature into the expression;

$$\mathrm{R}_{\Theta} = \mathrm{Q}/\mathrm{E}_{\mathrm{s,DN}}\mathrm{A}_{\mathrm{a}},$$

where Q is the solar heat conversion, $\mathrm{E}_{\mathrm{s,DN}} * \mathrm{A}_{\mathrm{s}}$ is the incident solar power.

The peak ratio of heat gain to solar power incident on the aperture was calculated at 0.72, at input temperatures >66 °C.

Achieving the theoretical maximum of 83% solar-to-thermal conversion efficiency as discussed in the ideal concentrator model is not practically possible. The reflectance of the aluminum in the ideal model is an average over all wavelengths of light. All reflective surfaces have their own spectral response governed by their index of refraction and extinction coefficients. Aluminum has lower reflectivity in the shorter wavelengths and over 98% in wavelengths above the near infrared. Additionally, as is well known and documented in ASTM G173-03 energy distribution of solar irradiance varies by wavelength. Integrating the spectral response of the aluminum, with the solar energy distribution, the theoretical solar-weighted optical efficiency of 89% can be determined for the collector reflection response. Further, assuming an expected intercept factor of 0.99 and a receiver conversion efficiency of 90%, results in a 79% solar-to-thermal efficiency. The measured collection efficiency of 72% achieved by the PSU Berks collector during the heat gain tests thus compares favorably with the near ideal 0.79 value of R_{Θ}, or 79% solar-to-thermal conversion.

There are potential improvements that can be made to the FOCUS collector mirrors that could improve optical efficiency and reduce cost. The reflectors used in the current tests were fabricated with each petal elastically formed by stretching the precut flat media over a mandrel and welding it to a frame to maintain its curvature. Forcing a flat piece of sheet metal into a parabolic shape intrinsically imparts stresses that result in reflector surface slope errors. In addition, the welding process leaves distortions that extend well beyond the domain of the weld. Collectively these effects account for the major portion of the optical losses and departure of the real reflector from that of the ideal reflector surface.

Future improvements in reflector surface manufacturing will reduce slope errors and eliminate the welding distortions. Petals will be fabricated using a stamping process similar to that used in the automotive industry to fabricate body panels. Low temperature adhesives will be used to assemble petals into the collector, eliminating potential welding distortions. These manufacturing processes will improve the intercept factor and the concentration ratio at the focal plane and will in turn allow the aperture of the receiver to be decreased, reducing convection losses. With these and other improved manufacturing and implementation approaches, it is not unrealistic to anticipate solar-to-thermal conversion efficiency for the FOCUS in the range of 74% to 75% or higher.

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How to Correctly Assess the Value of Energy Converted from Solar and Other Renewable Sources

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Abstract. In recent months various publications have appeared that report surprising reductions in the prices of the various technologies for the use of renewable energy sources, highlighting the photovoltaic solar and wind power. These collapses in prices are something that should not be surprising, since some aspects related to the advancement of technologies have been known for decades, like the Wright's Law and standardized methodologies to estimate, for example, the levelised costs of electric power generated by various technological options which have been refined over time. Now, the questions arises: How can be correctly assesed the future prices of energy generated from renewable sources? and, how to estimate its net present value to allow unbiased comparison with energy generated with other technologies? To answer them, we must first proceed to model what the Wright's Law implies and then identify the maturity stage of the technology in question. Once this is done, the evolution of prices can be modeled as function of time, at the stage of technology development previously identified. Finally, we proceed to the application of the well known techniques to estimate the LCOE using the information most reliable available, based on auditable facility costs already carried out.

Keywords: LCOEs · Wright's law applied to RE technologies · Energy economics

1 Introduction

Historically, the International Energy Agency - among many others- have made very wrong forecasts regarding the future prices and capacity of facilities for the use of renewable energy sources. Since prices are a very important factor in estimating the viability and sustainability of these facilities, it is necessary to have a simple but reliable methodology to quikly and correctly assess these possible future prices, even without consideration of environmental costs and other "economic externalities".

In the midst of the COVID 19 epidemic, various publications appeared that reported surprising reductions in the prices of the various technologies for the use of renewable energy sources, highlighting solar photovoltaic, wind, both on land and offshore, and

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electrochemical lithium-ion batteries with a large storage capacity (IEA 2020; IRENA 2020; Frankfurt School 2020; Ziegler and Trancik 2021). Figure 1 shows the change in the levelized cost of energy (LCOE, defined later in this section) for electricity generation between 2010 and 2020 using renewable sources, where a reduction of 85.04% stands out in the case photovoltaic systems, 68.24% for solar concentration plants, 56.18% for onshore wind power and 48.15% for offshore wind power, according to the latest report by the International Renewable Energy Agency (IRENA 2021). Generation costs using biomass have not changed, but those of generation with geothermal and hydroelectric plants have increased by 44.90% and 15.79%, respectively.

Although many specialists in energy issues are still unable to believe the current reality, these collapses in prices (with the exception of geothermal and hydroelectric) is something that should not be surprising, since some aspects (increasingly finer) have been known for decades related to the advancement of technologies and standardized methodologies to estimate said levelized costs of electrical energy generated by various technological options.

The so-called "economic laws" - which are descriptions of what would happen in the economic world under certain conditions, which are generally NOT fulfilled, unlike the laws of natural sciences, such as Mechanics and Thermodynamics, which are supposed to be definitive and universal - also provide solid bases for understanding, and above all forecasting, the future evolution of the prices of energy converted through the various technologies.

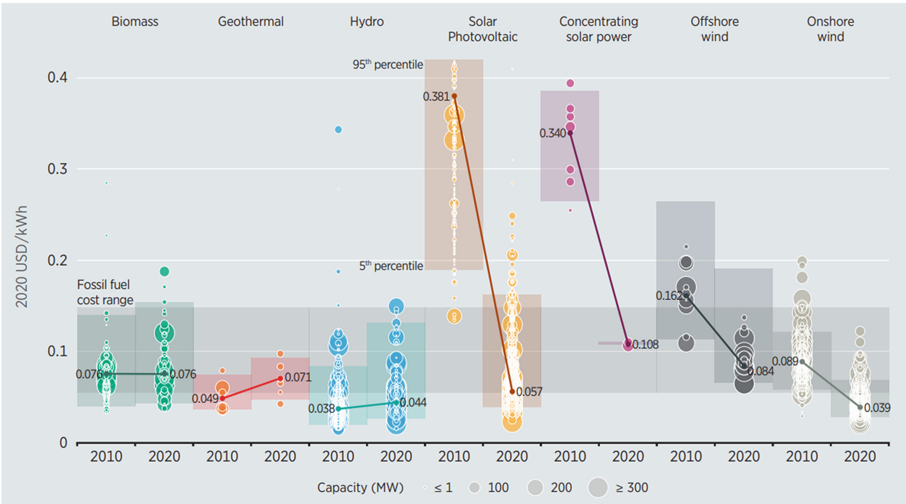

Fig. 1. Global LCOEs from newly commissioned, utility-scale renewable power generation technologies between 2010 and 2020 (IRENA 2021)

2 The Wright's Law

Among these, the "law of diminishing marginal utilities" stands out, as well as others that are less well known, but have been formulated for decades, such as "Wright's law" and "Moore's law". The latter, enunciated by Gordon Moore, co-founder of the Intel Corporation (Moore 1965), stated that the number of transistors that can be inserted into an integrated circuit (in fewer words, the capacity of electronic computers) would double every 18 months, which would imply an exponential growth over time of said computing capacity.

This so-called "law", which quickly became something of a mantra among untrained technologists and economists (who naively believed in exponential growth ad infinitum in a world with limited resources), has proven to be less precise than "Wright's law", originated decades before by the Theodore Paul Wright's observation in 1936 – on the eve of the 2nd World War - that the production costs of airplanes decreased by a practically constant percentage each time the number of airplanes manufactured doubled.

The decrease in costs was due to a complex mix of several factors -in addition to the disruptive advances in aeronautical technology- such as continuous innovations in manufacturing processes that reduce the use of materials, energy consumption, manufacturing times, but above all it was due to the accumulated manufacturing experience. This surprising finding reveals what is perhaps the closest thing to a general and universal economic law, applicable to virtually all technologies.

In a nutshell, "Wright's law" establishes that the unitary production costs of a technological artifact decrease as the quantity produced increases, and not as a function of time, as could be inaccurately inferred from Moore's law. Every time the quantity produced is doubled, the price decreases by a certain very uniform percentage. This Wright's law, which is graphically represented by the well-known "experience curves", constitutes one of the two solid pillars for the forecast of future costs and prices of energy converted with a given technology, which are discussed later.

Figure 2, which shows the experience curves for the price of crystalline silicon photovoltaic cells and lithium batteries, was published by Bloomberg New Energy Finance (BNEF) almost a decade ago. Based on these, the current price of the installed photovoltaic Watt peak (Wp) could be predicted with reasonable accuracy, although the prices of photovoltaic technologies include, in addition to the PV modules, the prices of inverters, wiring, controls, and a long etcetera, and each one of those technological components have their particular experience curves! The modules impact with only around a third of the total costs of large photovoltaic installations.

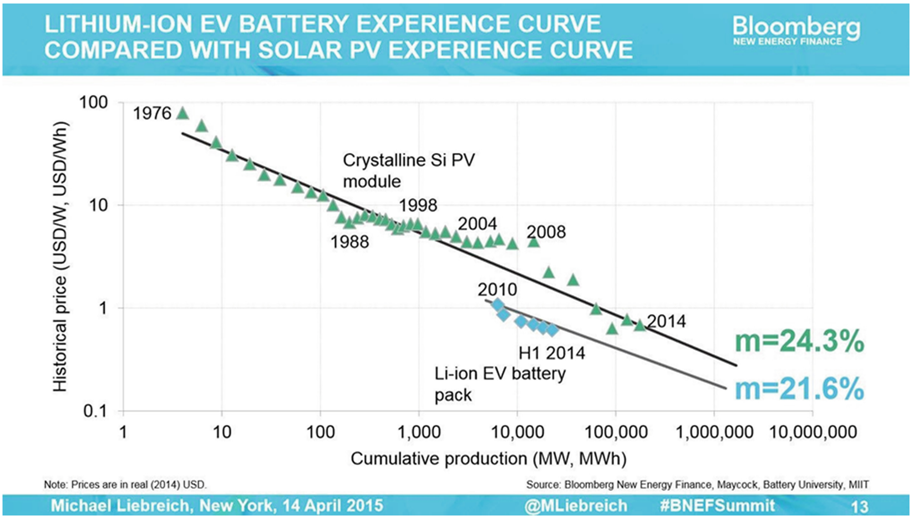

Fig. 2. Example of experience curves, corresponding to lithium ion batteries and crystalline silicon photovoltaic cells, (Liebreich 2015).

3 The Technologies Life Cycles

The other pillar is based on the observation that instead of an exponential growth over time of a technology (as suggested by Moore's law), quantified by the quantity of a good produced, for example the installed capacity for electricity generation, or the accumulated amount of electrical energy generated with this capacity, disruptive technologies have always followed a kind of "Life Cycle" (Technology Life Cycle) characterized by an "S" development (a "logistic" functional growth) where the four stages mentioned below are highlighted.

After the surge of an "emerging technology", it is followed by rapid growth that can be modeled as exponential -albeit for a limited period of time- which is in turn followed by growth that slows down as the technology matures until it reaches to a state of "saturation". After saturation, the emergence of a new emerging technology (which will also have an "S" development) is expected to displace the previous technology, which can go towards obsolescence. Identifying which stage of its life cycle a given technology is in is usually not a difficult task to do.

This "S" behavior can be clearly seen in Fig. 3, recently published by the Solar Heating and Cooling Program of the International Energy Agency (Weiss and Spörk-Dür 2021), where it is evident that this technology has reached full maturity. So, the emergence of a new solar heating technology seems to be imminent! It should be noted that the installed capacity for solar heating has already exceeded 0.5 TW_{th}.

Now, as an indisputable example of exponential growth, see in Fig. 4 the evolution of accumulated wind capacity in the period 2001–2010, during which this capacity doubled -almost perfectly- in three-year periods. The average annual growth rate during that entire decade -in which, by the way, the financial crash of 2008 occurred, which

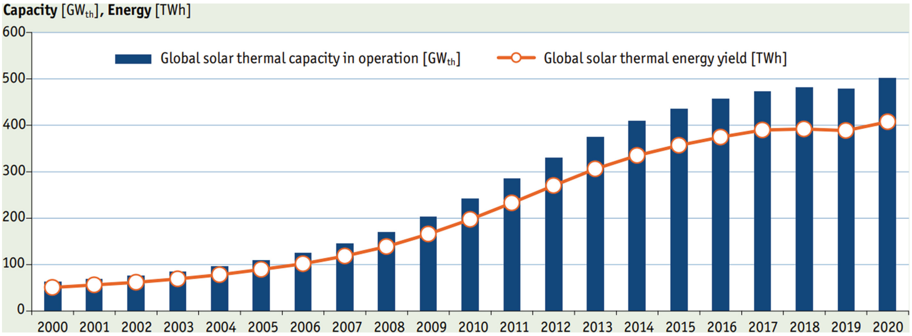

Fig. 3. Global installed solar thermal capacity in operation and annual heat energy supplied by solar heaters in the last 20 years, according to the SHC IEA (Weiss and Spörk-Dür 2021)

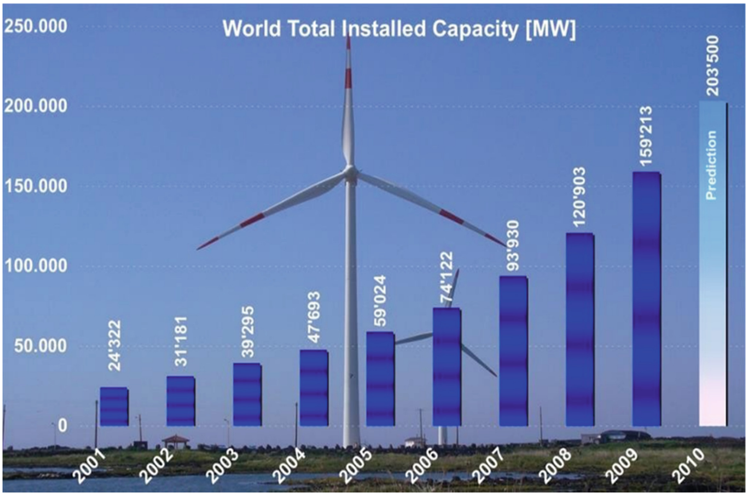

Fig. 4. Global installed wind capacity in the period 2001–2009. (WWEA 2009)

greatly affected the automotive industry and many others, but not the wind industry according to said figure - was 26.47%.

Had this growth rate been sustained, wind capacity this year would have already far exceeded global hydropower generation capacity, as shown in Fig. 5, published in 2011 on the World Wind Energy Association (WWEA) website at his statistical report for that year.

However, installed wind capacity evolved as shown in Fig. 6, published by the Global Wind Energy Council (GWEC 2021). The slowdown in the growth of onshore wind technology is clearly observed, evidencing its frank maturity, and the rapid emergence of offshore wind technology, which grew at an average rate of almost 30% per year during the last five years, heralding a new change technological.

Based on all of the above, the questions arise, how can the future costs of energy generated with technologies to take advantage of renewable sources be estimated? And

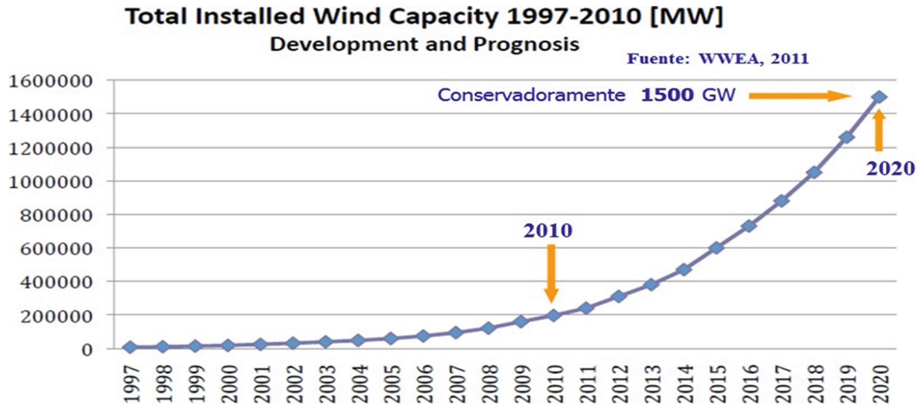

Fig. 5. Forecast made in 2011 for the wind capacity that would be installed in 2020, if the growth rate of the 2001–2011 decade had been maintained, with data taken from the World Wind Energy Association (WWEA)

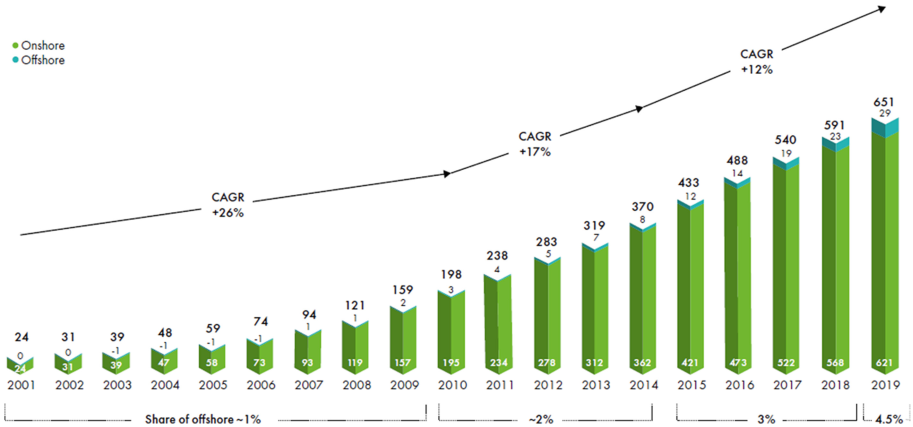

Fig. 6. Evolution of installed global wind capacity in the last two decades, according to the Global Wind Energy Council (GWEC 2021). The slowdown in the growth of onshore wind technology is observed, which shows its maturity, and the rapid emergence of offshore wind technology

how to estimate its net present value (NPV) in a way that allows an unbiased comparison with the NPVs corresponding to the energy generated with other technologies?

To answer them, we must first model what Wright's law implies, and then identify the stage of maturity of the technology in question. Once the above is done, the evolution of prices can be modeled as a function of time, in the stage of development of the previously identified technology.

Finally, we proceed to the application of the known techniques to estimate the levelized costs of converted energy (LCOE), using the most reliable and realistic information available, based on auditable costs of installations already carried out, discarding the prices offered by large companies. in the energy auctions that are currently being carried out all over the world, since these only reflect unreliable values, which the financial experts of the developer companies estimate can provide them with good profit margins (based on these same tools!) with projects yet to be realized in uncertain future months or years.

4 The Simple Model

Returning to Fig. 2, it can be seen that when plotting on logarithmic scales the historical prices of Wpeak photovoltaic cells (or lithium-ion battery storage units) as a function of installed capacity (or accumulated electrical energy generated with these PV cells), the fit to a straight line is evident, and this is corroborated by the correlation coefficients very close to one obtained in the data fit.

According to Wright's law, for practically all technologies, the price P, as a function of the accumulated installed capacity C, is modeled by the Eq. 1:

$$P(C) = P_0\left(\frac{C}{C_0}\right)^{\boldsymbol{n}} \tag{1}$$

where P_0 is the unit price of the technological unit when cumulative production is C_0 and $\boldsymbol{n}$ is the slope of the adjusted streight line on the logarithmic scale used, which has a negative value, since the price decreases as cumulative production increases.

In principle, the only thing that differentiates the evolution of prices between the various technologies is simply the value of said slope $\boldsymbol{n}$; the higher its absolute value, the more pronounced the decrease in the unit prices of the products. This is usually expressed by a "learning rate" (or rather "experience rate") TE, which indicates the percentage decrease in the price of products each time cumulative production doubles.

From Eq. (1), the experience rate TE is calculated as follows:

$$TE = \frac{P(C) - P(2C)}{P(C)}(100\%) = \frac{P_0\left(\frac{C}{C_0}\right)^n - P_0\left(\frac{2C}{C_0}\right)^n}{P_0\left(\frac{C}{C_0}\right)^n}(100\%) = \left(1 - 2^{\boldsymbol{n}}\right)(100\%) \tag{2}$$

It can be easily determined that the slope of the line corresponding to the PV technology in Fig. 2 is $\boldsymbol{n} = -0.40164$, that corresponds to an experience rate TE = 24.30%, which indicates that the price of Wp decreases 24.3% every time the installed capacity with this technology is doubled.

Now, once the decrease in the unit price of the technological product has been estimated each time the quantity produced is doubled, it remains to determine the period of time in which such duplication occurs. For doing this, it is necessary to identify the state of development of the technology, again based on recent data, corresponding to the last five years, for example. Thus, in a stage of exponential growth, properly defined by an average annual growth rate *tmca*, the quantity produced is expressed as a function of time by the following simple exponential growth model:

$$C(t) = C_0(1 + tmca)^{\boldsymbol{t-t_0}} \tag{3}$$

where $\boldsymbol{t}$ is the time (measured in years) from the year $\boldsymbol{t}_0$ in which the accumulated production $\boldsymbol{C}_0$ was had. Making the composition of the functions expressed in (1) and (3), we have the price as a function of time expresed as:

$$P(\boldsymbol{t}) = P(C(\boldsymbol{t})) = P_0\left(\frac{C_0(1 + tmca)^{\boldsymbol{t}-\boldsymbol{t}_0}}{C_0}\right)^{\boldsymbol{n}} = P_0[1 + tmca]^{\boldsymbol{n}(\boldsymbol{t}-\boldsymbol{t}_0)} \tag{4}$$

Thus, the price as a function of time can be modeled very simply as:

$$\boxed{P(\boldsymbol{t}) = P_0\,[1 + tmca]^{\boldsymbol{n}(\boldsymbol{t}-\boldsymbol{t}_0)}} \tag{5}$$

where *tmca* is the average annual growth rate of the quantity produced and $\boldsymbol{n}$ is the (in general negative) slope of the experience curve of the technology in question (which is a straight line when logarithmic scales are used for prices and quantities produced). Both parameters are quickly obtained from reliable historical data.

Finally, we proceed with the estimation of the levelized cost of energy converted (LCOE) by the well-known economic engineering model:

$$LCOE = \frac{\sum_{t=1}^{N}\frac{I_t + O\&M_t}{(1+i_p)^t}}{\sum_{t=1}^{N}\frac{E_t}{(1+i_p)^t}} \tag{6}$$

where:

I_t is the cost of investments made in period t
$O\&M_t$ are the operation and maintenance costs during the period t
E_t is the amount of energy converted during period t
i_p is the annual discount rate considered in the evaluation
N is the number of periods (usually annual) during the useful life of the project.

5 Conclusions

An extremmely simple procedure to assess the future cost of energy converted from renewable soureces has been presented. In this discusion, it should besides be noted that all technologies for the use of renewable energy sources maintain a growing trend in three key aspects:

1) The energy conversion efficiency (for example, commercially available PV modules have increased their energy efficiency; conversion from 12% to more than 17% in the last decade)
2) The plant capacity factors (wind farms have increased their plant capacity factors from a typical 20% in the 1980s, to more than 40% in the past decade, and over 62% for new offshore wind farms)
3) The useful life of system components (new good quality PV modules already have a useful life of well over 30 years). The combination of these factors leads to a rapid and sustained decline in levelized energy costs.

When applying the previous methodology, it must be noted that the levelized costs of the energy converted using renewable sources will continue their free fall, at values well below those predicted by the International Energy Agency and other stagnant instances. When comparing these with the costs of energy conversion with technologies that consume fossil and nuclear fuels, it can be concluded that these latest technologies are completely obsolete and unaffordable, regardless of the undesirable environmental and social problems that they entail.

For a world full of renewable energy sources, this is great news; there is still a great opportunity to make a transition to an energy system based on renewable sources and get rid of the current obsolete system, completely unsustainable.

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New Mexico's First Enphase Microinverter Rooftop Solar Installation – 13 Years of Performance Data

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Abstract. This paper presents a description of the first Enphase microinverter-based photovoltaic (PV) rooftop solar energy system in New Mexico installed in 2008. Annual energy production during the first 13 years of operation is presented. During the first six years of operation, the annual energy production met or exceeded predicted energy production using the PV Watts model. During the first 13 years of operation, the annual energy production showed a ~1.5% annual degradation assuming a linear regression. Degradation could include reduced performance of the PV modules and/or microinverters, soiling of the PV modules, and individual microinverter failures prior to replacement. Ten of the 15 original first-generation Enphase microinverters have been replaced due to failures within the first 14 years of operation.

Keywords: Rooftop solar · Microinverter · Reliability

1 Introduction

Over the last decade, microinverters have gained in popularity relative to central (or string) inverters because of purported advantages: (1) ability to produce more energy from an array of photovoltaic modules with partial shading, (2) greater reliability, (3) ease of installation, (4) safety (no high-voltage DC lines), and (5) ability to monitor performance of individual modules. Disadvantages include higher capital cost and potentially difficult access for rooftop mounted systems (microinverter is mounted underneath each module). This paper provides performance data for New Mexico's first Enphase microinverter-based solar photovoltaic (PV) rooftop system installed in 2008.

2 System Description

Figure 1 shows an aerial view of the 3 kW PV system installed on a two-story Spanish-tile roof in Albuquerque, NM. The original system consisted of 15 PV modules (200 W Sanyo HIP-200BA3) and 15 Enphase microinverters (200 W M200-32-240) with a 15-year warranty. The 10 modules on the top roof have an elevation tilt of 27°, and the five modules on the lower roof have a 30° tilt. Both arrays are flush mounted with the

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roof. The azimuthal orientation for all modules is 20° west of true south. Based on this configuration and the annual solar irradiance in Albuquerque, the system was predicted to produce ~5300 kWh using PV Watts [1], without consideration of partial shading or soiling.

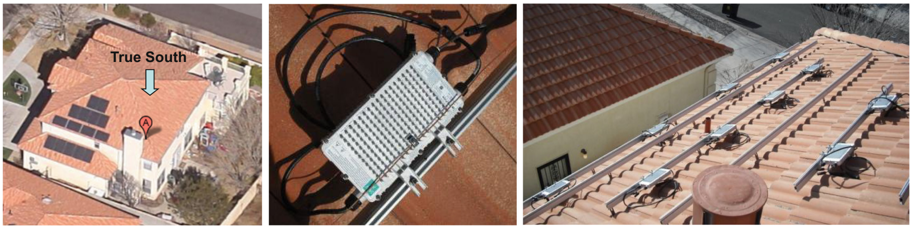

Fig. 1. 3 kW photovoltaic installation in Albuquerque, NM, using Enphase's first-generation microinverters.

3 System Performance

3.1 Energy Production

Figure 2 shows the actual annual energy production during the first 13 full years of operation from 2009–2021. During the first six years of operation, the system met or exceeded the predicted annual energy production of ~5300 kWh, despite no active cleaning of the PV modules (only periodic rain and snow). However, the chart shows a steady decline in annual energy output, which can be caused by degradation of the PV modules and/or microinverters, soiling, and/or periodic microinverter failures. When a microinverter failed, an automated e-mail notification was issued, but it often took several months or more to replace the bad microinverter (including obtaining a return merchandise

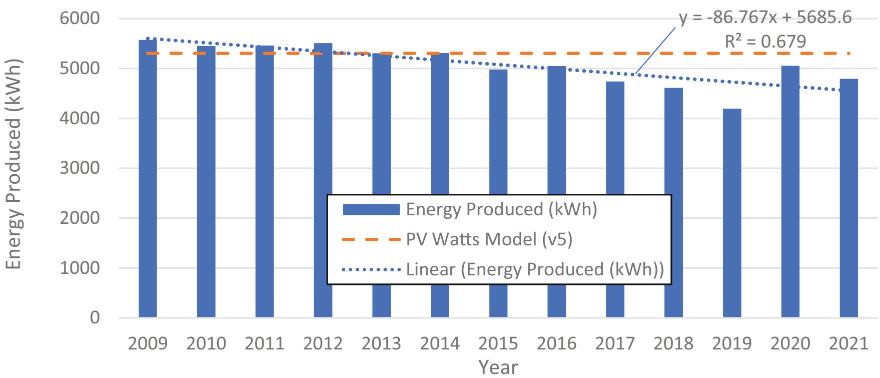

Fig. 2. Actual annual energy production from 2009 to 2021 for 3 kW photovoltaic system. Total annual degradation assuming linear regression is ~1.5%. PV Watts model prediction for annual energy production is ~5300 kWh.

authorization for the bad microinverter under warranty, scheduling a service technician, and replacing the microinverter). Accounting for all these factors, and assuming a linear regression of the actual annual energy output from 2009–2021, the annual "degradation" of the PV system was ~1.5%.

3.2 Microinverter Performance and Reliability

In general, the Enphase microinverters performed well when the units were functional. Frequent monitoring of the power production showed that during periods of partial shading from the chimney, power output was reduced only in the individual modules that were shaded. Figure 3 shows an example of the reported module power production during partial shading.

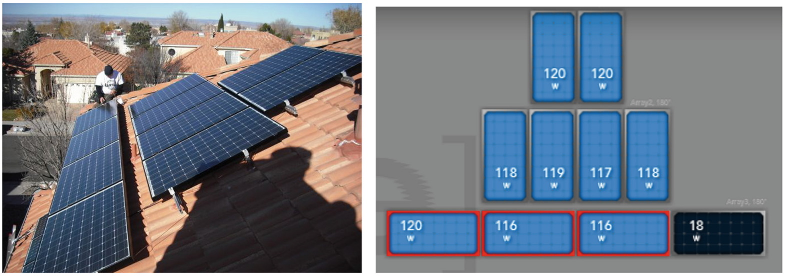

Fig. 3. Left: Photo of shading from chimney encroaching on panels. Right: Image of module power production showing impact of shading on one of the modules.

However, within the first 14 years of operation, 10 of the original 15 microinverters had to be replaced, and two of the replacements also failed. So, 12 microinverters in total

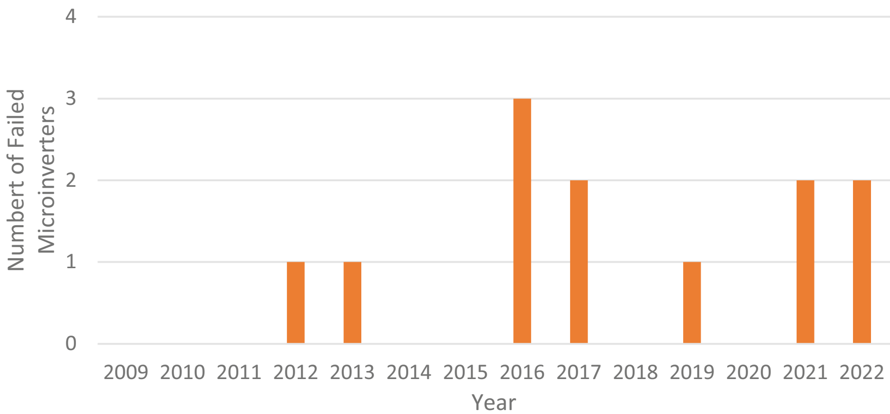

Fig. 4. Number of failed microinverters each year since 2009. A total of 12 microinverters on 10 PV modules have failed, and five originals remain.

failed during the first 14 years of operation. Figure 4 summarizes the number of failures by year.

4 Discussion

Analyses were performed to evaluate potential improvements to the system, including changes to the orientation (which was not readily possible due to the orientation of the roof and house) and sizing of the microinverters. It was predicted that changing the azimuthal orientation from 20° west of true south to 10° east of true south and the elevation tilt from ~30° (27° for the top array and 30° for the bottom array) to 35° would have resulted in a ~3% improvement in annual energy output. In addition, under sizing the microinverters (i.e., using a 175 W microinverter vs. a 200 W microinverter with the 200 W modules) could also increase the annual energy output due to greater efficiency of the smaller (lower-capacity) microinverter when the module output is less than the rated capacity of the microinverter,[1] but the predicted improvement was negligible in the current system (~0.1% improvement).

Replacing the Enphase microinverters was straightforward, from requesting replacements under warranty from Enphase to installing the new microinverters. There are numerous online videos describing how to replace the microinverters safely. Replacing the microinverters on a pitched Spanish tile roof was challenging, but with two people, it was manageable. Be aware that a special tool is required to separate the cabling between the module to the microinverter, and the negative coupler was nearly impossible to disconnect without cutting through the tabs that held the connection together for the 1st-generation microinverters. It should also be noted that the latest IQ7 microinverters do not require an external electrical grounding cable, which was required for the early-generation microinverters.

5 Conclusions

The 13-year performance of the first commercial deployment of Enphase microinverters on a residential rooftop photovoltaic system was reported in this paper. Of the original 15 first-generation microinverters, 10 have been replaced as of April 2022 due to failures and performance issues, and two of the replacements also failed and had to be replaced. Annual energy production of this 3 kW system was compared to predictions using PV Watts [1], and performance was comparable to predictions for the first six years. Over the last 13 years, degradation of the system output was determined to be ~1.5% per year, which included potential degradation in performance of the modules and/or microinverters, soiling of the modules, and/or microinverter outages prior to replacement. Optimizing the orientation, pitch, and microinverter sizing for this system relative to its deployed configuration was predicted to increase the annual energy production by several percent.

[1] A tradeoff exists between greater efficiency of the smaller microinverter if the module output is less than or equal to the rated capacity of the microinverter and clipping that occurs if module output is greater than the rated capacity of the microinverter.

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Economic Justice

Increasing Access to Solar for Low-Income Households in Multifamily Affordable Housing

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Abstract. Increasing access to onsite solar and community solar (CS) can provide numerous benefits to low-income (LI) households living in multifamily affordable housing (MFAH). Solar can help reduce their energy costs, preserve affordable housing, and create green workforce development opportunities. However, the MFAH market faces myriad barriers to accessing solar for LI residents, including lack of funding and other resources, low credit scores, and market and regulatory issues. ICAST (International Center for Appropriate and Sustainable Technology) is a national leader in delivering energy efficiency and renewable energy (EERE) solutions to LI households in MFAH. This paper leverages existing literature and ICAST's experience to discuss the aforementioned barriers; it also discusses ICAST's work to overcome them. ICAST is piloting an innovative and replicable program called Project Sunlight that incorporates technical and financial assistance and an innovative financing model to help MFAH owners surmount some of the most significant hurdles to accessing affordable solar for their LI tenants. Through Project Sunlight, ICAST can increase equitable access to solar to benefit LI households, MFAH properties, local communities, and society at large.

Keywords: Multifamily affordable housing · Solar · Low-income

1 Introduction

Increasing access to energy efficiency and renewable energy (EERE) solutions, such as onsite and community solar (CS) can reduce energy costs for low-income (LI) households, help preserve affordable housing, and create green workforce development opportunities [1]. According to the U.S. Department of Energy (DOE), the national average energy burden for LI households, i.e., the percentage of their income dedicated to covering energy costs, is 8.6%—three times higher than for non-LI households [2]. However, LI households—which constitute 44% of all households in the U.S. [2]—face myriad barriers to accessing solar, including lack of funds [3], low credit scores [3] (which can preclude them from accessing solar subscriptions), lack of home ownership [3] (renters do not have control over their roofs and thus, cannot pursue rooftop solar), and other regulatory and policy hurdles. There are numerous programs designed to expand access to solar solutions for LI households, including incentive and subsidy programs such as solar renewable energy credits (SRECs), or Utility CS programs with carve-outs for

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LI populations. However, LI households in multifamily affordable housing (MFAH) still face significant barriers to accessing solar, including the property owners' lack of resources and a lack of financing models tailored to the unique needs of this segment [1].

ICAST (International Center for Appropriate and Sustainable Technology) is a 501(c)(3) nonprofit with a 20-year history of delivering EERE solutions to LI and underserved communities. ICAST was selected by the DOE's Solar Energy Technologies Office (SETO) to implement a national initiative to overcome the hurdles of deploying solar in MFAH for the benefit of their LI tenants. MFAH is often older and energy inefficient, but historically underserved by clean energy programs [4]. In partnership with Utilities, MFAH owners, investors, and other stakeholders, ICAST has launched Project Sunlight, a scalable and nationally replicable approach to address the challenges of delivering affordable solar to LI households living in MFAH.

2 Benefits of Increasing Access to Solar for Low-Income Households in Multifamily Affordable Housing

EERE solutions such as onsite solar and CS can reduce LI residents' energy costs and enable them to dedicate their funds to other essential goods and services such as groceries and healthcare [5, 6]. Further, solar installations can help preserve and improve affordable housing, especially when delivered as part of whole-building EERE solutions [6] that provide significant upgrades to the property's building shell and mechanical, electrical, and plumbing systems. ICAST leverages this approach for all of its programs including Project Sunlight, as it increases the property's health, functioning, and safety, and brings down costs for the owners as well as the residents. Solar installations also create green workforce development opportunities for underserved communities [6]. The Bureau of Labor statistics found that the photovoltaic (PV) solar installer occupation is one of the five fastest-growing occupations in the U.S. [7]. Affordable solar tailored to LI renters in MFAH can also increase equitable access to EERE technologies. Renter households are far more likely to have lower incomes and to be households of color—48% of renter household are headed by a person of color [8]. Of the renter households earning less than \$30,000, Black and Hispanic households make up 25% and 19%, respectively [8]. Low- and moderate-income households are also more likely to live in multifamily housing [9, 10] than single-family homes.

3 Barriers to Increasing Solar Adoption in Multifamily Affordable Housing

3.1 Multifamily Affordable Housing is a Hard-To-Reach Market

MFAH owners often lack the resources (i.e., time, expertise, or funds) to pursue solar installs [4, 11], they have misperceptions regarding the cost and value of such installs, and they have a "split incentive" [4, 11]—i.e., in properties where the residents pay their own utility bills, owners are hesitant to pay for solar because they believe the cost-reduction benefits will accrue solely to the residents. Furthermore, few solar program implementers have knowledge or experience dealing with the issues faced by this market segment.

3.2 There is a Lack of Sustainable Financing Models for Multifamily Affordable Housing

Most of the solar programs that are operating at any appreciable scale offer LI households very low-cost or free [12–14] solar. The subsidies come from various sources, including government and philanthropic grants [14]. While states such as Illinois, Washington D.C., and California have LI solar programs with generous incentives, these are unsustainable and rare due to their high ongoing costs. Most statewide or Utility programs do not offer that kind of generous funding at any scale. In fact, a case can be made [15] that some Utilities would prefer an end to solar subsidies for LI because they believe the costs of providing free or discounted solar is being unfairly borne by other Utility customers. Further, reliance on government and philanthropic funding to subsidize large-scale solar programs is neither a scalable nor a sustainable [14] approach because both governments [12] and philanthropic sources have historically launched programs only to later move funding to other priorities.

3.3 Onsite Solar Projects for Multifamily Affordable Housing Are Technically and Financially Complex

Onsite solar projects for MFAH have higher upfront legal and setup costs [1], as a percentage of the project costs, due to the smaller size of onsite solar projects, often rendering them financially unfeasible. Also, many Utilities and states do not allow virtual net metering (VNM) [16, 17], making it difficult, if not impossible, to install solar at a MFAH property with individual solar equipment, connections, and utility meters for each LI tenant. Lack of VNM implies each tenant needs an individual connection to the Utility, decreasing the size of the solar project and increasing the costs exponentially.

Even if VNM is an option, the small size of onsite MFAH solar installations limit the volume efficiency needed to attract cost-effective financing. Most tax credit investors are not interested in small MFAH projects [18] and the few equity investors willing to provide financing require high returns. Debt providers such as banks and credit unions shy away from solar financing due to a lack of collateral, as solar panels may not be a bankable asset [19]. ICAST believes this lack of access to reasonable financing is the biggest hurdle to solar for LI residents in MFAH.

3.4 Existing Community Solar Programs Are Limited in Their Ability to Reach Low-Income Households in Multifamily Affordable Housing

While the CS approach aggregates solar subscribers to bring volume efficiency and reduce transaction costs, it is not a universal solution because it depends on policies such as community solar, VNM, Utility bill crediting, and other state and local regulations. Some states do not offer net metering [20], many do not offer VNM [17], and most Utility billing systems will not allow for pro-rata allocation of solar to individual apartment meters. Even in places where these models are working, they have not successfully driven solar access at scale.

Additionally, the annual process required by most CS programs for identifying and qualifying LI participants is cumbersome and expensive. This is especially true for LI households, which are more likely to move residences frequently [21]. The national annual turnover rate in multifamily is 47.5% [22], i.e., a multifamily property loses almost half of their renters each year. Further, a subsidized MFAH property owner/manager needs to go through a laborious and bureaucratic process to change the Utility and rent subsidy tenants receive in order to recoup their investment in any EERE upgrades. So, if a solar program changes the Utility costs for the LI tenants, the MFAH property needs to expend significant resources to recoup their investment. This adds to the effort needed by the MFAH property owner/manager and creates another hurdle.

4 How Project Sunlight Will Remove Barriers for Low-Income Households in Multifamily Affordable Housing

Project Sunlight overcomes barriers to serving LI households in MFAH by educating MFAH owners and property managers on the economic and environmental benefits of solar, providing access to financing, and increasing the volume efficiencies through aggregation, all while reducing overall costs by standardizing processes and contracts that encourage buy-in from both investors and Utilities.

Unlike many CS programs, which enroll individuals, Project Sunlight recruits the entire MFAH property, i.e., all of the LI residents on the property and the property itself, under one contract, to keep the cost savings benefit of solar with the property and its residents. Residents are signed up automatically with their lease agreements, at no cost to them. This further reduces costs to sign up subscribers, as the solar energy will continue to be utilized on the properties that sign contracts irrespective of the resident turnover.

ICAST also works directly with Utilities on these projects, gaining their buy-in by allowing local Utilities to own and operate the CS assets as long as they continue to serve LI populations. This ensures that Utilities do not see Project Sunlight as competition, but as a potential partner, removing one of the most common barriers to CS development. By not wanting to own the solar asset, ICAST can build partnerships with Utilities and MFAH owners who see ICAST as a facilitator rather than competitor.

The innovative, scalable, and sustainable aspect of Project Sunlight is ICAST's ability to partner with local Utilities, MFAH properties, and other stakeholders to launch large-scale, replicable solar projects in a manner beneficial for all parties.

4.1 Creation of a Cost-Effective, Sustainable Financing Model

ICAST is piloting a cost-effective and scalable new financing model for solar, leveraging components of current models to fund solar PV for MFAH, and utilizing its partnerships with Utilities and financial institutions. ICAST is combining components of four funding models—two of them utilize Utility funding, one uses a Special Purpose Entity (SPE) to take advantage of the tax credits, depreciation, and incentives from third-party investors, and the last is a philanthropic approach that heavily subsidizes solar for the LI population.

ICAST utilizes its ability to monetize the tax credits through a SPE, who offer an option to the MFAH owner or Utility to own the solar asset after year six (timeframe for depreciating all of the solar assets). Because the local Utility or the MFAH can serve as the manager, and later the owner, of the solar generation asset, there is high local buy-in. ICAST also incorporates a philanthropic model to the extent possible to help subsidize solar for LI households living in MFAH. By combining best practices from the current approaches, ICAST can leverage the benefits of different funding sources while offering a win-win solution for all parties, including investors, Utilities, donors, and tenants. This model is scalable nationally because it reduces/eliminates the need for subsidies.

4.2 Deployment of an Aggregation Database for Multifamily Affordable Housing

ICAST partnered with MFAH owners/managers, investors, and attorneys, to determine methods for aggregating risk profiles of the MFAH solar projects to reduce transaction costs. ICAST uses its aggregation database for project inputs as an efficient and cost-effective way to engage MFAH properties to sign up for this program. ICAST can aggregate numerous, similar solar projects together into a package deal for investment.

4.3 Standardization of Process and Contracts

ICAST worked with its attorneys to achieve a standardized contract approach that can reduce transaction costs with a comfortable level of risk. ICAST has established templates and provisions for a universal solar contract and documentation for aggregated projects to significantly reduce transaction costs. The process does require customizing to function in different states, with different laws and provisions that may come into play for aggregating demand from multiple MFAH projects into one financing package.

5 Conclusion

Increasing access to onsite solar and CS solutions for LI households in MFAH benefits the LI residents, the MFAH property, the community, and society at large. Existing models to increase access for LI households must be supported and enhanced by innovative financing models tailored to meet the unique needs of the MFAH market. By aggregating MFAH projects, standardizing the process and documentation, and borrowing the best practices from the industry to arrive at its innovative solution, Project Sunlight leverages existing resources and funding streams to facilitate equitable access to solar for historically underserved communities.

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Bringing Solar to Low-Wealth Neighborhoods

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Abstract. Norfolk Solar LLC and Sun Spots LLC are LLCs devoted to developing solar in marginalized and low-wealth neighborhoods in Hampton Roads Virginia. Their efforts have installed over $1M in solar in these communities. The financing methods and outreach process will be described, as well as the unique feature of hiring residents of these neighborhoods to be trained as full-time solar installers. These same methods could be used elsewhere to bring solar installations and jobs to disadvantaged communities. See https://www.norfolksolar.org for additional info and press links.

Keywords: Solar · Qualified opportunity zone · Energy justice · Energy burden

1 Introduction

Our feeling is that two of the most critical issues of our time are climate change and economic/racial inequity. One way to address both of these simultaneously is to install solar in disadvantaged, heavily-minority neighborhoods. An additional benefit can be gained by offering job training in solar to residents of the communities, as part of these installations.

1.1 Background

In 2017, Congress passed the Tax Cut and Jobs Act. Embedded in the Act were two new IRS sections known as 1400Z-1 and 1400Z-2. Commonly referred to as the Opportunity Zone legislation, 1400Z-2 introduced a unique capital gain tax incentive. Specifically, it offered a tax reduction, deferral of taxes, and tax exemption, for investments made in Qualified Opportunity Zones (QOZ). This tax code is one of the only vehicles that specifically incentivizes wealthy Americans to invest in low-wealth neighborhoods. As such, it has a huge potential for helping to heal the divide in this country between the rich and the poor, the haves and the have-nots.

Norfolk Solar QOZ Fund uses the tax benefits of QOZ investing coupled with the tax incentives for renewables to create an investment that has both a guaranteed return and a maximized tax benefit. With the originally enacted legislation, the timing was as follows: if an investment was made into a fund by December 31, 2019 and remains in the fund for seven years, the federal tax on the original investment is based upon 85% of the capital gain invested (i.e. $1.0 million is taxed at $850,000). In addition, the tax is not due until

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the end of the seven-year period; consequently, the time value of money has a valuation benefit for the taxpayer. If an investment was made after December 31, 2019 but before December 31, 2021 and is held for five years, the original capital gain investment is taxed at 90% (i.e. $1.0 million is taxed at $900,000). There is a final financial benefit for QOZ investments, but this one is not useful for a solar install; any capital gain in the QOZ investment is tax-free (e.g., if $1.0 million is invested and divested for $1.5 million, the $500,000 gain is not taxed). Since solar does not appreciate in value, this is not normally of use for a solar install. There is currently pending legislation that would extend these tax timelines to make current investments in QOZs financially advantageous.

2 Logistics

2.1 Creation of the Norfolk Solar QOZ Fund

Ruth Amundsen was the creator of the Norfolk Solar QOZ Fund. It came about through a confluence of three factors. First, at the end of 2018 Ms. Amundsen had just led a group of parents at an independent school to form an LLC and install solar on the school, paid for by the parents. The parents recouped the investment through tax credits and a 7-year Power Purchase Agreement (PPA) with the school, with no out-of-pocket costs for the school. Thus, she was intimately familiar with LLC formation, and tax incentives for renewables. Second, as a government employee, Ms. Amundsen was subject to the government-wide furlough in early 2019, meaning she had five weeks off work. During that time, she gave numerous presentations about methods to finance solar, and a suggestion at one such presentation was to consider Opportunity Zones. Third, it happened that at the same time she and her two sons received some unexpected capital gains connected to the sale of a family business. These three factors together, combined with the wish for the family to do more for the disadvantaged, led to the idea of creating a QOZ Fund dedicated to installation of solar.

There were a few unexpected complications. First, although the original desire was to help disadvantaged residents in QOZs directly, the laws in Virginia at that time precluded the third-party financing of solar on homes. Second, one of the tax incentives is the ability to take depreciation on renewable energy equipment. If the solar was purchased directly by the QOZ Fund itself, it would be purchased using ‘untaxed’ money, and thus depreciation could not be taken. The solution to the first issue was to install solar initially on businesses and non-profits that were in QOZs. The solution to the second issue was to create two levels of entities. At the top level would be the QOZ Fund and a second investment fund consisting of already-taxed money. These two would feed together into a second-tier entity, a QOZ Business, which would be the LLC to actually purchase the solar. Since taxed funds were included in the purchase, depreciation could then be taken.

Another aspect of the Fund structure grew out of the desire to be of more direct benefit to those living in disadvantaged areas. The fund could not install solar on the homes, but one way to be of direct benefit to the residents is to help with local employment. To that end, the fund decided to require in the solar installer contract to hire and train residents of the QOZs as solar installers. That effort was successful, and had led to at least 8 residents of the QOZs being hired and trained as solar installers. These individuals have been the first American Americans in the solar installation workforce in Hampton Roads Virginia.

The contract with the solar installer was somewhat unique, in that not only did the installer guarantee the hiring and training described, they also contracted for a single price for exclusive rights to installation of the entire amount of the Fund. The Fund totaled $750K, and the price agreed to was $1.68/W installed, with 10 years of maintenance and warranty service included. The contractor was taking a risk since they made no specifications of the number or type of roofs, so the fund could have requested any number of installs for that same total installation value. This single price made sizing and pricing of installs very simple for the fund.

2.2 Operation of the Norfolk Solar QOZ Fund

The Norfolk Solar QOZ Business has installed solar on the roofs of four family-owned businesses, two non-profits (an African American church and the boys and girls club next door) and a residence. The residence was made possible because in 2019, the state of Virginia passed the Virginia Clean Economy Act, and as part of that an addition of just a few words in the code meant that a PPA could be used for third-party financing of solar on a residence, if the resident was low-income by the Virginia definition (less than 80% of local median income). For Virginia that means roughly less than $70K annual income for a family of four.

Some of the installations and QOZ employees are shown in Fig. 1 and Fig. 2. These locations were found through a combination of searching online, in person outreach, and word of mouth. One of the first actions in outreach to sites was to create a website stating the purpose of the fund, allowing people to sign up to get solar, or to apply for a job as a resident of a QOZ. Norfolk Solar worked with numerous environmental and social justice groups to get the word out. One such group was Mothers Out Front, and due to their outreach, an African American church was one of the first signups on the site, and ended up having 70 kW of solar installed. Another site that signed up early was JD Miles Roofing, who happened to be one of the roofers that had worked on the independent school that Ms. Amundsen had installed solar on in 2018. This roofer was taking a lot of actions in their business to be more environmental, including transitioning to an all-electric fleet, installing EV chargers, and changing to higher efficiency HVAC. Installing solar fit right in, and as roofers who had already worked with a large solar install, there was no hesitancy about the safety of a solar installation on their roof. This early install got a lot of press, including the front page of the local paper [1], which helped get more signups and more installs in the pipeline.

To search online for suitable sites, satellite view maps were looked at in tandem with the maps of QOZ boundaries, to identify sites with suitable roofs within QOZs. One additional complication in Virginia was that PPAs would not be done with a commercial business for less than 50 kW, although non-profits could be smaller. That meant that not only did the roof need to have good solar exposure, it had to be over a certain minimum to be a viable site. A spreadsheet of likely sites was created, and outreach was done via social media, as well as phone calls and direct contact. Because these are disadvantaged and low-wealth neighborhoods, many of the buildings are in need of maintenance, and thus many of the roofs need substantial renovation before installation of solar. The ratio of potentials pursued to suitable sites was more than 10 to 1.

Fig. 1. Solar installations by Norfolk Solar QOZ Business.

Once a site was found to be suitable, the solar design was done and the payoff calculated. As a family investment fund that was more interested in social good than pure profit, the profit percentage necessary was very small, just enough to recoup the investment and pay legal and accounting fees. Most sites could have a term of 8 years at the current utility rate and still show positive return for the investor. A simple (one-page) template PPA was developed and used with tailoring for each site. Once a site signed the PPA, the install was scheduled. Once the install was complete, the site would be saving on their utility bill and using that to make regular payments to Norfolk Solar QOZ Business for the solar. In order to allow the site to build up enough savings to pay that bill, and to facilitate billing, the bills were sent on a quarterly schedule. Solar generation at the site was determined from the stored data on the inverter site.

Fig. 2. The first residence in Virginia with solar installed via a PPA.

3 Impact

3.1 Benefits

There are many benefits for the organizations that received these solar installations. After the installation they have a utility bill the same or less than before, but now the solar portion of that bill is fixed, and not subject to potential rate increases from the local utility. After the end of term, the organization can look forward to having a near-zero, or much lower, utility bill for the foreseeable future. Because the solar covers a good portion of the roof, the air conditioning costs are reduced since the solar is soaking up the sun rather than the roof. The protection of the roof from UV and also from extreme temperature changes extends the lifetime of the roof. For some of the sites, the press and notoriety from being a solar site was helpful – for example for JD Miles, being in the paper for the solar install and their efforts to be sustainable brought offers from an electric vehicle dealer for free trials of EV trucks and other benefits. Sometimes, the focus on energy generation due to watching the solar production can spark interest in energy efficiency, since the site has increased incentive to strive toward being net-zero energy. Often, many members of the organization will benefit by becoming more knowledgeable about renewable energy and associated effects like net metering. And, the emotional impact of being a community leader by being one of the first to move to renewable energy, can improve and inspire the morale of the organization.

3.2 Barriers

The disadvantaged communities in the Opportunity Zones have spent decades receiving less benefits from our society than the more well-off communities. Books like *The*

Color of Law lay out the tragic history in this country of why minority communities have ended up with less wealth, fewer homes, and lower paying jobs. In addition, many times promises were made to these communities by local and state governments, that have then been betrayed. Thus the trust in these communities is very low toward anyone coming to them telling how they are going to give them something good for free. As a well-off white person going into these communities, gaining the trust of the residents and organizations was the first and hardest barrier. Being in the paper helped to overcome it, as did leveraging the existing organizations such as Mothers Out Front that already do outreach in these communities. Going to civic league and community meetings, and laying out the case for solar, while acknowledging honestly the reasons people may feel suspicious, was a good way to start. At several community meetings, the discussion would start with how high people's utility bills were, and progress to giving out supplies for weatherizing their own home as well as educating on subjects such as why LED lights are beneficial, and basic methods of caulking. This helped build trust so that the discussion of solar could be a natural extension.

Another barrier, as already discussed, was the condition of the roofs in these areas. At least half of the candidate sites were unsuccessful due to roof condition. Lack of operating funds in the organizations led to two different barriers. One was that since many of these organizations are operating close to financial failure, there was a strong desire for the solar installation to be of financial benefit to them from day 1. This could only be accomplished by lowering the rate that the organization would pay for the solar on the PPA, which made the install less profitable for the investor, and stretched out the term making the investment less attractive. The other effect of lack of institutional funds had to do with the transfer of the system at the end of term. In a normal PPA, the sale of the solar system at the end of term is for Fair Market Value, FMV. Because this is a nebulous term with many possible methods for calculation, this would leave the organization looking at signing a PPA that could require them to purchase the solar system at the end of term for an unknown amount, likely many thousands of dollars, which would not be feasible for them. In some cases, these fears could be assuaged by a companion document to the PPA, that gave the organization a maximum that would be charged for FMV.

4 Outcomes

4.1 Solar Installations

Norfolk QOZ Business has directly installed over 400 kW of solar, with an annual production over 510 MWh, and thus over 360 tons of CO_2 production avoided every year. Additionally, many businesses have been educated and inspired by solar due to this effort, learned they could self-finance solar and use the tax credit have it fully pay off in 4 to 5 years, and decided to install solar on their own.

4.2 Norfolk Solar LLC

Partly because of the extensive press on this effort, including podcasts on Fundviews and Climify, presentations at national QOZ conferences, and webinars [2], many investors expressed interest in duplicating this work. One in particular, Rancho Solar LLC, was a QOZ fund that wanted to take the same actions and have the same impacts as Norfolk Solar QOZ Fund. The investor did not have local knowledge of sites and installers, and so asked Norfolk Solar QOZ Fund to deploy his funds in solar. The Norfolk Solar QOZ structure, as a family investment, was not set up to take in outside investors. Thus, Ms. Amundsen and her fund manager Alden Cleanthes decided to form a small woman-owned business, Norfolk Solar LLC, to help other investors duplicate this work. Norfolk Solar signed a three-way contract with their installer Convert Solar, and the Rancho Solar LLC QOZ Fund. This was a $750K investment fund entirely directed to installation of solar in QOZs. To date, two solar installations are completed from this fund, and more are pending.

One of the installations by this fund has been particularly heart-warming. A small African American church, Wesley Union AME Zion church, in the heart of Norfolk, was put in touch with Norfolk Solar. The church was over 120 years old, with a roof in very poor condition that faced east-west. Due to these issues, the decision was made to install as a ground mount, since there was suitable land on a lot adjacent to the church. Issues having to do with city permitting arose because the church was so old that there were no city planning documents of the land. With the help of local city council members, all issues were worked through and a ground mount solar array was installed. Because the church was in a neighborhood that has in the past experienced vandalism, there was some concern that the array could be vandalized. As one way to mitigate that fear, the pastor

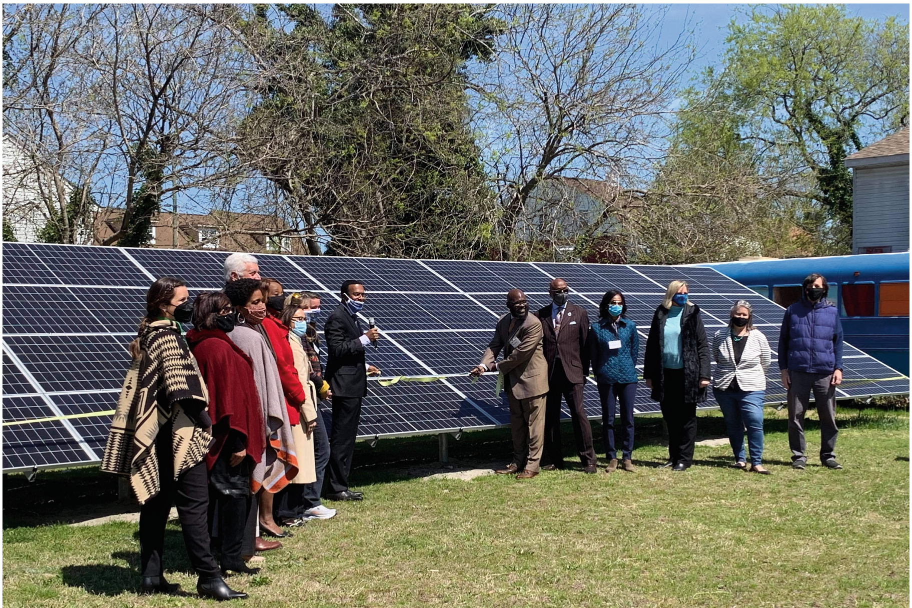

Fig. 3. Ribbon cutting for the AME Zion solar array.

of the church decided to have a ceremony to celebrate the array, to show the community what a good thing had come into their midst, and how they should care for it. As shown in Fig. 3, the ribbon cutting was highly successful, with many elected officials including the Norfolk mayor taking part, and neighborhood residents seeing how their church and their pastor were leading the way. The congregation felt a lot of pride in their church, and the pastor has made solar a key part of his message to the community.

4.3 Sun Spots LLC

The word of mouth from the first Virginia home to have solar installed via a PPA was immense, and in addition it was covered in the news media [3]. This meant that a number of people came forward requesting solar on their home, who did not happen to live in a QOZ, but were disadvantaged and could qualify as low-income per Virginia code. Thus, Ms. Amundsen started up an LLC (Sun Spots) to accomplish solar installations *not* in QOZs. This has resulted in one home solar install complete, and many more pending.

5 Opportunities

The fact that solar has come down in price so substantially over the last 10 years has meant that with tax incentives, a solar installation can pay off within 5–8 years depending on the organization. For institutions in low-wealth neighborhoods who often do not have the capital to do this themselves, and for non-profits such as churches who cannot take advantage of the tax incentives, this leads to a huge opportunity to leverage private wealth to improve the lives of those less fortunate. If every investor who was willing to trade a bit of their profit margin for the chance to support social, racial and environmental equity was aware of the possibilities inherent in solar, many more of these investments might be made. For many small investors, putting solar on just one or two low-income homes might be a very feasible part of their investment portfolio, and if this were widely replicated, thousands of low-wealth residents could benefit. Ways to spark this would be a national discourse on our current investment priorities, advertising widely the ease and profitability of solar investment, or establishing a federal framework that would facilitate this type of investment.

To address the training and employment piece, a federal guideline could be established that any large project in renewable energy must hire and train a certain percentage of their workforce from neighboring low-wealth communities.

All of this can be done without the QOZ legislation, which really adds little financial benefit but a host of tax and accounting complications. Investors can choose to invest in solar in disadvantaged neighborhoods without the umbrella of the QOZ legislation. Of course, if an investor has capital gains that they wish to shelter, this can obviously be used to advantage as was done by Norfolk Solar QOZ Fund.

Norfolk Solar is hopeful that the example they have set in terms of investment in these low-wealth communities, as well as providing jobs and training, will inspire others to similar efforts.

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Addressing the Gender Gap in the Energy Sector: The Case of Energy from Women. La Energía de las Mujeres

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Abstract. There is a clear linkage between the Sustainable Development Goal – SDG- 7 "Affordable and clean energy" and the SDG5 "Gender equality". However, SDG5, by itself, cannot be the only focus of attention to address the discrimination or inequalities that women face. SDG5 is also closely related to poverty reduction, climate change, and access to utility services such as energy, among others. Similarly, energy by itself is not enough. What matters here is the generation of goods and services and derived benefits to favor social development and sustainable livelihoods. In light of this, Energy from Women (EfW) is intended as a transdisciplinary collective of women created with two fundamental purposes: (i) to make professional women visible in different areas of knowledge and (ii) to give a voice to rural women, those who live in vulnerable environments, where there is still a high dependency on harmful primary energy. Therefore, EfW aims to spread awareness about working for a more inclusive energy sector in a gender-responsive manner.

Keywords: Gender equity · Gender equality · Gender gap · Energy sector · Energy from Women

1 Introduction

1.1 The Energy Sector and the Gender Gap

The 2030 Agenda for Sustainable Development has, among its main challenges, poverty reduction. This Agenda recognizes energy as a pivotal issue in eradicating poverty and building a sustainable future under three core dimensions: human development, environmental sustainability, and sustainable economic growth [1]. That means if the Sustainable Development Goal 7 (SDG7) "Affordable and clean energy" is achieved, there will be an impactful contribution to improving people's quality of life. The SDG7 is considered a catalyst of the Agenda. Thus, it has a direct or indirect relationship with the other SDGs, and among them, there is SDG5, "Gender equality".

To make it clear, SDG5 cannot be, by itself, the only focus of attention to address the discrimination or inequalities that women face. SDG5 is also closely related to poverty

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reduction, climate change, quality education, urban planning, access to utility services such as health, water, energy, and other aspects [2]. Similarly, energy access by itself is not enough. It must be accompanied by the generation of goods and services and derived benefits to favor social development and encourage sustainable livelihoods.

Therefore, how is it explained: the nexus between gender (SDG5) and energy (SDG7)? The response arises in two dimensions, energy consumption and energy production. On the consumption side, it is admitted that women are the ones who have traditionally assumed domestic work, who depends more on this resource, and who are the main ones responsible for cooking, providing water and energy to the home, and when it is not possible, who finds alternatives to ensure family well-being. In general, women are the ones who mostly suffer the impact of the lack of clean energy. On the other hand, the energy production side refers to the participation of women in the energy industry. In this sense, new technologies or renewable energy technologies play a fundamental role in positively impacting both dimensions. On the consumption side, when access to energy is guaranteed in remote and isolated communities that live in extreme poverty and vulnerable conditions, where traditional energy is still the main source of energy, affecting families' economies. Therefore, it is important to highlight that "energy access is key to opening up opportunities for women and men in developing countries". On the production side, when it is promoted greater participation of women in the labor market in the energy sector [2, 3].

According to a recent report [4], 759 million people have no access to electricity and 80% of this population is located in Sub-Saharan Africa. In addition to this, 2.6 billion people have no access to clean cooking solutions. Firewood is still the dominant fuel for cooking, while 2.5 million premature deaths every year result from air pollution in cooking. This fact mainly affects the lives of people who spend more time at home such as women, children, and the elderly [1, 5]. However, what happens when the population has access to clean energy technologies? A diversified family basket is possible since food can be preserved better or cooled for the first time, allowing access to other kinds of food. Additionally, women's safety is strengthened, health indicators can be improved, and the use of time changes. Time spent collecting firewood is used for access to telecommunications, information, and education. Also, there are possibilities to boost economic development, raising entrepreneurship opportunities, especially, empowering women.

In the study: "Renewable Energy: A gender perspective" by IRENA [3] in the renewable energy (RE) sector, women only represent 32% of total full-time employees, of which only 28% of women are dedicated to STEM (science, technology, engineering, and mathematics) activities, while the other 45% is dedicated to administrative activities. This study also analyzes the presence of barriers to women's participation. After conducting 1,500 interviews, this study identified that 75% of women recognize the existence of barriers to their participation in the RE sector, and the other 25% do not see them. By contrast, 40% of men recognize the presence of barriers to women's participation. Data clearly shows that "it is much easier the presence of barriers goes unnoticed for those who do not have to overcome them" [6]. Beyond that, the study also identified the most prominent barriers, social and cultural norms, especially in European countries and the United States, such as the lack of gender competencies and training programs and the lack of inclusive policies and programs highlighted in LAC countries.

Under these scenarios, considering that the COVID-19 pandemic has maximized inequalities, endeavors for a global energy transition should be more inclusive. Undoubtedly, energy transition would bring a series of social, environmental, and economic benefits, such as employment creation, that is why both men and women should have equal access to these opportunities. This is even more important in a sector of constant evolution, which demands new and innovative skills. Likewise, it is also necessary that the needs and opinions of everyone are deemed in decision-making, public policies, and the definition of programs [7].

Even though there are well-known international initiatives [8–10] working on the inclusiveness of the energy sector through mentoring programs, networking and technical assistance, they are still limited in offering an active role to beneficiaries, especially those that do not usually hold decision-making positions or leading roles in energy initiatives. There is still the need to make women visible in the energy sector, especially to those who are dealing with the daily work and have not had the opportunity to share what they are capable to do in the middle or lower positions, and at the same time, there is the need to highlight diversity in knowledge, experience, cultures and perspectives, to get an inclusive energy sector based on equity and equality. Therefore, the next section presents a new proposal to close these gaps and cover a higher population worldwide.

2 Energy from Women: A Network and Transdisciplinary Collective of Women

2.1 Conceptualization

In light of the above, Energy from Women, a network and a transdisciplinary collective of women, started in March 2021 with two main objectives. The first one, making professional women from different areas of knowledge visible in the energy sector worldwide, recognizing the value of diversity, multiculturalism, and equality. The second one, give a voice to rural women, those who live in isolated, remote, and vulnerable environments, where there is still a high dependency on harmful primary energy and low opportunities for development. Energy from Women has a real commitment to making changes in society under the umbrella of cooperative work and strategic alliances, basing its vision on the following:

- **Sharing experiences and stories of women**, inspiring women as new role models;
- **Motivation** to engage women in discussions of interests, to work on inequalities and build a community based on constancy and sorority;
- **Knowledge sharing,** publishing analyses, articles, and material of interest, authored by a community that supports the construction of a present and a future based on equal rights for all;
- **Dissemination** of activities and events that promote the participation of women in the energy sector and other linked areas to combat climate change;
- **Transdisciplinary work,** design and implementation of research and/or practical projects in a gender-responsive manner to bring together different areas of knowledge, professional backgrounds and experiences. The initiatives are mainly

focused on development cooperation and social responsibility funds to cooperate with international organizations, NGOs, the private sector, academia and communities;
- **Capacity building,** development and implementation of training programs, organization of conferences with gender mainstreaming;
- **Strengthening of the platform** through the establishment of partnerships and getting more women involved.

Similarly, Energy from Women is featured by the following values (see Fig. 1):

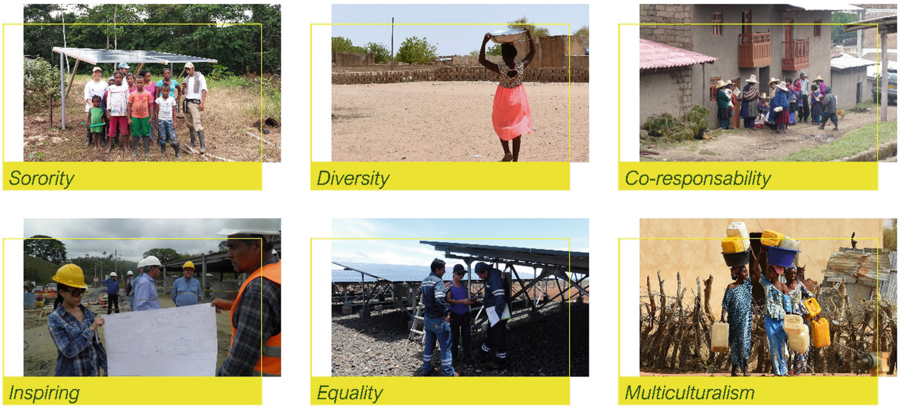

Fig. 1. Values of Energy from Women. Photos: Andrea Eras-Almeida, Tatiana Vásquez-Hernández, Diana Rojas, Miguel Egido-Aguilera.

From its beginning to now, Energy from Women has registered several achievements, which are summarized in the next section and have demonstrated the need to contribute to a better and more inclusive society. Energy from Women gives value to diversity and looks for ensuring active participation of its volunteers and project beneficiaries.

2.2 Results

In its mission, Energy from Women has published 11 articles and five stories. Articles that address topics such as climate action, environment, international cooperation, the energy sector, refugee population, sustainable architecture, biotechnosphere, chemistry, biomass and biofuels, green hydrogen, sustainable mobility, solar technology, and urban planning, among others; topics so diverse but that also tackle the gender perspective from a critical point of view. Similarly, the five stories, whose protagonists take the audience to different countries and regions and different realities, get across dreams and desire to become better human beings, diversity of knowledge and experiences, such as courage, bravery, and dedication to inspire them to continue giving their best, and thus, to make this world a fairer place.

Energy from Women continues progressing beyond its initial objectives, supporting communities and working on real-world projects. The first project refers to the case of

Table 1. Energy from Women projects and their linkage with SDGs

Project	Activities	Country	SDGs
La Bendición School	• Technical support the community and school to get funds through ONGs to repair the solar system. • A story about the women leader of the community was published in the EfW blog [11]. • Creation and promotion of crowdfunding to support the school. • Establishment of partnerships	Arauca, Colombia	
Fraternidade Association	• Technical support the association to get funds through ONGs to efficient energy, improve quality electrical service, and access to quality education and services. • A story about the association was published in the EfW blog [12]. • Creation and promotion of crowdfunding to support the association.	Teresina, Brazil	
Mamas Solares[14]	• A story about the community and the women leaders in the EfW blog [13]. • Video about the project "Mamas Solares" on social media for promotion and visibility.	San Salvador, Ecuador	

La Bendición School [11], led by María Yenny López and located in an isolated area of Arauca, Colombia, to provide access to electricity to a school that receives 30 girls and boys. This project is intended to recondition a PV system of 1.5 kWp through the recycling of solar panels and the installation of some electric components such as batteries and inverters. It will make it possible that the students could have access to quality education, drinkable water, and communications. The second one [12], located in Teresina, Brasil, is to implement energy efficiency measures in the Fraternidade Association that supports young people and children in vulnerable conditions through pedagogic activities, child psychology, and dentistry services, among others. While the third project, Mamas Solares [13], in San Salvador, Ecuador, aims to support women leaders, who are specialized in solar installations and look for bringing access to electricity to their community with solar home systems. Their objective is to provide at least 242 families with SHSs and empower more women within the community. Further information is depicted in Table 1.

Several partnerships and collaborations have been materialized to support the implementation of the above-described projects and other activities for visibility and cooperation, among them are alliances with Anécdotas con Energía from Mexico, IEEE Colombia, IEEE Ecuador, IEEE Brazil, private companies, and academia. These partnerships are also helping Energy from Women to get its message across. Likewise, Energy from Women, through voluntary work, actively offers awareness talks on gender equality in private companies, academia, forums, conferences, and interviews through different media like radio, television, and Facebook lives, which also contributes to the visibility of the network and its mission.

During this time, lessons learned have confirmed how fruitful it is to work in diversity and with a collaborative spirit. Today Energy from Women is represented by 30 volunteers between professionals and community leaders from various countries and cultures, including Spain, Ecuador, Colombia, the United States, Russia, Bolivia, Chile, Algeria, and Brazil. It is clear that gender equality and equity require significant efforts and for this, collective work is extremely necessary.

3 Conclusions

The largest challenge of the 2030 Agenda is to eradicate energy poverty where energy (SDG7) is recognized as a catalyst to achieve the SDGs, being SDG5 "Gender equality". The clear interlink between SDG7 and SDG5 states the importance of designing and implementing inclusive solutions where women's participation is secured. Based on this, Energy from Women emerges intending to make women at the professional level visible in different areas of knowledge and to give voice to those women living in vulnerable conditions, showing their leadership capacities to support community development.

"La Energía de las Mujeres", better known as Energy from Women, is made up of valuable women, women who with their knowledge and motivation contribute to endeavors for real gender equality and equity, to close knowledge gaps in society, to give value to multiculturalism, to work for a more fair and empathetic society with diversity, a society with equal opportunities. Energy from Women also represents women who lead and undertake initiatives to positively transform impoverished or vulnerable environments. Women with a strategic vision for building alliances to support the purpose of the network. Women with an open attitude to learning and collaborative work. Women who represent diversity, co-responsibility, equality, sorority, multiculturalism, and inspiration.

After more than one year of its start, this platform has demonstrated that the empowerment of women is a transformer element to impulse the economic and social development, reduce inequalities and prove the key role women can play by leading initiatives and sharing knowledge and experience.

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Evaluating a Third-Party Ownership Solar System in a Regulated State

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Abstract. Wisconsin is a regulated state which can limit retail sales of energy to the public in designated utility territories by non-utility providers. In 2014 the Legacy Solar Wisconsin Cooperative (Legacy Solar Co-op, or LSC) was founded to allow a wider group of individuals and organizations to invest in solar and energy efficiency projects. The model works by matching a "tax sponsor" with a host site that could use the energy saving technologies but cannot directly take advantage of either the investment tax credit (ITC) or commercial depreciation due either to the host site's tax status, ownership structure, or availability of tax liability against which to apply the benefits. The project site is typically a church, a library, a school, a farm, another community institution, or a cooperative. This tax financing model also allows for community residents and institutions, who join LSC, to buy co-op bonds (a private offering only to Wisconsin residents who are member-owners of the Co-op). The Co-op then can make a secured loan to qualified solar projects and in so doing provide another form of capital to reduce the out-of-pocket costs to the site host and the tax sponsor. This aspect of the model expands access to supporting clean energy projects to include a plurality of stakeholders, as well as provide a source of financing for the tax sponsor to leverage debt along with tax equity to improve the financial profile of the project for all. What results is a win-win-win for the host site, co-op member bondholders, and a tax sponsor, all of whom earn a modest return on their investment, with the host site being the long-term stakeholder for the decade's long-life expectancy of the solar project. In 2016, Don Wichert worked with the Legacy Solar Co-op and the Madison, WI based Willy Street Grocery Co-op to implement this model. The system includes a 26 kW DC solar electric system and 114 LED drivers and 228 LED lamps replacing the existing florescent tubes and ballasts. All energy projects have their own specific characteristics, but this tax-financed energy project using the Legacy Solar Co-op model appears to have been an energy and economic success for all parties involved. This paper lays out the description of this tax-financing model and analyzes the financial inputs and outcomes now that the project has fully matriculated and a flip in ownership between the tax sponsor and the host side landlord has now taken place.

Keywords: Tax financed · Solar · Economic return

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1 Introduction

Wisconsin is a regulated state, which means only public utilities can sell retail energy to the public. In addition, many organizations cannot access or have trouble accessing the federal tax credits for solar energy and energy efficiency. In addition, there are tax, security, and utility barriers for individuals, groups, and institutions looking to fully democratize investments into clean energy projects. To mitigate these problems, Legacy Solar Coop (LSC) was started. LSC seeks to guide local stakeholders into developing and funding their own solar and energy efficiency projects through tax financing mechanisms (Fig. 1) that combine the resources of host sites, tax sponsors, and sometimes even the Co-op's own bondholders in the project. The tax sponsor can use the tax credits from the part of the project they invest in and own, the host site enjoys lower energy bills and is able to obtain aninterconnection agreement with the local utility, and bondholders are able to grow the Co-op's bond loan fund which is used to make secured loans to qualified solar projects. The energy bill savings generated from the project drive the financial payback for all the stakeholders.

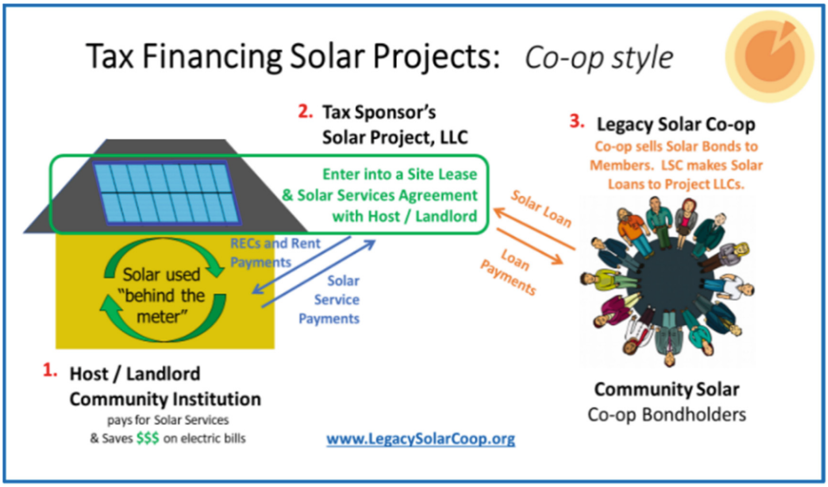

Fig. 1. The Legacy Solar Coop tax financed model

The tax sponsor's limited liability company enters into a site lease and energy savings service agreement with the site host, paying rent to the host site (landlord) while providing solar Renewable Energy Certificates (RECs) for at least 5 tax years before the site host (landlord) is eligible to buy out the project from the tax sponsor, usually at fair market value, according to IRS rules governing the disposition of qualified energy equipment enjoying tax benefits written into tax code. If and when there is a flip in ownership, the tax sponsor is made whole with the buyout, the Co-op is made whole from the loan payoff, and the bondholders are made whole by a recall or reinvestment opportunity within the terms of the bonds issued to Co-op members. If the host site decides not to buy out the tax sponsor, either the tax sponsor stays involved for the long run, or the Co-op can buy out the tax sponsor as a back-up "off-taker" for the project. Either way, the Co-op bondholders earn a modest return over time indirectly through the terms of the bonds issued by the Co-op, whether the Co-op owns the debt used in the project, or the Co-op owns the project itself and its service agreement with the host site. Having multiple options for the arrangement, long-term, is both a necessity (to adhere to IRS rules) and a benefit (for instance, nonprofit host sites cannot be compelled to ever buy out the tax sponsor), so a state of perfect indifference to the outcomes should be enjoyed by all. That is not to say that the tax sponsor isn't motivated to "cash out" at its earliest opportunity, but the rules prevent a pre-ordained sale between the parties of the service contract, especially if the counterparty is a nonprofit organization.

Because Wisconsin is a regulated state, the issue of tax financed energy projects by a third party requires careful legal handling. There are many examples of similar third-party ownership and leasing projects for solar electric, solar water heating, and energy efficiency in the state. An individual entity that only provides energy services to one party is not selling power to the "public" and is widely viewed to be in compliance with the state's utility laws.

2 The Project

Fig. 2. The host site: Willy Street Grocery Co-op

In 2016, Don Wichert worked with LSC and the Madison Wisconsin based Willy Street Grocery Co-op (WSGC), to implement this tax-financing model. The system includes a 26 kW DC solar electric system and 114 LED drivers and 228 LED lamps replacing the existing florescent tubes and ballasts. In a number of ways, this project represents a near perfect tax financed energy project as:

- The solar energy system will fill the un-shaded roof and all the energy provided by the solar system and savings from the efficient lighting, which are on 17–18 h a day, will be fully utilized by WSGC at the avoided retail rate.
- WSGC (Fig. 2) is open every day and has a significant electricity demand from cooling pumps and compressors, lights, and air conditioning to reject heat from the many people in the store. This demand is always much greater than that provided by the solar and lighting measures.

2.1 Steps Involved in the Project

There are a number of steps in setting up a tax financed projects through its final sale. Kurt Reinhold's consulting company, Solar Connections, coordinated the initial process and then the LSC provided financing after all the contracts were initiated. The major steps included:

1. Finding a host site, the Willy Street Grocery Coop;
2. Setting up an LLC for the tax sponsor, Willy Eudai Solar, LLC;
3. Developing contracts between the tax sponsor and the host site landlord;
4. Selling Co-op bonds to Members to help capitalize the loan fund for projects like this one;
5. Developing a contract, installing, and maintaining the lighting system;
6. Developing the Promissory Note and the Security Agreement between the Co-op and the tax sponsor;
7. Assisting and helping develop and score an RFP for a contractor to install the solar system;
8. Designing likely proforma economic impacts for the project;
9. Setting up quarterly spreadsheets to use in billing for the solar RECs, energy-savings measures, and loan payments;
10. Assisting in selling the project to the host site after the tax benefits had been exhausted by the equity investor and the project had satisfied the IRS tax recapture period for this class of equipment.

Fig. 3. The Heliene solar panels on roof

After securing an arrangement with the host site, the next step involved finding a solar contractor. A Request for Proposals (RFP) was developed, and five contractors submitted bids. The bids were evaluated based on project cost, the use of North American panels, employment practices, and local sustainability activities by the solar contractor. Full Spectrum Solar, a Madison, WI based solar contractor, was hired to install a 26 kW DC solar system, which consists of 80 Heliene 320-W panels (Fig. 3), made in Canada, and two 10 kW Fronius inverters with extended 20-year warranties. Twenty kilowatts (20 kW) alternating current (AC) was, at that time, the limit for retail rate net-metering in the Madison Gas & Electric (MGE) territory, the serving utility. The panels were orientated southwest at 45 degrees from south to reduce peak power demands in the afternoon from the store's refrigeration loads, and in order to fit more panels on the roof.

2.2 Project Costs and Sources of Capital

The entire project cost was $70,439, composed of five separate parts (Fig. 4):

1. Coordination &Consulting: 4.7% ($3,343);
2. Solar system installation: 83.2% ($58,585);
3. Inverter Extended warranty: 2.6% ($1,800);
4. Roof inspection: 2.1% ($1,500);
5. Lighting installation: 7.9% ($5,586).

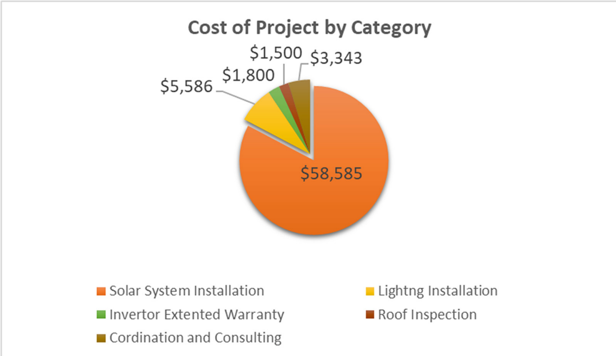

Fig. 4. Cost of the project by category

The Source of the capital (Fig. 5) came from:

1. The tax sponsor (Willy Eudai Solar, LLC);
2. Legacy Solar Co-op (LSC) Loan;
3. The Host Site (WSGC) Landlord.

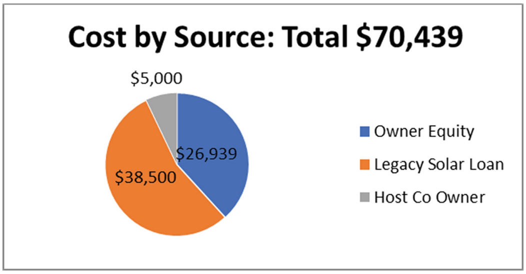

Fig. 5. Cost of capital by source

3 Energy Performance

The project went online in October of 2016 and the site lease and energy savings service agreement continued for 5.5 years until the project was sold to WSGC in March of 2022. The solar system energy production (RECs) totals were measured and tabulated on a continuous basis through the Fronius inverters connected to the internet. A software problem in one of the two inverters occurred in the first six months and was reset under warranty by the installer after a few weeks of power loss. The lighting system was analyzed for power demand before and after the new LED lights were installed. This difference, 228 W, was used to estimate the saving based on the 17 h a day the lights were on. There were no maintenance issues with the lights over the 5.5 years. The energy system saved 185 MWH over the 5.5 year life of the project.

The solar energy performance by year was fairly consistent as shown in Fig. 6 on the left; but had some variation over the 5.5-yeartime period. The energy performance was about double in the six months of the high solar months in the summer compared

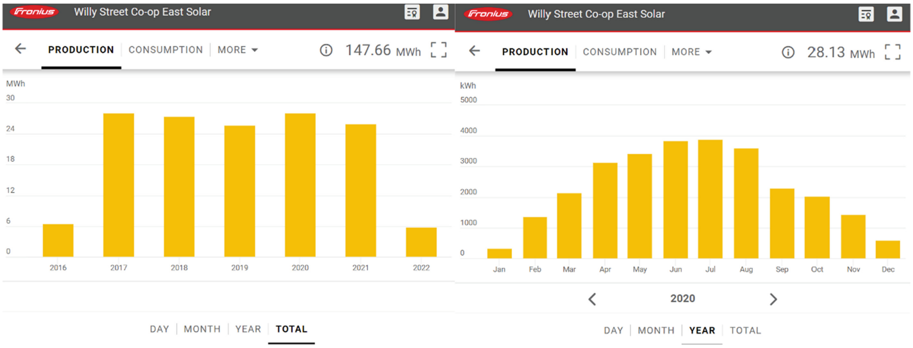

Fig. 6. Energy production by year and month

to the low solar months in the winter, as shown in Fig. 6 on the right, which is typical in the Midwest climate.

The 20 kW inverters limited the production at 20 kW, as shown on a very sunny spring day (Fig. 7), on the left. Snowfall, followed by cold weather, can virtually eliminate solar generation, sometimes for 2/3 of a winter month, as shown (Fig. 7) on the right.

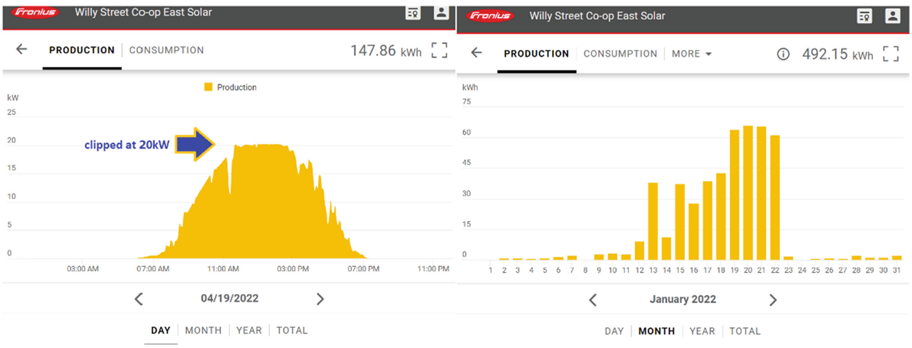

Fig. 7. Energy production variables

4 Economic Performance

A major goal of this project was to assess whether a small, distributed energy system on a commercial property could be profitable for a tax savings investor using the LSC tax investor model.

Total costs of the project over the 5.5-year project, which ended in March 2022, totaled $81,699 and consisted of six components (Fig. 8):

1. Investor equity;
2. Loan payments;

3. Loan buyout;
4. Maintenance costs;
5. Roof lease;
6. Insurance.

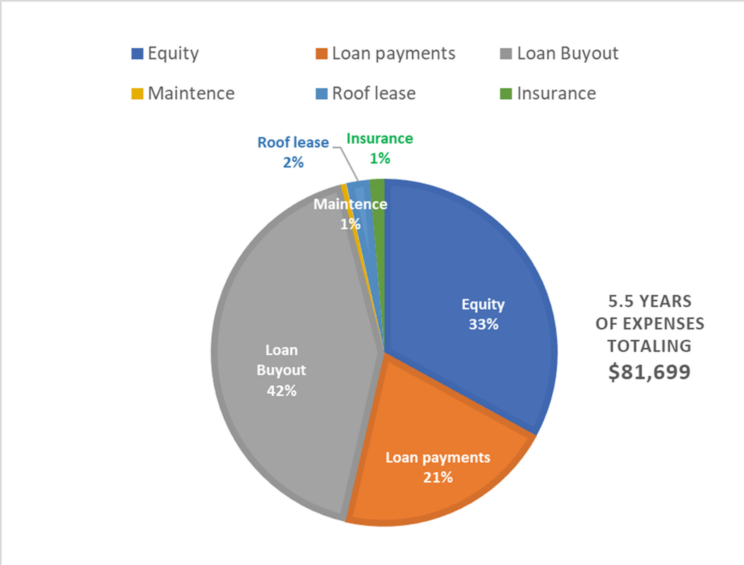

Fig. 8. Total expenses over 5.5 years

Total cost recovery came from solar RECs and lighting saving income, federal tax credit, depreciation, and deductible expenses created pass-through benefits over the 5.5 years consisting of seven components and totaled $89,775 (Fig. 9):

1. Loan disbursement (reduces out-of-pocket cost for tax sponsor);
2. Income from the sale of RECs and energy savings measures (kWh's saved from LED Lighting);
3. Federal tax credit;
4. Depreciation (Modified Accelerated Cost Reduction System, MACRS, 5-yr recovery schedule);
5. Loan interest expense deduction;
6. Other deductible expenses (insurance, roof rent, maintenance, administrative costs);
7. Final after-tax buyout sale by WSGC.

To determine total return for the equity investor, the expense of $81,699 was subtracted from the cost recovery of $89,775. The project's profit for the equity owner was $8,077. This was the return from an equity investment of $26,939, or about 30% over the 5.5-year project life. On a compounded annual basis, this is about 5 percent.

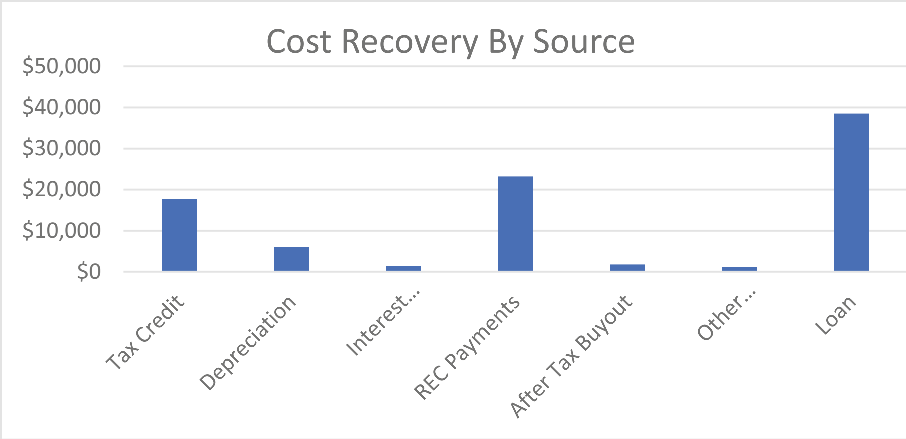

Fig. 9. Cost recovery by source

5 Observations

REC sales and energy savings from the LED lights to the host totaled $23,182. The lighting savings produced about 30% of the revenue with the remaining 70% came from solar system RECs. Considering that the full cost of the solar system was $61,885 while the lighting system was $5,586, the lighting system cost less than one tenth of the installed cost of the solar system. It's clearly in the interest of solar projects as well as projects where large energy efficiency saving opportunities exist, to do the cost-effective energy efficiency projects first, or do what we did and blend the PV and lighting retrofit into one investment to leverage the incentives for both technologies simultaneously.

The impact of snow on panels with an 18-degree pitch was also a factor in reducing winter energy production from the solar system. Another contributing factor was shading on the lower part of the solar panels due to the low angle winter sun from the top of a panel in front, starting at 2 PM from mid-November to mid-February. This shading caused a dramatic reduction of energy production during this period. However, there is not a huge amount of solar radiation during this period in Madison WI, but deserves mentioning.

This project was one of the first using the LSC model and due to the ambiguity on whether the project would qualify for the Wisconsin Focus on Energy incentive for solar, the project did not apply for a reimbursement incentive of 15%, up to $2,500. LSC projects that followed have applied and been awarded Focus incentives, which is used by the utility customer/host site to purchase and own some of the equipment directly.

The prospect of a buyout sale price of $40,297 was identified in the original contract between Willy Eudai Solar, LLC and WSGC. The expected amount was based on the cost of the system minus half the tax credit and a straight-line 1/25th reduction in buyout cost each year based on overall class of equipment of 25 years for the solar system. It was useful for all parties to have a buyout estimate (termination value, or Fair Market Value (FMV), whichever was greater). The parties did not have to apply the FMV rules since neither party was a nonprofit organization.

At closing, in March 2022 (Fig. 10), WSGC received $20,926 from LSC to pay off the remaining cost of the bonds bought by WSGC directly. After earning interest on their bonds for several years, WSGC ended up with an energy system for just under $40,000 with at least 20 years of guaranteed production left on the solar system and an estimated 10 years on the lighting system, while netting over $13,000 on energy savings after paying Willy Eudai Solar, LLC for the solar RECS and lighting retrofit savings.

WSGC*	Willy Eudai Solar, LLC**	Legacy Solar Co-op***
($40,297.05)	$40,297.05	
$20,926.64		($20,926.64)
	($34,619.14)	$34,619.14
($19,370.41)	$5,677.91	$13,692.49

Fig. 10. Final sale disposition at closing

LSC received $13,692 which was used to buy out the remaining bondholders outside of WSGC itself. WSGC purchased $22,500 in bonds and by the time of the sale, there was $20,926.64 left on the principal. During the 5.5 years of loan payments from Willy Eudai Solar, LLC, the Co-op earned approximately 1% on that note after paying the bondholders principal and interest for their bonds.

The equity investor ended up receiving $5,678 pretax, after the LSC loan was paid off. This was in addition to all the income & credits that were received previously. However, it's likely the full buyout amount of $40,297 will be taxed at the expected marginal rate of 11%, which will reduce the net gain to $1,782.

At this point, it appears that this energy project was a win, win, win economically for all the major parties in the project.

5.1 Tax Questions Remaining

At the time this paper was submitted in April, 2022, there were two additional questions that have not been resolved that could impact the equity investor's return:

1. The impact of the project from reduced Wisconsin state taxes. Wisconsin has a state tax of 6.2% on income. The equity investor always received a refund from the Wisconsin Department of Revenue during the project time period and believes the project was responsible for this refund. However, the specifics of how to calculate this benefit, if any, are still under discussion with the equity investor's tax accountant.
2. Determining how to allocate the final sales price after capital gains taxes have been deducted. Should the taxes be based on the overall sale of the project, $40,297, or the estimated profit of $8,139, or should it be on the amount remaining after all bills paid, $5,677. This impact is still under consideration at the time of this writing, but the default is paying an 11% marginal tax on the overall sale, which reduces the net gain from the buyout for the equity investor, after taxes, of $1,782. This assumption takes into account two accounting principles at work:
3. Depreciation recapture;

4. Loan forgiveness being counted in the taxable gain at the time of the sale.

6 Conclusions

All energy projects have their own specific characteristics, but this tax-financed energy project using the LSC model appears to have been an energy and economic success for all parties involved. The LSC model worked for all parties: the tax sponsor investor, the host site, LSC, and the Co-op bondholders. Each party made a return on their investment while supporting a project that reduced dependence on fossil-based energy.

The solar and lighting systems performed about as expected with the exception of some shading and snow blocking issues on the solar system in the low sun energy winter months of November to February. Both systems are low maintenance and reliable and are good energy saving technologies for commercial properties with a constant, year-long, energy demand.

This was the first project using the LSC model that went through the entire process from conception through final sale. It appears to be repeatable, although each project is unique.

Since 2015, Legacy Solar Co-op has helped over 40 community institutions, farms, and other cooperatives with similar type of arrangements, all successful so far, with each project posing its own unique challenges and opportunities.

Check for updates

Disparities in Approved Vendor Outcomes in Illinois Solar for All

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Abstract. Illinois Solar for All (ILSFA) is an incentive program designed to bring the benefits of solar energy in communities across Illinois. ILSFA increases participation in solar energy projects serving low-income and environmental justice communities. Incentives are offered to Approved Vendors who develop PV projects for residential properties, properties that house non-profits and public facilities, and community solar projects serving customers with low incomes. As the program completes its fourth program year, disparate outcomes are observed for Approved Vendors (AVs). Afro-American AVs which comprise 14% of the AV pool, are not participating in the program at the same level as Euro-American AVs who have captured 85% of the total program-wide Renewable Energy Credit (REC) awards. Most of the Afro-American AVs did not submit a project application and thus did not capture any incentive dollars. As a group, their Euro-American counterparts tended to submit more applications, indicating they were able to move further through the project development cycle compared to their Afro-American counterparts. The program's sole Native American AV did not secure any approved projects. The program's sole Asian-American AV secured a single project REC award. Preliminary research underway suggests that multiple factors contribute to outcomes: internal planning capacity and a robust and curated project pipeline, social networks, access to capital, educational attainment, prior experience in solar, and familiarity and facility navigating with programs with complex requirements. Research includes program data analysis and one-on-one interviews with AVs.

Keywords: Energy transformation · Equity · Economic justice

1 Illinois Solar for All

The Illinois Solar For All (ILSFA) program [1] intends to bring the benefits of solar energy to low-income and environmental justice communities. Incentives are offered to Approved Vendors (AVs) who develop PV projects for residential properties, properties that house non-profits and public facilities, and community solar projects serving customers with low incomes. Approved Vendors secure 15 year Renewable Energy Certificate (REC) contracts for approved PV projects.

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2 ILSFA Approved Vendor Diversity

As the ILSFA program approaches the conclusion of its fourth program year, we can look at the degree to which AVs from diverse backgrounds have been able to access the program. Program participation may be construed as a series of steps, beginning with a registration application to become an AV and culminating in an energized completed project. In between are numerous other discrete tasks: business development/customer engagement, site survey/analysis, system design engineering and permitting, proposal, contracting utility interconnection, ILSFA program application, and many other steps. At one level, the ILSFA program approaches a level of ancestral diversity comparable to the Energy Efficiency workforce in Illinois where Euro-Americans comprise 76.6%, Hispanics 14.9%, Afro-Americans 9.1%, Asian-American 6%, Native American 1%, and 8.3% other [2]. The ILSFA program has a higher percentage of Afro-American AVs (14.2%), but is lower in the percentage of Asian-American (1.4%) and Hispanic (none reported) AVs. The participation rate of Native Americans is consistent with the Energy Efficiency workforce. Table 1 presents the ancestry demographics of the AV pool as reported to the Program Administrator.

Table 1. Approved vendor pool ancestry demographics

AV demographics	Total	% of total
All approved vendors	70	100
Non-MBE[a] AVs	59	83
Afro-American AVs	10	14.2
Asian-American AV	1	1.4
Indigenous/Native American AV	1	1.4

[a] MBE = Minority Business Enterprise

As of April 2022, the program has issued REC awards totaling approximately $83,000,000, with over 84% going to AVs owned by individuals of European ancestry. Fifteen percent of the REC awards went to Afro-American AVs, and the remaining fifth of a percent went to an Asian-American AV (Table 2).

Currently, the author is conducting interviews with Approved Vendors to understand the barriers non-European AVs face in program participation. In discussions with both Euro and non-Euro AVs, preliminary conversations and data suggest that a variety of factors may present challenges to AVs which result in attrition at key project development process steps. Conversely, the interviews also suggest that there are a variety of factors that contribute to an AV's success in securing an ILSFA REC contract. These include:

- Prior work experience in the solar industry
- Ability to develop a robust and curated project pipeline
- Technical expertise and proficiency
- Access to capital

Table 2. Approved vendor REC capture ($) by ancestry

AV ancestry	REC capture/value of REC contract	Percentage of total program REC award
	Total program-wide REC award[b] $82,969,198	100
Non-MBE/Euro-American	$70,230,476	84.6
Afro-American	$12,591,054	15.2
Asian-American	$147,668	0.2
Indigenous/Native American AV	0	0

[b] As of April 15, 2022

- Level of educational attainment
- Experience and proficiency with complex governmental programs
- Social networks

The preliminary findings suggest that there may be opportunities to lower barriers and improve access and outcomes for under-represented groups. To date the program has provided support to all Approved Vendors, but a better understanding of the points where attrition occurs may indicate areas where additional support and resources can be provided.

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The Northland Solar Commons: An Industry, University and Tribal Community Partnership to Use the Sun's Common Wealth for Reparative Justice in Northern Minnesota

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https://solarcommonsproject.org/, https://heliene.com/

Abstract. The Northland Solar Commons Project is a creative partnership among the University of Minnesota, the solar manufacturing firm Heliene, Inc., and the Bois Forte Ojibwe Reservation. To make sure that the sun's common wealth is shared with its tribal community neighbors, Heliene will host a 500 kW Solar Commons behind the meter of its manufacturing plant in northern Minnesota. As a Solar Commons host, Heliene accepts a twenty-year obligation to pay forward its solar savings (approximately $70,000 annually) to a community trust whose beneficiary is the Bois Forte Food Sovereignty Group working on reversing the disproportionate health impacts of colonization and commodity food on its tribal members. Together with the Solar Commons Research Project at the University of Minnesota, Heliene and Bois Forte members will be co-creating and piloting the legal and digital peer governance tools that will make community trust solar ownership—Solar Commons™—a robust economic tool for low-income community benefit. In this panel CEO of Heliene and Founder/Director of the Solar Commons Project present their work to test a reparative justice, community economy tool for a more just energy transition.

Keywords: Community solar · Solar ownership innovation · Just energy transition

A Solar Commons™ array can gather the sun's common wealth by generating clean electricity and accumulating electricity bill savings on a host's electric meter.[1] Thanks to its embeddedness in a community trust ownership legal structure, that array is tied to a social obligation: the host agrees to pass those solar savings (minus any O&M costs) to a community trust fund. Day after sunshining day, investors in that solar array are mitigating climate change while passing on market value solar savings to the trust. Every year for the twenty-some year life of the array, those investors are sustaining

[1] The Solar Commons name and model are used with permission of **Solar Commons**, a 501(c)3 nonprofit corporation (https://www.solarcommons.org/).

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a trust that converts its social wealth funds into a revenue stream that supports the reparative justice work of its local community beneficiary. The Solar Commons Model is an innovation of community trust ownership for solar energy assets and benefits. At the University of Minnesota, the Solar Commons Project research team is piloting the model in northern Minnesota with Heliene, Inc., the state's only solar manufacturing firm located in Mt. Iron, a rural town on Minnesota's historic Iron Range. Heliene will be the Northland Solar Commons's host. A forty minute drive north from Heliene lies the Bois Forte Indian Reservation. There, the Bois Forte Food Sovereignty Group (BFFSG) has joined our community-based research team as the beneficiary of the Northland Solar Commons Trust. BFFSG is made up of members of the Bois Forte Ojibwe Tribe working to decolonize the industrialized food system and its Standard American Diet (SAD) that displaced Indigenous foodways and practices and brought nutrient-related disease in its wake. Together, university researchers, Heliene administrators, and BFFSG members constitute a "living lab" to pilot a 500 kW Solar Commons array that will use clean solar energy to power Heliene's manufacturing plant and direct an annual revenue stream of approximately $70,000 for twenty years to grow and empower BFFSG's food sovereignty work. Together, these community partners are co-designing the legal and digital peer-governance tools that will allow them to build transparency and social trust. Together they will creatively deploy 21st century technologies of solar energy and digital platforms and shape them with ancient, enduring social forms of community trust ownership. Together they act as neighbors and share the work of repairing a world that is suffering from impacts of fossil fuel and colonialism.

We are two of the establishing members of the Northland Solar Commons living lab. We bring knowledge from the solar industry and from legal anthropology to the task of shaping solar technology to meet practical, ecological and social needs of our historic moment and place. We are two years into our Northland Solar Commons initiative. All of us on the community-based research team have our day jobs and understand that it takes time to raise the capital, build the peer-governance tools and support the capacity-building that the Bois Forte Food Sovereignty Group is doing to create the physical and social infrastructure to transition their local food system. In this short essay, we offer some thoughts based on our empirical work on the Solar Commons project. For us, Solar Commons brings insight on the economic value and the potential of solar technology in our historic energy transition.

The first point concerns what photovoltaic arrays can teach us about our economic system. With the Solar Commons project, we know that the sun shines freely everywhere for everyone. It is a form of common wealth. If a Solar Commons host accepts an obligation to use the photovoltaic arrays to gather and pass along the sun's common wealth to neighbors, those neighbors will follow the general rules of the Solar Commons Agreement and use the wealth to generate more community wealth. This flow of wealth becomes transparent and visible in the digital peer governance dashboard tools our research team is building for solar commoning partners (see Fig. 1). But what everyone on our research team sees is that the sun's free common wealth passes through values established in the market price of solar. The market price of electricity in the US is dynamic: it depends on the monopoly utility jurisdiction that overlays the land where the sun freely shines. In Minneapolis we have a "value of solar" pricing system and hard won legislation that compelled the local utility to allow communities to own their own solar arrays. In Minnesota's Northland we have a different utility, different pricing and no ordinance to compel the local utility to allow third party community ownership. Because of these local rules, a Solar Commons in Minneapolis will make alot more money for its community trust than a Solar Commons on the Iron Range. Through the prism of a Solar Commons, community partners see the value of common wealth interacting with the values of the marketplace. Suddenly, common wealth is seen in relation to market wealth and market wealth, in the electricity sector, can be viewed more clearly: the market price of electricity appears less related to market competition (the relative costs of generating power from wind or solar versus coal or nuclear) and more subject to the rule-making political power of the local monopoly utility.

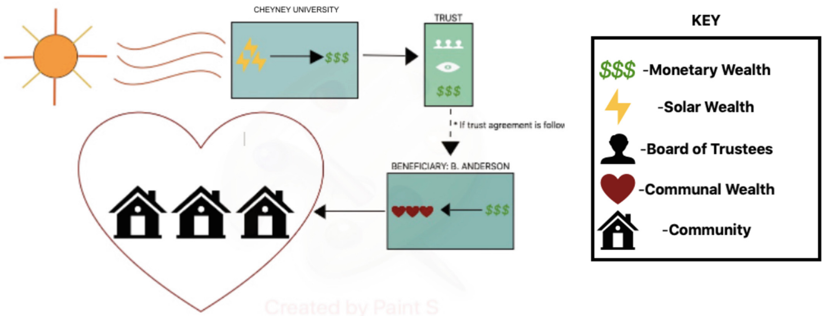

Fig. 1. A design for a Solar Commons flow of wealth dashboard created by students in Prof. Milun's "New Commons Design" anthropology course.

A Solar Commons dashboard makes visible these interconnected, changing values of solar energy. It shows the radiant flow of sunshine through the kilowatt units generated by photovoltaic technology. It shows the market sector political economy of solar energy pricing transformed into a common wealth trust fund for community good. By the time the flow of solar wealth reaches the Bois Forte Food Sovereignty Group, it appears on the dashboard in photographs and stories of reservation youth-built community gardens for elders and newly flourishing reservation farmers' markets. The economics of a sustainable energy transition, the dashboard shows, can also support a sustainable food system transition.

Photovoltaic arrays, operating in a Solar Commons system, become part of an institution (dependable, shared rules and tools) in the "commons" sector of our economy. The economist Kate Raworth offers a diagram (see Fig. 2) of a 21st century "embedded economy" where provisioning for needs and wants takes place within an ecological ceiling of planetary boundaries and a social equity floor where basic needs are met. There are four "sectors" of economic activity in this 21st century embedded economy: state, market, household and commons. Solar Commons is a much-needed innovation of the commons sector. Most readers and economists can recognize everyday practices and institutions in the state, market, and household sectors. State sector agencies raise money for public good through taxes. Market sector actors raise funds for private industry through banks. But what institutions do civic groups (in particular historically disadvantaged civic groups) have to build long-term revenue streams for collective action in their communities? Solar Commons would be an institution in the commons sector. One outcome of the Northland Solar Commons community-based research project will be to create well tested, open source legal templates and free DIY peer-governance dashboard design tools available to civic groups wanting to fund reparative mutual aid work through "solar commoning." Integrated into our 21st century energy transition, Solar Commons offer a vision of photovoltaic arrays as social-ecological technologies that can help drive a more just, integrated, energy transition.

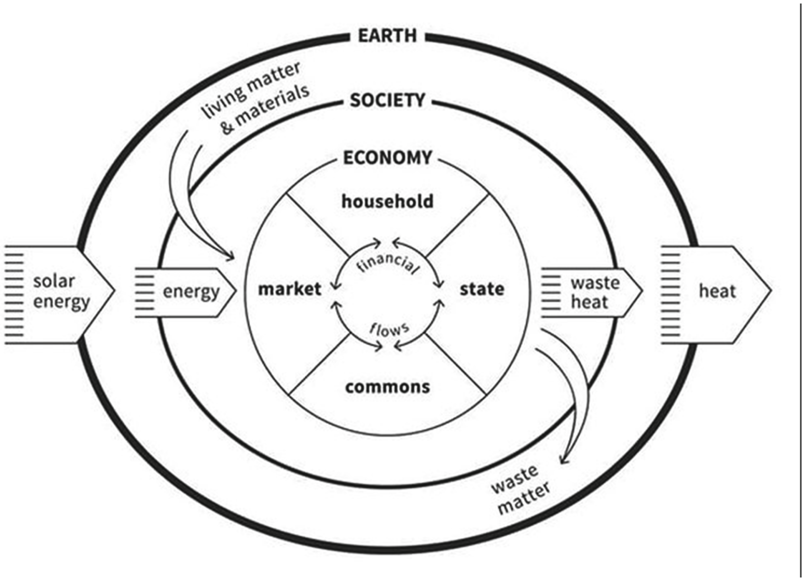

Fig. 2. The commons sector in an embedded economy [1]

A final point that our Northland Solar Commons project allows us to make concerns the potential of solar technology in our historic energy transition. We know that the Solar Commons financial model has the capacity to scale throughout the United States to over ten gigawatts over the coming decade [5]. As it iterates in new ecological and economic niches, Solar Commons will also be showing us an even greater potential of solar technology. The entrepreneur and author Peter Barnes argues that common wealth trusts of the sort we are designing with Solar Commons are "structures of transition." Barnes notes that "new economic thinking, shifts in consciousness, and grassroots initiatives can set the stage for the needed transition, but without structural change"… such as the legal innovation and experimentation of holding common wealth in social trusts, we will not be able to overcome the double tragedy of inequality and environmental destruction. For Barnes, a system of common wealth (even sunshine itself we might add) properly organized in social wealth trusts can be part of the broad structural innovation we need for the needed transition of the 21st century energy [6].

At global (COP26) and local scales, we urgently need new legal and governance forms to better protect and more equitably share the earth's common wealth—from the fragile atmospheric zone to the sun's abundant radiation. The 2009 Nobel economist Elinor Ostrom [2] encouraged experimentation with the property framework of "commons" and peer governed community trusts. The Northland Solar Commons project shows how Ostrom's theories apply to solar energy by channeling the sun's common wealth into peer-governed revenue streams for reparative justice ends. For us, a solar industry leader and an academic researcher, our partnership to create an iterable 500 kW "Solar Commons" array in Northern Minnesota is well summed up in the ancient wisdom of *tikkun olam,* "repair of the world," an aspiration to behave and act constructively and beneficially. Our partnership with the Northland Solar Commons beneficiary, the Bois Fort Food Sovereignty Group is part of the reparative justice work of the world.

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Energy Policy

Solar Energy for Native Energy Sovereignty

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Abstract. Native Nations are sovereign Nations. Employing renewable energy on Indian reservations allows RCR to not only promote that, but live it. We are building new visions for tomorrow and for the 7th generation through solar application and education, solar advocacy, and solar warrior attitudes. Hear the story of how a Native-led renewable energy organization is supporting Mother Nature and bringing us back to harmony.

Native Nations have been in right relationship with Earth Mother since time immemorial. Through reciprocity and respect, they cultivate this wisdom and pass it to the next generation. Not taking more than they need, giving back what they take, avoiding extractive methods are part of Indigenous consciousness. The opposites of these, greed, selfishness, and extraction stem from white supremacy culture. White supremacy culture lives life for today, not tomorrow. Native Nations live life in deep contemplation of how each action will affect not just the next generation, but seven generations down the line. White supremacy takes from the land, often without building a relationship with her or return of those gains. Native Nations share, ask permission of the land before planting or harvesting, leave something behind for next year, and keep sacred seeds. White supremacy culture uses the power of the sun to generate electricity without giving back to Mother Earth while Native Nations honor the sun for its many gifts of renewable energy.

Keywords: Native Energy · Native American · Native Nations · Energy sovereignty · Indigenous · Indian Country · Pine Ridge Reservation · Solar energy · Solar training · Native training · Native leadership

1 Solar Energy Potential

The various applications of solar power are not being considered because white supremacy culture remains to be the face of what solar power looks like. It teaches solar electric. In Indian Country, there is a solar warrior movement, predicated on shifting intergenerational trauma, poverty, and addiction into stories that heal with the help of the sun. Solar water pumping, solar furnaces, solar blankets –these are the many faces of solar that the general public doesn't often see or hear about. With so many basic needs met off the reservation, it's no surprise that these innovations go unnoticed. In Indian Country, these types of solar applications are becoming the foundations upon which a sovereign nation is standing tall –under the protective cover of sunbeams, they rise and they shine.

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Despite having access to plenty of sunshine, 222 days on average, there are plenty of barriers that prevent forward momentum in solar energy independence on the Pine Ridge Indian Reservation. Average life expectancy on Pine Ridge is 66, the lowest in the United States.

According to the Pine Ridge hospital, life expectancy for men is 47 and for women, 55. Per capita income is $7,773; average for all reservations is $10,543 and the United States average is $27,599.The officially reported poverty rate for American Indians living on Pine Ridge is 53.75%. The United States average is 15.6%.https://www.olceri.org/vision.

While solar training is taking hold in Indian Country, the factors that make it slow coming are great. Basic needs often go unmet, safety and security included. According to Maslow's hierarchy of needs an individual will not be able to cannot become a good person that serves their family and communities with their own unique skills, gifts and talents, without their basic needs being met first. There are many organizations on Pine Ridge that support basic needs, but the needs still remain, year after year.

It has been poverty of tangible things, not of spirit, that have placed Native Americans behind non-Natives. 16.7% of American Indian families earn less than $15,000 each year, compared with only 5.9% of non-Native, in this case whites. Only about one in ten (11.1%) of white Americans live below the poverty threshold; in contrast, 26.4% of American Indians – including 33.3% of those under 18 years of age – live in poverty (Ibid) [1]. In fact, no major racial or ethnic group experiences a higher poverty rate than American Indians. The impoverished and (typically) rural living conditions of most American Indians combine to foster other associated problems as well. American Indians experience higher unemployment, lower phone coverage, lower broadband internet access, and lower home computer ownership than white Americans [2].

Statistics highlight the truth, that is their function. The disparaging living circumstances that white supremacy has left for Native Nations serve to tell the story that is often left untold or under-told. However, these same statistics can be used for good, as motivators. And that's exactly what Chief Henry Red Cloud is doing at Red Cloud Renewable.

2 Solar Energy Bridges the Divide

Chief Henry Red Cloud has been the touchstone for solar in Indian Country for the past decade while simultaneously advocating for Natives and non-Natives working together. The sordid past between Natives and non-Natives can no longer be ignored, there are too many stories heard for us to pretend under the guise of white supremacy that Native Americans have somehow disappeared or gone extinct. We know forced assimilation, direct and indirect genocide, and systemic racism are all too real. But today, at Red Cloud Renewable, with the sanctioned guidance of the sun, Natives and non-Natives are actively and daily writing history –retelling a story that favors people over profits, truth over lies, healing over harm.

At Red Cloud Renewable on the Pine Ridge Indian Reservation, the gift of the sun traces far back to the roots of the Lakota Peoples. *Anpetu Wi*, first light, is the source of all life, it is the sole purpose for the Sundance, the sacred ceremony with Father Sun.

Lakota Tribes are the people of the sun. Chief Henry Red Cloud awakens the spirit of the solar warrior in all of us, Native and non-Native alike.

Supplying Native Nations with an epicenter for solar training, practice, and experiences, Red Cloud Renewable doesn't just build dreams, it fosters and imbues them with the energies of the sun. In an otherwise dark and hopeless world, RCR is a beckon transmitting more than light alone, it offers change, possibility, and community!

3 Solar Energy Education

The four pillars of RCR, like the four directions, are what give the organization its foundation and shape; 1) housing as human right through alternative building materials (like foam crete, compressed earth blocks, and straw bale), 2) food systems and sovereignty through education and garden experiences, 3) land care through tree planting, and 4) solar energy advocacy through awareness building and training. The solar energy sector of RCR is the core of the organization, lighting the path forward towards a new world, ripe with sustainability and heavy in regenerative practices. RCR knows the future is solar power through education. All good things start with education.

Solar education is RCR's foundation and, like many things on the reservation, a challenge. Educational attainment is correspondingly low among the South Dakota's Native American population, only 11.6% of Native Americans hold a bachelor's degree or higher, compared with 26.4% of the state's white population (US Census Bureau, 2010b). Drop-out rate is over 70%; 28.7% of the native population of Pine Ridge Reservation reports having attained a high school diploma, GED or alternative; 10.7% of the native population report having a bachelor's degree or higher [4]. Native American students are often excluded from postsecondary data and research due to their small sample size; and are more likely to need and receive grant aid assistance than other students, but less likely to take out student loans [3]. These statistics only make RCR more determined to follow the path of the sun and re-write history. This is why RCR offers all solar courses to all Native students free of charge, funded by donor scholarships and taught by Native trainers.

Energy transformation depends on drivers and innovation as motivators. Under Native leadership, RCR provides onsite solar training, taught by Natives for Natives to ensure cultural practices, like prayers and language, are integral to their solar warrior pathway, supporting their coursework. Motivated by training, yes. But also by innovation. Students get hands-on experiences with solar builds and installs, in real time, with Chief Henry Red Cloud and his Native trainers. The key to adoption of any kind is giving folks the chance to put their hands on something, to see and feel it, to experience it. In order to move us into a renewable energy reality, we must increase solar energy adoption. RCR provides onsite in real time experiences to give Native Americans the opportunity to vision a future for themselves in solar, to see its potential isn't something of the future, but something of today.

The RCR 10-acre campus has truly stepped into the solar field supplying folks, far and wide, displays and examples to facilitate solar knowledge, experience, and adoption. Projects on-site include the following:

An integrated Solar System Lab currently being developed will be very similar to the 20 kW system RCR built for the Kili Radio Station on the Pine Ridge Reservation.

A 22.5 kW solar array provides electricity for the Red Cloud Renewable Energy Center, while serving as a significant training lab for Native students.

"Mock Roof" solar training lab provides a realistic rooftop experience with the maximum safety for teachers and students.

A stand alone "Pole Mount" solar array is still under construction and will give students a battery based system to learn on and work from.

Two styles of mobile solar power station labs —a pull behind trailer that can power camp radios and/or construction sites and a highly mobile "Handcart" version used to power computers, phones, and drones.

Water pumping station for Farm and Gardens Lab which provides water for our 1,000 gallon water tank and our farm dripline system.

RCR has installed over 1,000 solar furnaces on Pine Ridge and trained over 1,000 students from over 70 different Tribes across the United States. When driving around Pine Ridge, solar panels dot some of the landscapes, reminders that the dream at RCR is growing. Slowly but surely, folks are being awakened from their slumber. There is a shift from dependence on fossil fuels to energy sovereignty and it's happening before our very eyes. This is the prayer being walked forward, prophesied by Chief Red Cloud and being fulfilled by his 5th generation descendant, Henry Red Cloud. Chief Red Cloud foresaw that in the 7th generation there would be harmony between Natives and non-Natives, humans the Earth mother. At Red Cloud Renewable, that prayer is held close and cultivated daily, it is not just part of the work we do, it is reason we do the work that we do.

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Grid Integration and PV Advances

How Photovoltaic Solar Kitchens Can Modernize Remote Cooking

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Abstract. Photovoltaic powered solar cooking systems have become cost competitive with wood, charcoal, kerosene and propane fuels. A PV-powered, low complexity 12 VDC system based on a high efficiency solar hot plate teamed with small battery is described and results of testing are presented. The 12 VDC hot plate is designed to conserve energy and reduces power from 400 W to 200 W as the food heats up from room temperature to 100 °C thus providing only the power needed to heat food, then sustain a boil. The hot plate can reach 275 °C (527 °F), hot enough to bake and fry foods. Unlike bread box solar cookers that need direct sunlight and frequent reorientation, PV panels collect both direct and diffuse radiation. Charging of a battery allows for cooking day or night.

Keywords: Solar cooking · PV · Hot plate · 12 VDC cooking · Off grid cooking

1 Introduction

Many parts of the world have depended on wood, charcoal or kerosene/gasoline as a cooking fuel for centuries. However, overpopulation and drought are causing massive deforestation, and fuel wood gathering is taking more and more time as the distance traveled to collect the wood increases. Most fuel is used to boil water for cooking rice and beans, bread, vegetables and meat. Most homes with wood or kerosene cooking stoves have no access to electric power to run pumps and fans, so cooking pollutes the indoor air and is unhealthy for the cook and any people in the cooking area. Cooking is mainly done by women, who suffer from illnesses due to smoke inhalation. Wood gathering is often done by girls who should instead be in school. Solar energy is plentiful in most of the arid regions of the world where there are limited supplies of wood.

Standard solar thermal cookers for remote installations are based on an insulated cooking pot or chamber with blackened surfaces exposed to the sun, often with a window to suppress heat loss and solar reflectors to somewhat concentrate the solar insolation. With some solar concentration these solar ovens can reach 180 °C to boil water and bake

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bread. They typically provide 80–200 W of power into the food, based on Solar Cookers International ASAE S580.1 testing (compared to grid-tied electric stove elements which provide 500 to 1,000 W of heating). These solar box ovens are cheap, but a problem with them is that they must be moved frequently (e.g., hourly) to stay aligned with the sun and need direct sunlight to function (they don't work well on cloudy days). Reflective solar cooking devices work best up to about four hours either side of solar noon.

2 System Description

The remote system described in this paper consists of a photovoltaic (PV) solar array of 300 to 1,000 W connected to a solar controller to charge a storage battery, and an efficient electric hot plate developed by Butler Sun Solutions. The system is shown in Figs. 1 and 2 below. The hot plate is therefore capable of boiling water in pots to cook rice, beans, pasta etc., and also to fry tortillas, breads, vegetables, and meat. Placing an insulated enclosure over the hot plate heater element forms an oven that can be used for baking meals, cakes and breads. Since there are no flames or extreme temperatures, insulation can be formed from inexpensive materials like cardboard or paper mache. The system does not require grid electricity to operate, and because it has its own battery storage it can store solar energy in the daytime (even in hazy and low light conditions), for use later at night or in the early morning.

2.1 PV Panels

New PV panel prices are now below $1.00 dollars per Watt, so a 400-W panel array costs about $400, and prices continue to fall. Used, refurbished panels can sell for $0.35 per Watt in India and Africa. One advantage PV panels have over direct incidence thermal cookers is they effectively collect diffuse solar energy on cloudy days.

2.2 Solar Charge Controller

A pulse-width-modulation solar charge controller is needed to connect the "12-17V" solar panels to the battery to prevent overcharging. This solar controller also has USB outputs for charging cell phones, and 12 VDC outputs to power LED lights to illuminate the home at night.

2.3 Battery Bank

A battery is needed to match solar production, which maximizes around solar noon, to cooking needs during the early morning and late afternoon and night. A battery of about 400 Wh (40Ah at 12VDC) has been found to be sufficient. Current systems use sealed lead-acid or car batteries, which are available everywhere. Better (Li-Ion-Phosphate) batteries are coming down in cost rapidly, with longer service lives. They will be the future.

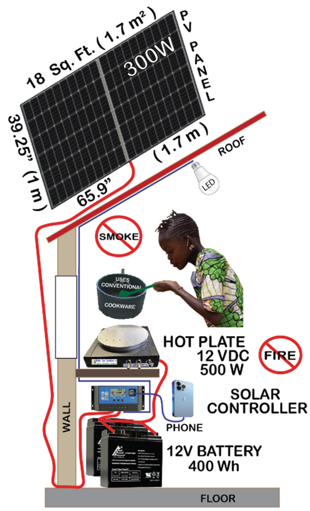

Fig. 1. PV solar cooking systems

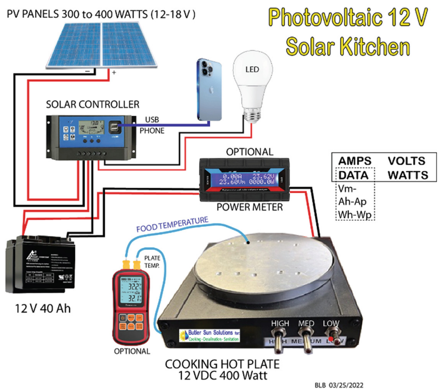

Fig. 2. PV solar cooking system wiring

2.4 Optional Power Meter

A power meter has been included in our test systems to measure their performance. The meter displays real-time Amps, Voltage, and Watts delivered to the hot plate. In addition, maximum Volts, Amp-hours, peak Amps, Watt-hours, and peak Watts are stored and may be displayed. The meter is shown in Fig. 2.

2.5 Solar Hot Plate

The hot plate in our system is a low-voltage (12 VDC) unit so it runs directly from the battery voltage A unique feature of the hot plate is the use of Positive Temperature Coefficient (PTC) self-regulating heater elements combined with standard resistive heaters. The PTC elements initially produce high power to quickly heat food to boiling, but as they heat up their resistance increases so power output decreases to be suitable to simmer food. The conventional elements are used when more power or higher temperatures (up to 275 °C) are desired. Manual switches allow for multiple power levels from 50 W (keep food warm) to 200 W (slow cooking) and up to 400 W for high temperature frying and bringing food to a boil quickly. The hot plate is insulated to reduce heat losses from the back side of the unit (Fig. 3).

2.6 Optional Thermocouple Meter

The hot plate comes with a Type K thermocouple bonded on the underside center of the hot plate disc. An additional external thermocouple and a reader with two ports is optional for cooks using commercially supplied systems. All test systems were supplied with this meter to determine how well the system was performing. The meter is shown in Fig. 2.

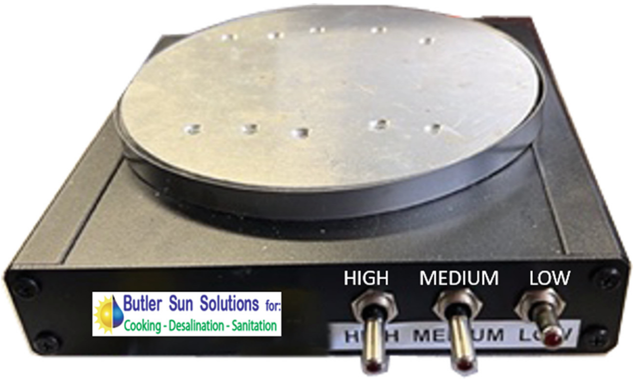

Fig. 3. Energy efficient 12 VDC hot plate used for the testing

3 System Testing

3.1 Cooking Power Versus Plate Temperature for Boiling, Baking and Frying

The solar hot plate was used with a pot to boil 1 L of water in about 20 min – roughly twice as fast as a bread box solar cooker. With water initially at 25 °C the power into the hot plate was 380 W; once the water boiled at 100 °C the power was down to 180 W (due to the PTC heating elements), and the water continued to roll boil. The average current was 23 amps for 30 min, or 140 Wh. For reference, a 300 W PV panel produces about 25 amps around solar noon. At simmer, the current was only 15 amps, well below what the panels put out, so the battery could be recharging while the food simmers. The energy needed to bring the pot and water to a rolling boil represented about 20% of the energy capacity in the battery. When using the frying pan to cook bacon and eggs, power was needed for a much shorter time. A full strip of bacon and a single egg took about 20 Wh of energy over a ten-minute period. These experiments have shown us that the foods people like can be cooked with this PV powered system, perhaps a bit more slowly than over a fire but with much less wasted energy (Fig. 4).

Fig. 4. PV hot plate solar cooking of various foods

3.2 System Testing and Costs in Kenya

Three test systems have been built and sent to Duncan Onyango Mbuge, Faculty of Engineering, University of Nairobi, Nairobi, Kenya for more extensive, real-world testing. Only hot plates, solar controllers, and wiring harnesses were shipped, as 12 V car batteries can be procured there for $100, and PV panels can be purchased locally for $0.75 cents a Watt. It would have been much more costly to ship a lead-acid battery and PV panels from the USA.

Mr. Mbuge has provided us with recent fuel costs for alternatives in Kenya. They are shown below in Fig. 5. The bolded figures are the annual costs for each of the fuels. We have estimated the annual cost of our system as well, shown at the right-hand end of the diagram. As shown, **the solar PV-powered kitchen is much less expensive than any of the other alternatives, except for free gathered firewood** (although the time and danger involved in firewood collection and transportation were not monetized). It should be noted that these are only bare fuel costs, and a stove or burner system would be required in addition to the fuel costs for each of the other alternatives, adding to their costs. It should be noted that in the solar kitchen, only the battery needs to be replaced periodically – the other components of the system have lifetimes of 20–50 years. The long-term cost of the PV-powered kitchen can therefore be expected to decrease as costs of batteries continue to decrease over time and their performance (lifetimes) continue to increase (e.g., Li-Ion-Phosphate).

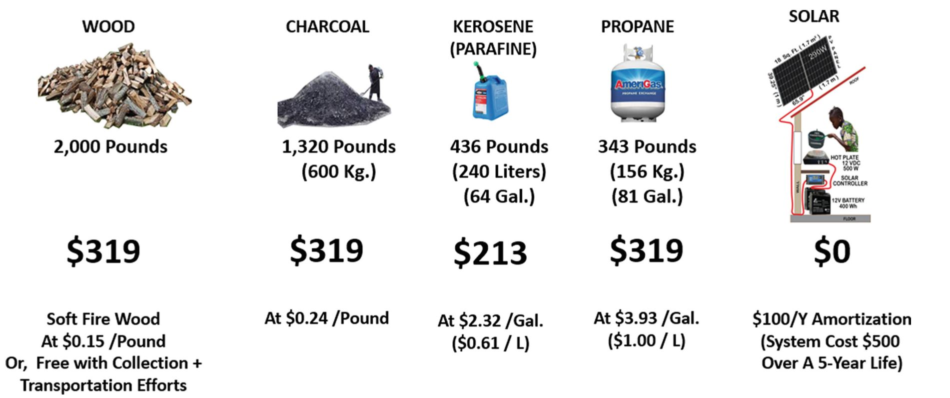

Fig. 5. Annual fuel needed to cook three meals per day for a family of four in Kenya (2022)

4 System Benefits

4.1 Fuel Savings/System Financing

The fuel costs in Kenya today were shown in Fig. 3 Now the question is, "How can someone afford a capital-intensive system costing $500 to $700 dollars, even if the amortized cost is much less than other alternatives?" We believe this should be financeable on a pay-as-you-save fuel basis using cell phone banking and micro-lending. The demonstration systems should be able to prove the concept and provide a basis to seek capital for further implementation. Local production of the systems is also expected to be an attractive option to generate in-country employment.

4.2 No Fire/Instant On and Off/Thermally Isolatable/No Shock Hazard/Skin Burn Hazard

There are many technical and health advantages to the PV solar kitchen compared to burning fuels. Since there is no open flame combustion, the PV solar kitchen will not produce indoor pollution gases like carbon monoxide, or fine particulate emissions that lead to asthma and other illnesses. The hot plate can be turned on when needed and shut off when not needed. By contrast, a fire is not easily stopped and started, and requires constant tending. The autoignition temperature for cardboard is about 425 °C. That for paper mache, made of craft paper, flour and water is similar. Hence, pots and hot plate surfaces can be thermally insulated with inexpensive and available materials. The electrical components are all low voltage, so there are no hazards related to electrical shock and no need for Underwriters Laboratory approval. Like any other hot plate there is a risk of skin burns, so care must be taken not to come in contact with the hot plate when it is on. But that hazard is much less than the hazard of having an open flame in the home.

4.3 Cooking Schedule

Figure 6 shows how the PV solar kitchen allows cooking to be done on the cook's preferred schedule, not just when the sun is out. So, breakfast can be started before daybreak, and dinner can be cooked or held warm long after sundown.

4.4 Health and Social Benefits

The most immediate benefit from the PV solar kitchen is that the cook and the family do not have to spend their time and limited monetary resources to gather or buy, store, or transport fuel. Also, since the cook is not constantly tending a fire (feeding firewood, cleaning up ash), there will be more time for other activities. The health of the family will be improved from not breathing smoke or being exposed to open flames. Also, the cook can do everything inside a residence or building, out of the hot sun. The family can also benefit from cell phone charging and lighting provided from the same system that powers the cooking. Finally, although the system is not theft proof, mounting collectors on the roof or elsewhere using permanent mounts, and having other components inside the house does offer some level of protection from theft.

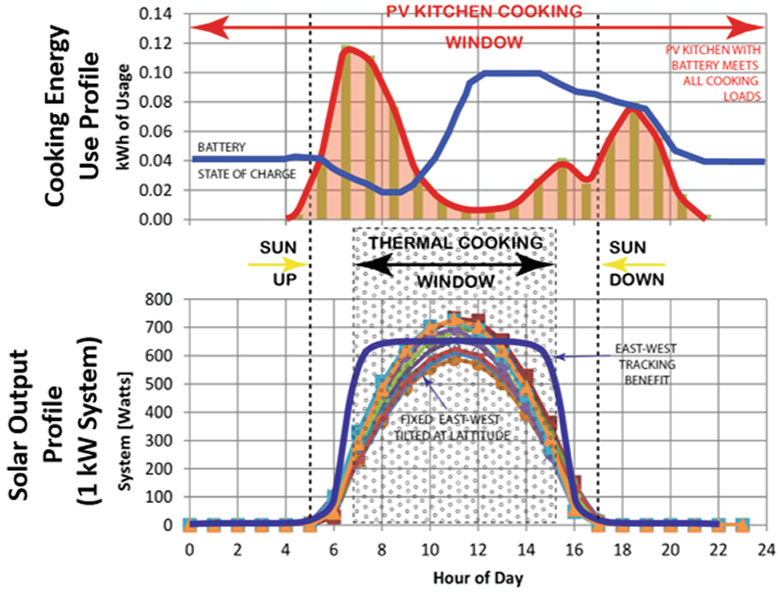

Fig. 6. PV kitchen cooking window extends into night

5 Conclusions

A PV-powered solar kitchen represents a new approach to remote cooking that has the potential to improve the lives of people (particularly women) in developing countries. These people can have the benefits of electric cooking in their own homes. The proposed system is simple, with low-voltage, highly-reliable components. The system's first cost is still somewhat high, but system leasing or pay-as-you-save loans could allow for market penetration. The potential for a large market exists, but acceptance will be based on real world testing to demonstrate the advantages of the system over existing fuel-based systems.

Dual Hybrid 3D Solar Module and Test Results

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Abstract. This paper describes a dual hybrid 3D Solar module and presents results of 3rd party testing of a prototype module. This dual hybrid module incorporates both low concentrating photovoltaic (PV) and thermal collection elements. The data obtained from testing the prototype demonstrate a 75% increase in electrical output per solar cell, while also collecting nearly twice as much thermal energy from each cell. For each 1 W of solar PV cell placed into the 3D Solar module, the 3rd party testing lab measured ~5 watts of total power output: 1.75 watts electrical plus ~3.3 watts thermal.

The 3D Solar module pairs two flat aluminum reflectors per solar cell. The reflectors and the solar cell are arranged at a 90° angle to each other within the module. Each solar cell in the module also has a small copper fin-tube attached to the rear surface of the cell, enabling the capture and removal of heat from the module via a circulating fluid (i.e. water). A prototype module was tested in late 2021 at Solar PTL in Arizona in a "side-by-side" test setup where the electrical output of a single laminated PV cell within the prototype was compared with an equivalent single laminated PV cell outside the prototype. Both modules were placed on 2-axis tracker and test data was collected between 10:30 am and ~2:15 pm on November 3rd.

Keywords: Solar · Concentrating · Photovoltaic · Thermal · Dual hybrid

1 Motivation

Some years ago, at a time when solar cells and modules were substantially more expensive than they are now, I developed and patented a solar module design using flat reflectors and simple geometry to "squeeze" more energy out of each photovoltaic (PV) solar cell inside a module. I also started a company, 3D Solar Inc., to commercialize this module design, and began constructing and testing what has now become a series of prototype modules.

There have been a large number of attempts over the years to concentrate or focus sunlight onto relatively small areas of solar cells using all manner of optical tricks. There appears to be a convention of differentiating the type of concentration using the descriptors of high, medium, and low—where high is in the range of 100x–1000x concentration, medium is between 10x–100x concentration and low is below 10x. The design discussed here is at the low end of low concentration, in theory my design can provide 2x optical concentration—sometimes called 2 "suns". I have noticed that increasing the amount of

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solar concentration tends to increase the complexity of the system. In general, these complex concentrating systems have failed to achieve broad commercial success. I wanted to keep my design as simple as possible, while still capturing some benefits from low concentration.

2 Description of 3D Solar Prototype Module

I therefore determined to use flat reflectors and standard PV cells for the 3D Solar module. I also employed a simple geometry where each cell and reflector pair are aligned perpendicular to each other. If you are familiar with a corner cube (a.k.a. corner reflector) simply imagine replacing one of the three reflectors in the corner cube with a solar cell and you should have a good image of how the three surfaces relate to each other. (See Fig. 1) I decided that thin flat sheets of aluminum make very good low-cost reflectors. I settled on using flat reflectors because solar cells prefer uniform illumination, which flat reflectors provide. And when it came to building my prototype, I decided to use individual "laminated" solar cells. A laminated cell in this case includes a 6 inch square monocrystalline solar cell embedded in a 7 inch square glass—encapsulant--and cell with backsheet "sandwich". The ½ in. white strip surrounding each PV cell in the prototype is the backsheet showing through—since the encapsulant and glass are transparent. I determined that such a laminate would be much easier to work with (handle & transport).

I also determined that I should provide thermal cooling to the cells in the prototype. Without cooling, there was a risk that much of the anticipated optical gain would be eaten up by thermal losses if the cell operated at a high temperature. Early testing revealed that cell temperatures were increasing above what I had anticipated.

Adding the thermal cooling into this prototype was something of a design pivot, after I had already begun prototype assembly. Specifically, I had already attached full module sized junction boxes to the rear of each cell, which took up a considerable amount of real estate on the back of the cells. Using the full module junction boxes—as most of you will surely realize—was a poor design choice. The "large" junction boxes came with pre-attached cables which I thought would make it very easy to connect the cells together. And while the cables were very easy to connect together, they were each designed (~3ft of cable and relatively large diameter wire) to transmit the power produced by the 60–72 cells in a standard module. Trying to use cables sized to connect 540–648 cells together, caused so much resistance there was no output to measure at either end of my 9-cell prototype. The good people at Solar PTL quickly discovered my error, and we soon hit upon testing the output of a single solar cell within the prototype and to compare that with the single cell outside it. This was how the test was run.

Returning now to the cooling design element, I decided to use a "modified" copper fin-tube since the real estate on the rear of each solar cell was limited. I calculated that I could compensate for a smaller area of fin in contact with the cell by creating a larger area of thermal contact between the tube and the fin. I determined that I could dramatically increase the area of thermal contact between the tube and the fin by flattening (i.e. squashing) the copper tube somewhat. (See Fig. 1) This turned out to require some tricky metalworking since I also needed the tube to complete a 180° turn in order to have room to connect the fin-tubes together in series. Based on the test results, I'd say the cooling design performed very well.

Fig. 1. (A) Close up of multiple cell reflector pairings. Cell is placed at a 90° angle to each reflector. The reflectors have a protective coating—giving them a dull yellow appearance. (B) Close up of back side of a laminated cell. Shows modified (squashed) copper fin-tube in contact with ~½ of the back of each cell

3 Prototype Module Test Method and Results

Solar PTL located in Tempe, Arizona, performed the tests and prepared a report containing the details on their test method and data collection procedures. I have excerpted several figures and tables from this report with permission. Turning now to the testing of the module, I have included a photo of the prototype in my home without the glass

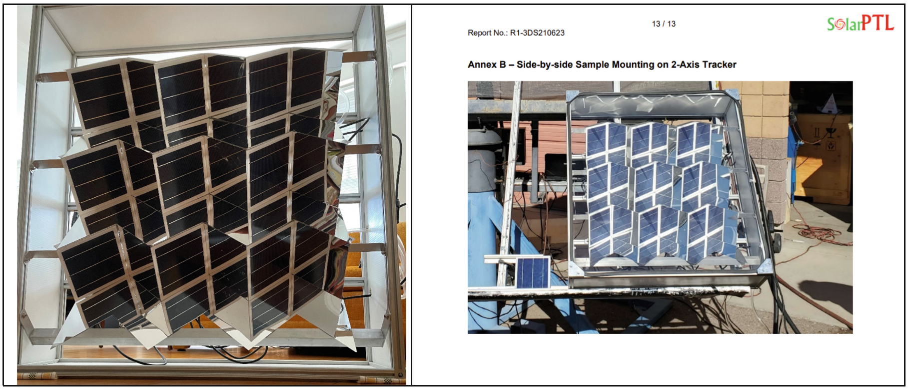

Fig. 2. (A) 3D Solar "dual hybrid" prototype module, containing 9 PV cells. Cells are located on the upper left, with reflectors on right and below. (B) Side-by-Side testing setup on tracker at Solar PTL. Individual "control" cell on lower left; 3D Solar prototype on right.

cover, see Fig. 2. This photo captures the module in the same orientation as it was placed on the test bed at Solar PTL—see Fig. 2.

Solar PTL suggested that the best way to test this prototype module was to measure the output of a single cell within the prototype and compare it to the output of a single cell outside the module. Solar PTL assigned my prototype the designation 3DS0001, and they assigned the single cell laminate the designation of 3DS0002. Both the module and the single cell were oriented by Solar PTL on the test bed (with 2 axis tracking) to collect the optimal amount of sunlight throughout the test period. Table 1 is a screen shot of the performance test data provided in the report that Solar PTL produced. It shows the measured electrical performance of the single cell inside the prototype (upper row) and the single "control" cell (lower row). The last column of the table labeled "Average Pmax [W]" really tells the story. The cell inside the prototype produced 3.7 watts of power on average as compared to 2.1 watts of power from the control cell. Hence my conclusion that the 3D Solar module produces 75% more power per cell. This electrical power increase is a result of both the higher current due to optical gain and the increased voltage or thermal "gain" achieved by cooling the solar cell which was inside the prototype.

Table 1. Performance test data–produced by Solar PTL

Report No.: R1-3DS210623 8 / 13 SolarPTL

Test Data

Performance test – Side by side, as measured on November 3, 2021.

Test Date (MM/DD/YYYY):		11/03/2021					
Test method		☐ Simulator	☒ Natural sunlight				—
Irradiance [W/m²]		1000 ± 50					
Sample no.	Average I_{sc} [A]	Average V_{oc} [V]	Average I_{mpp} [A]	Average V_{mpp} [V]	Average FF [%]	Average P_{max} [W]	—
3DS0001	11.6	0.6	9.7	0.4	55.9	3.7	—
3DS0002	8.8	0.5	6.7	0.3	43.0	2.1	—
Supplementary information: For sample 3DS0001, all measurements taken with cooling fluid (water) flowing thru the target cell. Raw data available upon request.							

Table 2 is a screen shot of the solar thermal data that Solar PTL measured. Solar PTL used a reservoir of water as the water source (and destination) of the water that they used to "cool" the solar cells inside the prototype. The water circulated through the entire module (i.e. cooling all 9 cells), and they measured the water temperature at the input and output to the module throughout the test period. In retrospect I wish that I had specified that the water used for cooling was at a lower temperature. On average the water temperature increased by slightly over 1.25 °C (2.25 °F) across the module. Based on this change in temperature, the listed flow rate, and knowing the fluid used was water, I calculated that the module captured/produced ~62 watts of thermal power. Given that there are 9 cells in the module, I then calculated that each cell collected ~6.9 watts of thermal power. I further divided 6.9 watts by the single "control" cell output of 2.1 watts to calculate a "normalized" (i.e. per watt) contribution of ~3.3 watts referenced in the abstract. Adding the 3.7 watts of electrical output, to the calculated 6.9 watts of thermal power suggests over 10.5 watts of combined power captured per cell, versus 2.1 watts total from the single control cell. The 3D Solar prototype collected 5 times as much total power from the cell inside the prototype as the control.

Table 2. Solar thermal data summary produced by Solar PTL

Solar Thermal – Data Summary

Test Date (MM/DD/YYYY):		11/03/2021		
Test method		☐ Simulator	☒ Natural sunlight	—
Irradiance [W/m²]		1000 ± 50		
Sample no.	Average T_{in} [C]	Average T_{out} [C]	Average Flow-rate [GPM]	—
3DS0001	31.92087	33.200786	0.18716	—
		—		—
Supplementary information: For sample 3DS0001, all measurements taken with cooling fluid (water) flowing thru the entire 9-cell sample.				

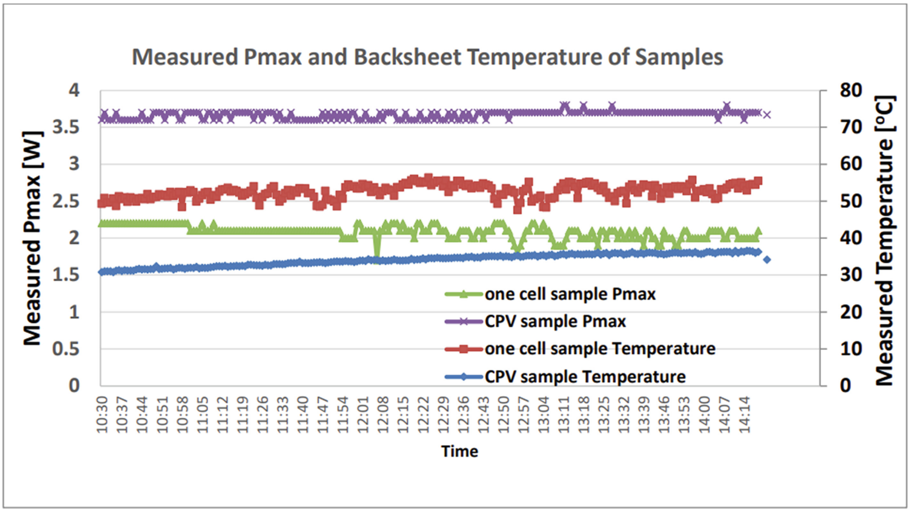

Fig. 3. Full day outdoor performance as measures on Nov 3, 2021.

I assumed Solar PTL would use water at room temperature to cool the solar cell, so I was surprised to see that the water they used was 90° Fahrenheit. As can be inferred from Fig. 3, a screen shot of the data plot shown below—blue line/plot and right axis—the temperature of the water reservoir rose by several degrees centigrade throughout the test day. Although 90 °F seems warm to me, the temperature of my prototype was maintained at a temperature significantly below the temperature of the uncooled control cell (red line in plot below) despite the higher radiation the cells in the prototype received. The benefit of cooling the cells in the prototype is clear.

I think it is reasonable to expect that using water at a temperature below 90 °F for cooling would result in the solar cells operating at a lower temperature which should increase the electrical output while also boosting the amount of thermal energy/power captured by the water circulating through the module. Most solar cell manufacturers report something like a 1% increase in power output for each 2.5 °C decrease in operating temperature.

4 Conclusion

Satisfactory test results that were obtained from the 3D Solar module, despite errors made in building the prototype. The overall design utilizing flat reflectors and simple geometry produced a significant increase in power. Because cooling was provided by relatively warm 90 °F water, better results than those reported here appear likely simply by using lower temperature water. The 75% increase in electrical power measured—plus the additional thermal power captured—therefore represent a floor rather than a ceiling on the performance one might expect from the 3D Solar module design.

Predicting Solar PV Generation Using Weather Station Data

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Abstract. Electric power generated from Solar Photovoltaic (PV) panels is estimated to have increased globally by 22% in 2019, to 720 TWh [5]. It is now considered the third-largest renewable energy technology after wind and hydro powers. The primary reason for this growth is the need to utilize free energy resources that are also environmentally clean. PV-generated power, however, is uncertain and varies from time to time and season to season. Dealing with this uncertainty requires having predictive and forecasting models that accurately estimate generated power from historical data. This paper reports on an in-progress research project that explores weather-related variables such as humidity, temperature, and wind speed and uses them to predict and forecast generated power using a dataset collected over three years by a weather station at Southeast New Mexico College in Carlsbad, New Mexico. Various predictive and forecasting models are built, trained, and evaluated. The goal is to explore these variables and report on what makes a good predictive model and how such a model behaves over time.

Keywords: Photovoltaic modules · PV generation forecasting · Weather station · Solar irradiance

1 Introduction

In 2020 despite the Covid 19 pandemic, solar Photovoltaic (PV) panel installation was up by 23% and the renewable energy market expanded by 45%: the highest growth rate since 1999 [8]. In addition, the US Energy Information Administration projects that solar PV modules installation will reach 46% of all the renewable energy sources by the end of 2022 [2]. Many factors contribute to this growth. Concerns about climate change and energy crises, for instance, have been linked to such substantial growth in solar power generation [1].

PV-generated power, however, suffers from uncertainty and varies from time to time and season to season. The solar irradiance is reliant on several geographic and atmospheric factors. The PV-generated power of a solar panel depends on its location and the weather conditions at that location. Important variables here include but are not limited

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to temperature, humidity, wind speed, wind direction, and time of day [4, 9–11, 17]. The efficiency of a solar panel is also impacted by the aforementioned weather conditions. For example, as the temperature of the panel increases, its efficiency decreases. Similarly, as the wind speed increases, the panel cools down, and the efficiency increases [4, 10]. Being able to forecast PV generation based on historical data is an important way to deal with such uncertainty. It is also important for better power planning and management [3].

This requires creating and evaluating multiple predictive models. Indeed, many such models have been proposed that use weather-related data to predict solar intensity and/or PV generation. One such model tries to forecast PV generation utilizing site-specific forecasting models trained using data from the National Weather Service (NWS) [15]. Doing so resulted in a 27% improvement over the performance of existing forecasting models. Another model attempted to predict PV generation utilizing a combination of weather and PV system parameters [11]. The effect of wind speed and air velocity, measured by PV panel surface temperature at different angular positions, on the performance of solar PV modules has also been studied [4]. This experiment showed that as the panel's temperature drops, its efficiency and power output increases. Another study investigated how temperature and wind speed affect the PV module efficiency [10].

More studies have looked into the impact of temperature and wind speed on the performance of PV modules [9, 10, 17]. The effect of humidity has also been studied [14]. Humidity creates a minimal sheet or layer of water on the PV module surface and a concentration of water vapor in the air, which reduces solar radiation and causes it to be reflected away from the PV module surface. This leads to decreased PV productivity by 10%-20%. Many machine learning models have been used in these studies such as artificial neural networks (ANN) with mean absolute percentage error (MAPE) [13]; hidden Markov models and support vector machines (SVM) [12]; and an artificial neural network with a self-organizing feature map (SOFM) [19].

This paper 1) explores the relationships between weather-related variables and solar irradiance. It uses data collected over three years using a weather station installed at the campus of Southeast New Mexico College (formerly New Mexico State University - Carlsbad) in Carlsbad, New Mexico. It then 2) utilizes multiple machine learning models to predict solar irradiance given these weather-related variables. Treating the solar irradiance data as a time series, it 3) uses an additive forecasting model with logistic growth to forecast future solar irradiance values given historical ones.

The remainder of this paper is organized as follows. Section 2 describes the approach taken to satisfy the above three tasks. Section 3 presents the obtained results, and Sect. 4 concludes this paper and discusses future work.

2 Approach

The main goal of this paper is to show how weather conditions affect solar irradiance, which, in turn, affect power output. As stated in the last section, this paper focuses on three tasks. The first task explores how weather-related variables such as humidity, temperature, and wind speed affect solar irradiance. Unlike the studies cited in the last section, this paper also considers the impact that meteorological seasons have over these variables. Understanding how these variables affect solar irradiance is critical to being able to perform the second task. The second task involves the use of machine learning models to predict solar irradiance. As will be shown later in this paper, solar irradiance is also a good predictor of voltage and power output. The third task looks at the solar irradiance data as a time series and employs a forecasting model to forecast future values given historical ones. For brevity, we only forecast solar irradiance values. The same approach can, however, be applied to other variables such as voltage and power outputs.

The data used in this paper comes from a Campbell Scientific CR6 series weather station installed outside the campus of Southeast New Mexico College in Carlsbad, New Mexico since January 2019. This station is equipped with a solar PV panel and a data logger. The solar panel faces true south, with a fixed tilt of 30° angle for the whole year. This station collects information about the following variables:

– **timestamp** which is the date and time of when the data example or record is added to the data file.
– **relative humidity** as a percent (%). This is also related to the dew point temperature, also measured by the station.
– **temperatures** in °C. The station supports three temperatures: ambient, panel, and dew point. The panel and ambient temperatures are very similar, while the dew point temperature is more related to humidity. This paper uses only the panel temperature; this is the temperature of the surface of the PV panel.
– **wind speed** measured in m/s. Wind direction is also supported but not used in this paper.
– **solar irradiance**, which according to the National Renewable Energy Laboratory (NREL) is the "incident flux of radiant power per unit area expressed in W/m2" [18]. This is a key variable for the analysis and models of this paper. It is also different from irradiation, which is irradiance integrated over time and expressed in kWh/m2.
– **voltage output** measured in Volts.

The station reads these variables every minute. These readings, however, are not recorded directly to the data file. They are combined (averaged) and recorded every fifteen minutes. In addition to this fifteen-minute frequency data file, the station also provides hourly, daily, and monthly data files. Only the fifteen-minute and hourly data files are used in this paper. In addition to the above variables, three calculated variables are utilized: the power output of the PV module, its power input, and its efficiency. The power output is calculated based on the formula:

$$P_{out} = \frac{V^2}{R}$$

where V (in Volts) is the voltage output and R (in Ω) is the load connected to the module (≈19Ω). We opted to calculate the power output this way, instead of descaling the solar irradiance by an arbitrary factor, because the load is known, and we have direct measurement of the voltage output. The power input is the same as solar irradiance adjusted for the area of the PV panel in (m2). In other words:

$$P_{in} = Irradiance \times Area$$

The efficiency of the PV panel is the calculated using the formula:

$$Efficiency = \eta = \frac{P_{out}}{P_{in}} \tag{1}$$

Two additional variables are extracted from the timestamp variable: time of day and meteorological season. These variables tell how solar irradiance changes from time to time and season to season.

As is typical with data files, the files produced by this station require cleanup and preprocessing. Some examples have `inf` and `NAN` solar irradiance values. These examples are removed from the dataset. For prediction, all data examples with negative irradiance or negative humidity values are also removed. The daily time points are extracted from timestamps, converted to numeric, and used as an input variable. The data examples outside the time period of 5:00 am to 9:00 pm, where solar irradiance is around zero, are removed from the dataset. Moreover, the data examples where the calculated efficiency is more than 100% are removed. For time series forecasting, only the timestamp and solar irradiance variables are required. In addition, only the data examples where solar irradiance is `inf` or `NAN` are removed. This is to avoid disturbing the time series or adding gaps to it.

This paper uses data collected over a period of more than 3 years (January 2019 to April 2022). The first exploration task is done using the Pandas and NumPy Python packages. The second prediction task uses Scikit-learn [7]. While there are many machine learning models to use, we only report the results of four models: linear regression, k-nearest neighbors, decision tree, and random forest. Not all machine learning models are the same, however. Some models such as linear regression or decision trees are simpler than others such as radial basis function networks (RBF) or artificial neural networks (ANN) [6]. Simpler models tend to be easier to understand and produce results that are easier to visualize and interpret. This is why the aforementioned four models were chosen by this paper; they are all simple models to understand, interpret and visualize. Finally, the Python Prophet package [16] is used for the third forecasting task. The next section elaborates more on these models and presents their obtained results.

3 Results

3.1 Data Exploration

First, we explore how humidity, temperature, and wind speed relate to solar irradiance per season. Figure 1 does not show a clear relationship between humidity and solar irradiance except for the fact that large humidity values seem to correlate with lower irradiance values, which suggests the existence of a negative relationship. There is no clear relationship between wind speed and solar irradiance either. There seems to be, however, a positive relationship between temperature and solar irradiance. In addition, summer and spring data points coincide together while fall/winter points do the same. Dividing seasons into these two groups is a better fit for the actual weather pattern of Carlsbad, New Mexico, where it is more like two seasons than four. Figure 2 shows the same data as above but for two season groups: spring/summer and fall/winter.

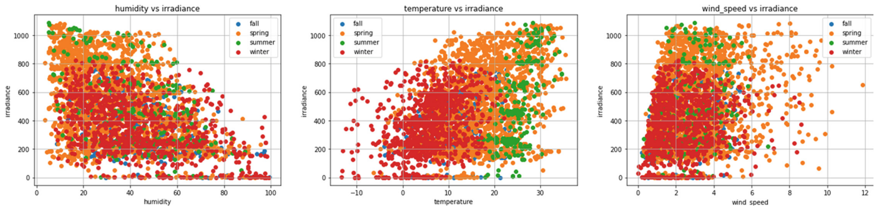

Fig. 1. Humidity, temperature, and wind speed vs solar irradiance per meteorological season

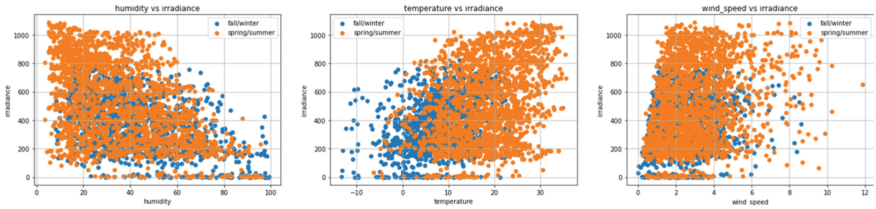

Fig. 2. Humidity, temperature, and wind speed vs solar irradiance using two season groups

Figure 3 depicts how these variables behave on average over a 16-h (5:00AM to 9:00PM) period for the two-season groups. Humidity, as expected, is high in the morning before it decreases throughout the day. Temperature and wind speed, on the other hand, increase throughout the day before they decrease at night.

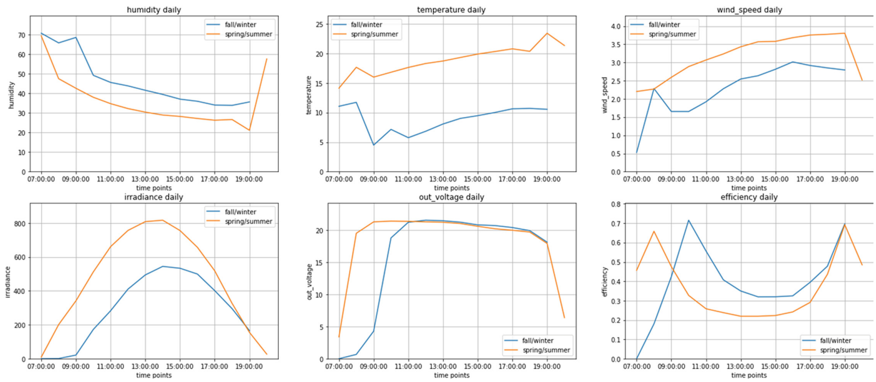

Fig. 3. Humidity, temperature, wind speed, solar irradiance, output voltage, and efficiency averaged over a 5:00 AM to 9:00 PM time period.

Figure 3 also shows how solar irradiance, voltage output, and efficiency behave on average throughout the same time period. The solar irradiance curves are bell-shaped. The spring/summer curve is earlier, wider, and higher than the fall/winter curve. It corresponds to longer days with lower humidity curves, and higher temperature and wind speed curves. The spring/summer voltage output curve is earlier than and peaks and flattens at the same level as the fall/winter curve. The efficiency curves are, however, interesting. They increase in the morning before they change direction and decrease. At midday they bottom out at about 22% for spring/summer and 32% for fall/winter. This can be attributed to the interplay between temperature and wind speed and the effect of that on solar irradiance. Higher temperatures decrease the efficiency of the PV module while stronger winds cool the PV module down and increase efficiency.

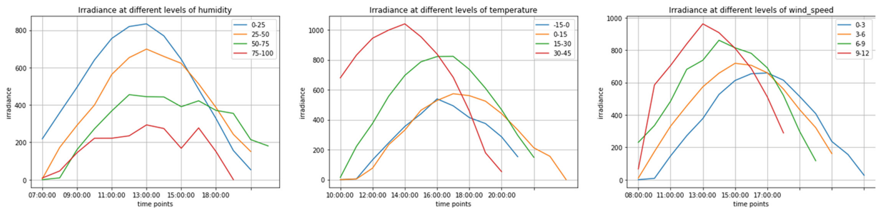

Fig. 4. Solar irradiance at different levels of humidity, temperature, and wind speed

In addition, we can have a better picture of how humidity, temperature, and wind speed affect solar irradiance by drawing solar irradiance curves at different values of these variables. To make this manageable, we divide the range of these variables into four levels and draw a solar irradiance curve at each level. Figure 4 shows these curves. It is clear from this figure that higher levels of humidity correspond to lower solar irradiance, and higher levels of temperature and wind speed correspond to higher solar irradiance.

In summary, the humidity, temperature, and wind speed variables affect solar irradiance and the efficiency of the PV module. Next, we see if these weather-related variables are good predictors of solar irradiance. We also evaluate how good a predictor solar irradiance is of the voltage output.

Table 1. Performance of multiple solar irradiance-predicting models with different dataset configurations (Hmd = Humidity, Tmp = Temperature, Wnd = Wind Speed) tables.

Predictor	Hmd	Tmp	Wnd	Hmd & Tmp	Hmd & Wnd	Tmp & Wnd	All
Linear regression	0.27	0.22	0.10	0.31	0.29	0.23	0.31
K-Nearest neighbors	0.55	0.62	0.29	0.67	0.56	0.59	0.70
Decision tree	0.65	0.70	0.45	0.70	0.63	0.67	0.73
Random forest	0.47	0.50	0.40	0.49	0.47	0.48	0.46

3.2 Making Predictions

As mentioned before, this paper uses four machine learning regression models for their simplicity, understandability, and interpretability. These models are linear regression, k-nearest neighbors, decision tree, and random forest. Before the results of these four models are presented, we briefly describe them. Linear regression is a parametric model for learning the parameters of a linear equation of the form:

$$y = f(X) = w_0 + w_1x_1 + w_2x_2 + \cdots + w_mx_m$$

where $x_1, x_1, \cdots, x_m$ are the input variables, y is the output variable, and $w_0, w_1, \cdots, w_m$ are the parameters learned by the model. The goal is to assign these parameters values so as to minimize the mean square error (MSE). In addition to its simplicity, linear regression is robust against overfitting, which is the process of overexposing the model to the training data. Once trained, the equation above is used to calculate the output values of unseen data examples.

The k-nearest neighbors is a non-parametric model that predicts output values based on the mean of the values of its nearest neighboring points. The number of neighbors is a parameter used to control for overfitting.

Decision tree is another non-parametric model that uses the data to learn a set of if-then-else rules, which effectively divide the input space into multiple partitions. It is a simple model to understand, interpret, and visualize. It can, however, easily overfit the data, and we use the maximum depth parameter to constrain the tree and guard against overfitting.

Random forest is an ensemble method that applies a technique called bagging or bootstrap aggregation to decision trees. The idea here is to take multiple bootstrap samples from the given dataset and to train a decision tree using each sample. It also uses a technique called feature bagging, which requires that only a randomly selected subset of the input variables is considered at each node during the construction of the decision trees. The predicted value of an unseen example is the average of all the output values predicted by all the trained trees.

The described four models are used in this paper to see if humidity, temperature, and wind speed can accurately predict solar irradiance. We trained these models using all combinations of these variables as input and solar irradiance as output. All these models resulted in very low R^2 scores (0.0–0.13). This is because one important variable is missing from these models. That variable is the time of day, which is needed to tell the models when solar irradiance is low and when it is high. Once added to these models, the scores improved significantly.

Table 1 summarizes the performance of these models. As can be seen from this table, the best performance happens when all three variables (humidity, temperature, and wind speed) plus time of day are considered. The best performing models with scores of .70 and .73 are the k-nearest neighbors (k = 3) and the decision tree (max-depth = 5), respectively. The linear regression model did not perform well, which suggests a non-linear relationship between input and output variables.

Predicting voltage output from solar irradiance is also investigated. The same models, as before, are used, and Table 2 shows their obtained scores. These scores indicate that solar irradiance is a good predictor of voltage output. It is also a good predictor of power output, because power output is calculated using voltage output. The linear regression model performed the worst here as well, which again suggests a non-linear relationship between these variables.

Table 2. Performance of multiple output voltage-predicting models.

Predictor	R-Squared
Linear regression	0.13
K-Nearest neighbors	0.92
Decision tree	0.96
Random forest	0.94

3.3 Forecasting Solar Irradiance

Lastly, forecasting future solar irradiance values given historical ones is investigated. This is motivated by the fact that solar irradiance is a time series with a pattern that repeats, with minor changes, every day. It also changes slightly from one season to another. Only the results of forecasting solar irradiance are presented in this paper. The same approach could be used for other variables such as voltage and power output.

To this end, an additive forecasting model that takes the form:

$$y(t) = g(t) + s(t) + h(t) + \epsilon_t$$

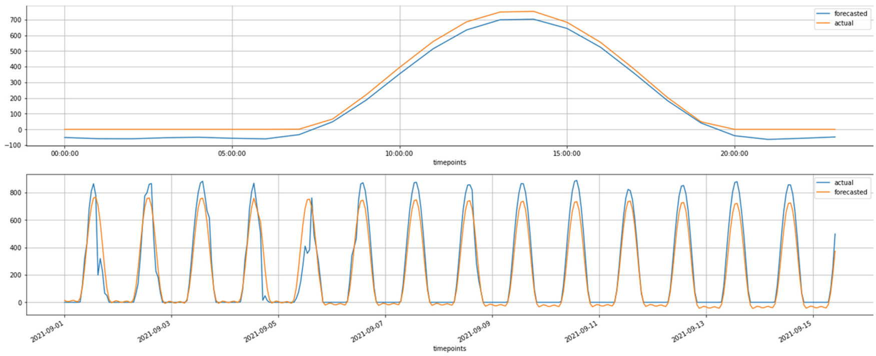

Fig. 5. Forecasted values vs actual values

where $g(t)$ is a growth function, $s(t)$ is a seasonality function, $h(t)$ is a holiday function, and ϵ_t is an error term [16]. The growth function $g(t)$ represents the trend of the data. The seasonality function $s(t)$, which uses a Fourier series as a function of time, represents the periodic changes, and the holiday function $h(t)$ represents the effect of holidays on the timeline. The error term ϵ_t represents any changes not captured by the model. In this paper, a logistic growth function with a saturating minimum of 0 and maximum of 1200 is utilized. The seasonality was automatically detected from the dataset. No holidays were specified.

The resulting model is a simple one with a single variable: solar irradiance. Figure 5 shows the results of such a model and compares forecasted values to actual ones. The top graph shows the forecasted future values against the actual ones averaged over a day. The bottom graph shows both values over a two-week period, immediately after the time series that the model was trained on. As Fig. 5 shows, both values are close with some peak differences. Parameter tuning and/or utilizing a more complex forecasting model is likely to improve these results. These improvements, however, are left as future work.

4 Future Work and Concluding Remarks

The scope of this paper is determined by the data provided by the weather station, which only supports a few weather-related variables (humidity, temperature, and wind speed) in addition to solar irradiance and voltage output. As has been shown, these weather-related variables impact solar irradiance, which, in turn, impacts generated power output. As cited studies have shown, these are not the only relevant variables. Missing from the dataset used in this paper are variables such as sky cloud cover, air quality, and precipitation potential, to name a few. These variables are not tracked by the weather station of this paper. There is a need to improve the performance of the models presented in this paper by augmenting the data collected by this weather station with outside datasets such as the ones provided by the Carlsbad Environmental Monitoring & Research Center and/or the National Weather Service (NWS). Additional predictive models could then be evaluated using the combined data.

In addition, forecasting models can also be used to predict the future solar irradiance, voltage, and/or power output values given historical data. The forecasting model presented in the paper is a simple one with a single variable. More complex forecasting models that utilize a time series with more than a single variable are yet to be investigated.

The weather conditions at the locations where solar panels are installed add uncertainty to their generated power output, which also varies from time to time and season to season. Predictive and forecasting models such as the ones presented in this paper, are useful tools to cope with this uncertainty. They are also important for better power planning and management.

In summary, this paper explored the relationships between weather-related variables and solar irradiance. Such exploration is critical to understanding how these variables interact with and affect the PV-generated power. It then utilized multiple machine learning models to predict solar irradiance given these weather-related variables. The performance of these models varies from one model to another, which suggests a complex relationship between input and output variables that some models capture better than others. The fact that the linear regression model performs the worst suggests a non-linear relationship between these variables. Finally, the paper utilized an additive forecasting model with logistic growth to forecast future solar irradiance values given historical ones. This model yields good results that can still be further improved by tuning and adding more variables.

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A Lifecycle Framework for Industrial Decarbonization

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Abstract. A lifecycle framework has been developed to categorize needs and opportunities for industrial decarbonization. The framework includes the following four categories: (1) carbon-free feedstocks and chemical processes, (2) fossil-free heating and electrification, (3) novel greenhouse-gas sequestration, and (4) recycling, repurposing, and recovery. Energy efficient processes underlies each of these four areas. This paper provides a summary of gaps, challenges, and research opportunities for industrial decarbonization in each of these categories, along with a discussion of technoeconomic analyses that can be used to help prioritize activities and potential impacts.

Keywords: Industrial decarbonization · Feedstocks · Solar heating · Hydrogen · Biofuels · Electrification · Sequestration · Recycling · Repurposing · Recovery

1 Introduction and Background

The United States Environmental Protection Agency estimates that industrial processes contribute nearly a quarter of greenhouse gas emissions in the U.S. (Fig. 1). Industrial processes all require energy in the form of heating and electricity. Nearly three quarters of the energy used for industry is for heating, and about a quarter is used as electricity [1]. The vast majority of this energy (~90%) is currently produced by burning fossil fuels, either in gas- or coal-fired power plants, to generate electricity or by burning coal, natural gas, or oil for heating [1].

In addition, some industrial processes, such as the production of cement and steel, produce carbon dioxide (CO_2) during high-temperature processes to decompose and purify the feedstock into useable materials. For example, in cement production, calcium carbonate (limestone) is heated to high temperatures during the calcination process to produce calcium oxide, but CO_2 is also released as a chemical byproduct during the reaction. CO_2 is also emitted when iron ore is heated and mixed with coal to produce iron for steel production. Nearly a ton of CO_2 is emitted for each ton of cement produced, and nearly two tons of CO_2 are emitted for each ton of steel produced. Conventional cement production contributes ~ 3–5% of global CO_2 emissions [2, 3] and ~8% of anthropogenic CO_2 emissions [4]. About 60% of CO_2 emissions results from the calcination of calcium

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carbonate, ~30% is from burning of fossil fuels to supply heat for the highly endothermic reaction, and ~10% is for indirect energy needs (e.g., electricity and transportation) [4]. Steel has a similar contribution to global CO_2 emissions. Combined, cement and steel production contribute to ~15% of global CO_2 emissions. Predictions of growth vary, but several sources expect cement and steel production to grow through 2050. Cement demand is expected to grow by a total of ~10%–25% by 2050, and steel demand is expected to grow by 0.4–1.4% per year through 2035 with growth driven largely by Africa, India, and other developing countries [5]. China currently leads the world in cement and steel production.

As a result, comprehensive global decarbonization will need to include decarbonization of industrial processes, including reduction of fossil fuels for heating and reduction of carbon-intense feedstocks for material processing. This paper describes a total lifecycle framework to categorize and identify gaps, challenges, and opportunities for industrial decarbonization.

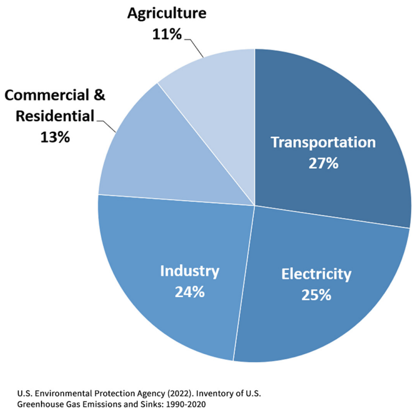

Fig. 1. Total U.S. greenhouse gas emissions by economic sector in 2020 (U.S. Environmental Protection Agency [6]).

2 Framework for Industrial Decarbonization

Sandia National Laboratories has developed a lifecycle framework for industrial decarbonization as part of its new Climate Change Security Center strategy. Sandia's objective is to utilize its diverse and cross-cutting capabilities to mitigate greenhouse gas emissions in all sectors, including transportation, electricity, and industry (Fig. 2). The framework for industrial decarbonization includes four major areas: (1) carbon-free feedstocks and chemical processes, (2) fossil-free heating and electrification, (3) novel greenhouse-gas sequestration, and (4) recycling, repurposing, and recovery. It should be noted that energy efficiency underlies all four areas.

The industrial decarbonization framework enables an intuitive and integrated categorization of key stages in a product's lifecycle. Examples of gaps, challenges, and research opportunities to reduce greenhouse gas emissions in each of these areas are presented in the following sections.

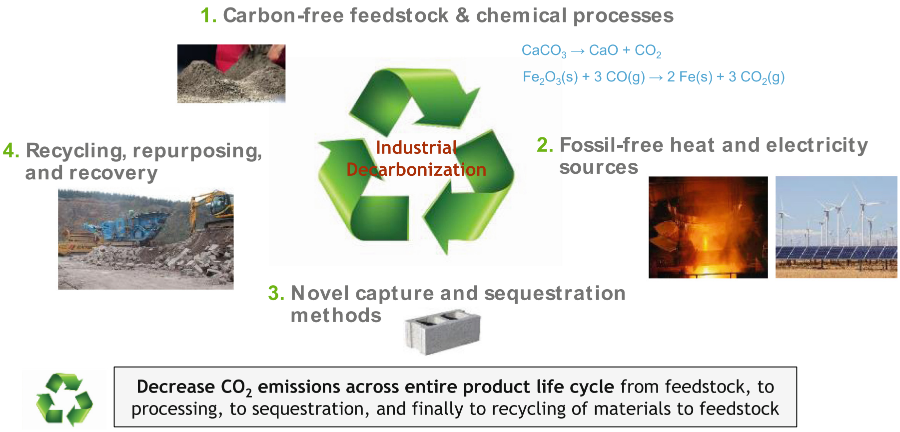

Fig. 2. Lifecycle framework for industrial decarbonization.

2.1 Carbon-Free Feedstocks and Chemical Processes

As discussed above, common feedstocks for cement and steel production emit significant amounts of CO_2 during processing. Low- or non-carbon-emitting binders have been proposed for cement (e.g., phosphate-based cements [7] or belite binders [8]), but research is needed to understand aging properties, processing temperatures, and optimal compositions. Carbon-free reduction of iron ore to produce steel using hydrogen instead of coke is also being investigated [5].

Carbon-free chemical processes, such as photoelectrochemical, electrolysis, and solar thermochemistry, to produce H_2 and/or CO (for syn gas) via H_2O or CO_2 splitting, respectively, have also been studied [9–15]. For example, in one type of solar thermochemical hydrogen production, metal oxides are heated using concentrated sunlight and reduced, liberating oxygen. When cooled, the reduced particles re-oxidize by stripping oxygen from either steam or CO_2 to yield H_2 or CO, key ingredients for synfuels. Energy-intense chemicals such as ammonia, which consumes 1–2% of global energy, can also be made sustainably using green electrolysis or solar thermochemistry [16]. Additional research is required to increase the efficiency and scalability of these processes.

2.2 Fossil-Free Heating and Electrification

High-temperature processing can be enabled by carbon-free sources (e.g., electric arc-furnaces powered by renewable energy, combustion of clean hydrogen or biofuels, concentrating solar thermal). Development of economical methods for energy conversion, conveyance, and storage is needed, and demonstrations using local renewable resources, showing regional value, should be prioritized.

Griffiths et al. provides a review of socio-technical challenges and opportunities for industrial decarbonization using hydrogen, which has high energy density and can enable long-duration storage. However, hydrogen combustion for industrial applications faces challenges relative to carbon-based fuels: high combustion velocity, non-luminous flame, low radiation heat transfer, corrosion and embrittlement of metals, and explosive properties. Clean hydrogen utilization for industrial decarbonization will require additional socio-technical advancement, ranging from basic research and development to market stimulation.

Concentrating solar technologies use a large array of mirrors to focus and concentrate sunlight onto a receiver, which can heat a fluid or media to very high temperatures (>~1000 °C). This high-temperature heat can be used for various industrial processes [17, 18]. Studies have been performed that show concentrated sunlight can heat a gas to ~1500 °C for use in clinker formation [19]. Challenges include storage and conveyance of high-temperature heat from the point of generation to the point of use.

2.3 Novel Sequestration of Greenhouse Gases

Carbon sequestration can occur in a wide variety of different systems including terrestrial, biological, oceanic, geological, and engineered materials. There has been growing interest in terrestrial and biological options of carbon sequestration, but traditionally, the US Department of Energy (DOE) has focused on geologic sequestration as part of the Office of Fossil Energy and Carbon Management portfolio.

Carbon sequestration in building materials connects with the recent focus on the creation of carbon neutral, or even carbon negative, building materials in support of industrial decarbonation. Carbon sequestration within the building material, such as cement or concrete, supports decarbonization of the cement life-cycle, without requiring injection of CO_2 into geologic repositories. Conversely, geologic sequestration has the ability to sequester carbon captured from any source (such as from post-combustion gas streams) and is considered to be one of the most promising avenues for large scale CO_2 sequestration, with the USGS estimating that the US has a potential CO_2 sequestration capacity between 2400–3700 metric gigatons of storage.

Key challenges include demonstration of long-term sequestration, scale-up, and potential impacts on materials of long-term aging.

2.4 Recycling, Repurposing, and Recovery

The final stage in the industrial decarbonization lifecycle framework is recycling, repurposing, and recovery. Materials recycling is commonly performed in industry, though most commonly for purposes of reducing material waste or recapturing valuable materials/commodities. Recycling as a strategy for industrial decarbonization, though, is relatively nascent. An exception is steel recycling, which is already a widespread practice. An estimated 1.5 kg of CO_2 emissions can be eliminated for every kg of steel recycled, and steel recycling is expected to double by 2050 [20, 21]. Recycling of other building materials, such as concrete, is possible, but uncertainty exists regarding performance and aging properties of recycled concrete aggregates [22]. Hopewell et al. [23] provide a comprehensive study of challenges and opportunities associated with plastics recycling, and studies are emerging that show potential for wide-spread carbon benefit of post-consumer polymer recycling [24].

As an alternative to explicit material recycling, repurposing of CO_2 emitted during industrial processes such as cement and steelmaking has also been studied. As described in Sect. 2.1, CO_2 can be combined with H_2 to produce hydrocarbon fuels, and there are additional studies about reintroducing CO_2 to recycled cement as a means to improve its properties [20]. In addition, recovery and reuse of waste heat from high-temperature industrial processes can also be performed to reduce CO_2-generating fossil-fuel consumption for heating. Recuperation of heat for use in low-temperature district heating is possible [25], and studies are looking at use of industrial waste heat for electricity generation [26]. Tools and methods for industry to identify cost-effective waste-heat recovery efforts have been developed [27] and may lead to significant gains in carbon reduction.

2.5 Discussion

The previous sections provide key challenges and opportunities to decarbonize industrial processes. A method that can be used to help prioritize which activities and opportunities should be pursued is probabilistic technoeconomic analyses (TEA) [28, 29].

Probabilistic TEA honors the inherent uncertainties in a system by sampling uncertainty distributions for input parameters that describe the features, events, and processes of a given system. Numerous runs (realizations) are modeled to evaluate the desired metric (e.g., cost, greenhouse gas emission, energy yield, social equity). The results provide a probabilistic evaluation of potential outcomes, and statistical regression analyses can be performed to determine the most significant input parameters or processes that impacted the simulated metric. This enables prioritization for future research to yield the most impact for a given investment ("best bang for the buck").

Energy efficiency is another opportunity that underlies all four areas in the industrial decarbonization lifecycle. Andrei et al. [30] report that energy efficiency is viewed as Europe's "first fuel" in various 2030 decarbonization scenarios, and that it should be treated as an energy source because it represents value in saved energy. In the U.S., Whitlock [31] reports that 15% of industrial emissions can be cut through efficiency measures, energy management, and smart manufacturing.

3 Conclusions

This paper has described a lifecycle framework for identification of key gaps, challenges, and opportunities to decarbonize industry. The four major categories in the framework include: (1) carbon-free feedstocks and chemical processes, (2) fossil-free heating and electrification, (3) novel greenhouse-gas sequestration, and (4) recycling, repurposing, and recovery. Significant reduction of greenhouse gas emissions can be achieved in each of these four areas, but challenges and research opportunities remain and have been highlighted in this paper.

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Buildings Innovations

Evaluating the Performance of a Passive Architectural Element in a Hot-Dry Climate Through Natural Ventilation and Thermal Impact Analysis

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Abstract. This study aims to mitigate the lack of integrating ideas from local architectural elements such as windcatchers, used as climate systems in hot climates to provide occupants comfort in modern housing designs. The average air temperature is 30 °C in summer, and 24 °C in winter, with an annual average relative humidity of 55%. The study investigated various windcatcher types: one-sided, two-sided, and four-sided and look for the appropriateness of their use to provide indoor thermal comfort conditions. The study includes an analysis of the integration of the windcatchers in different room designs (single zone) that is expected to be included in a single-family home proposal. The study makes a performance comparison that also considers the room door position, variations in inlet and outlet sizes, as well as windcatcher size and their placement. The analysis used CFD tools to see the potential variation in thermal profiles and air speed distribution. The results show that all integrated windcatchers alleviate indoor thermal conditions by adding natural ventilation, but a simple windcatcher design has the highest potential to provide comfort, which simplicity would be appreciated in construction. The conducted CFD simulations found reductions in air temperature from 2 °C to 7 °C for different wind speed conditions. The indoor air velocity was kept in the comfort range from November to March, particularly in the daytime.

Keywords: Hot-dry climate · Passive cooling · Windcatcher performance · Thermal comfort · Computational fluid dynamic (CFD)

1 Introduction

A key aspect of increasing the energy consumption of cooling new houses is neglecting passive local architectural element techniques to cool spaces. Such techniques should be developed with modern architecture to avoid energy consumption and provide occupants more control over natural ventilation [1]. It is a fact that air conditioning (AC) systems cannot be dispensed forever. The AC system is indispensable for any new building in a hot-dry climate. However, it is also a fact that integrating local architectural elements

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into a new design can potentially achieve thermal comfort for occupants through natural ventilation and reduce the need for annual cooling energy consumption, especially in warm weather. The residential sector accounted for about 21% of the total U.S. energy consumption in 2020 and 55% of the energy used for heating and cooling [2]. In comparison, the buildings sector in Saudi Arabia (KSA) uses 80% of the total electricity in the country, and 70% of that is used for air conditioning only [3, 4]. The energy in KSA generates by oil at 62%, natural gas at 38%, and renewable energy at 0.3% [5]. Additionally, electricity prices in KSA increased by 260% from 2016 to 2018, from 0.01 USD/kWh (0.05 Saudi Riyal/kWh) to 0.05 USD/kWh (0.18 Saudi Riyal/kWh) [6]. Therefore, using nonrenewable resources to produce electricity has a significant harmful impact on the environment, and the continuing increase in electricity prices has a negative effect on Saudi society.

Reducing electricity consumption is challenging and has many paths to follow, like using efficient technologies in buildings to help decrease energy demand. Unfortunately, that is insufficient to save energy consumption because real-estate developers can follow many ways to save energy by following sustainable building codes and practices to achieve better energy savings [3]. One of the most significant challenges to reducing the cooling energy consumption in hot-dry climates is the weather conditions, which have a considerable impact on natural ventilation, and this study focused on Jeddah, KSA. Jeddah's air temperature in summer ranges from 19 °C to 50 °C, with an average of 30 °C; in winter, the air temperature ranges between 9 °C to 33 °C, with an average of 24 °C. Jeddah's relative humidity is very high in general; in summer, the peak is 80%, with an average of 55% throughout the year. While the wind mostly comes from the seaside direction (the north and west) with a speed of 3.6 m/s (8 mph) on average for most of the year, Jeddah's annual average wind speed is higher than Phoenix at 2.8 m/s (6.2 mph) and Houston at 3.2 m/s (7.2 mph) and less than Miami at 3.9 m/s (8.5 mph) and Las Vegas at 4.2 m/s (9.5 mph). According to the Adaptive Comfort Model, the comfort zone area for that hot-dry location ranges between 23 °C to 31 °C [7]. Many scholars have examined the effects of natural ventilation to improve indoor quality and thermal comfort using passive local architectural elements. In 2003, Badran studied cooling tower performance in different climate regions that need air conditioning in Jorden, such as the desert, valley, and coastal areas. The paper concludes that 15 m height cooling towers in traditional buildings are unnecessary because that does not affect the dry-bulb temperature and air velocity parameters. Thus, if the height reached 9 m instead of 15 m, it would be better because it reduces costs and provides the same performance. On the other hand, the author found that the suggested requirement to have comparable performance to a 1 ton refrigeration machine in the Jordan valley or desert areas, the cooling towers should be 4 m in height within a 0.6 m × 0.6 m cross-section; that can provide an excellent cooling effect with airflow of 0.3 m/s and reduce the dry-bulb temperature from 36 °C to 25 °C [8]. Furthermore, Attia's 2009 study found that adding one Malqaf (Arabic word refers to windcatcher) to the design can provide 5.6 air changes per hour (ACH) within an opening ratio of 0.6 and air velocity of 2 m/s [9].

With the same objective, in 2014, Kamal and Al-Shehab conducted traditional passive cooling systems in hot climates such as mashrabiya, chimneys, and wind towers. It consists of two outlets: one for catching fresh air and the other for ejecting. The fresh air is directed through inlet ducts to building rooms; these ducts contain filters to eliminate bacteria and moisture, and the use of vent fans is helpful for air circulation. However, the traditional techniques need more development to create good thermal comfort; see Fig. 1. For example, Kamal and Al-Shehab's study found wind temperature is high due to hot climate, but the high wind tower catches the wind and makes the air pass through cold pods and wet clothes to cool down the air and then pass it into the rooms. The paper claims traditional elements can work together to achieve thermal comfort in one house, cooling it in summer or warming it in winter.

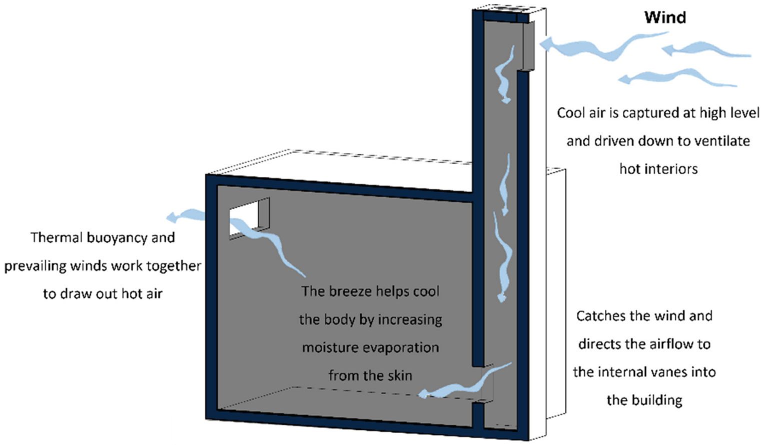


Fig. 1. Windcatcher catches the wind and directs the airflow to the internal vanes into the building, and the breeze helps cool the body by increasing moisture evaporation from the skin.

In a different study, Pruitt et al. (2017) identified research questions related to finding comfortable building solutions from vernacular architecture for the future of climate control with modern technology and design that rely on less energy and cost. To give an example, the wind tower catches the wind and directs the airflow to the internal vanes into the building, working like air conditioning with four main principles: the tower directs outdoor wind to high levels and exits the indoor hot air, and the humidity factor is provided by the *qanat* (underground channel or tunnel systems that bring infiltrated groundwater or surface water) under the ground and the insulated walls. When the passing air moves above the water in the *qanat*, it loses heat because of the evaporation effects, and the dry air becomes more humid. On the other hand, if there is no *qanat* due to waterless houses, the function of the windcatcher works as a solar chimney [10]. However, the traditional systems techniques were neglected because of the Industrial Revolution and mechanical systems. Additionally, the energy crisis has increased the need for low-energy buildings, and the traditional passive building techniques may be part of the solution [10]. Moreover, investigating the environmental performance of windcatchers in Jeddah was attempted by Mohamed and Mohammed (2018). This study focused on windcatcher use as an essential air movement strategy to achieve indoor thermal comfort for passive design. The research includes theoretical and field studies to quantify the passive elements' effectiveness and investigated two houses in Jeddah's old town, Bait Nassif and Bait Noor Wali. The study found that building structures for windcatchers are different between regions. For instance, windcatcher size is different depending on the outdoor air temperature; if the outdoor air temperature is high, the area of its horizontal section should be small, and if the outdoor air temperature is low, the area of its horizontal section should be significant. In some cases, other structures include burnt charcoal to help absorb unpleasant odors from the air [11].

Most windcatchers have been built in desert climates and are classified based on the number of openings, such as one-sided, two-sided, four-sided, six-sided, and eight-sided, depending on the prevailing wind in that area [12, 13]. In addition, square windcatchers are more common than other shapes like the circle, hexahedral, and tetrahedral cross-section. According to Hussain (2020), evaluating the efficiency of a ventilation system or natural ventilation can be achieved by measuring the local mean age of air (LMA) as a parameter to measure the relationship between changing the old air to new air in the space; better indoor quality has a lower age of air. In other words, LMA is the average time that fresh air needs to travel from the inlet point to any point in the space that is used to check fresh air availability, and using a CFD tool can provide LMA analysis for early design decision to improve indoor air quality [14].

Many aspects of these hypotheses in the literature have been questioned, determining the fundamental flaws and strengths of local architectural elements in research design. For example, well-designed buildings for natural ventilation can provide comfort better than mixed-mode buildings [15]. Furthermore, traditional elements like windcatchers can provide fresh air, reduce the indoor temperature, reduce CO_2 emissions for occupants' health, and reduce building energy consumption [16]. Additionally, Elnaklah et al. (2021) highlighted a gap between the observed and predicted thermal comfort (PMV); developing a new localized thermal comfort model is recommended to mitigate the energy demand for space cooling and to fit occupants in each country because one international standard is not suitable for all locations in the Middle East [17]. Most researchers in the area have agreed that traditional buildings techniques like windcatcher are a sustainable, environmentally friendly passive strategy for cooling many building types: residential, medical facilities, and even super skyscrapers. Therefore, it should be one of the primary goals for designers to reduce energy use and lead to minor operation and construction costs because that will mitigate environmental problems by reducing the dependence on fossil fuels and being more climate-responsive [1, 10, 11, 18].

Unfortunately, the lack of research on practical technical design perspectives through applying them in new modern homes designs creates some serious limitations in achieving the sustainable building concepts of these passive buildings techniques for reducing building energy consumption. This presented study agrees with Mohamed and Mohammed's (2018) findings, which showed that these kinds of hypothesis research are valuable to raise awareness of helpful passive strategies for a modern building, reducing the amount of energy required to cool down our buildings. This research aims to integrate and investigate the detailed impact of passive local architectural elements in new single-family homes, namely the windcatcher, in a hot-dry climate like Jeddah by exploring the use of CFD tools to study the potential functional challenges of that element through natural ventilation. These detailed thermal analyses can be listed as follows: (1) investigating various windcatcher types and finding the appropriateness of their use to provide indoor thermal comfort conditions; (2) evaluating the performance of a windcatcher in hot-dry climate through natural ventilation/wind potential data; (3) evaluating the potential variation in the thermals and air profile distribution, air temperature and airflow, and air volume; (4) evaluating the efficiency of the natural ventilation through measuring the LMA; and (5) evaluating the potential of windcatcher for one-zone and multizone/floors.

2 Methodology

To address the gap in the literature, this study integrates windcatcher in-home designs and evaluates windcatcher performance using the CFD tool to see potential variations by addressing four headings: wind data, windcatcher types, thermals, and air profile distribution. Evaluating the windcatcher's performance depends on natural ventilation/wind potential data for thermal impact. Hence, the study analyzed the wind data using a Typical Meteorological Year (TMY3 from 2004 to 2018) for Jeddah to identify the wind conditions and the most dominant wind direction each month. Moreover, single-room models with a windcatcher were created to investigate the effects of various windcatcher types and configuration thermal comparisons. The geometry model had room area and volume of 18 m^2 and 72 m^3, respectively, while the room height is 4 m, and the windcatcher height is 6 m attached to the room. Additionally, the room door was assumed to be opened/closed, refers to an outlet area, and the room was assumed to be empty. Also, the building envelope is assigned based on the minimum requirements for Climate Zones "1B" Very Hot–Dry, as presented in the Saudi Building Code - 602, 2018 [19]. Finally, the orientation of the rooms faced north based on the most dominant wind direction results throughout the year.

Furthermore, first investigation analyses include six identical rooms attached to a windcatcher, but each room has different windcatcher types: one-sided, two-sided, and four-sided, with different cross-section sizes of large/small, 0.8m × 0.8m, and 0.4m × 0.4m, respectively. In addition, each windcatcher has different inlet areas corresponding to the number of opening sides, and all inlets and outlets are assumed to be open for all cases. The second investigation analyses include four rooms with different windcatcher positions front/central, including a one-sided front/central windcatcher in the room and a two-sided front/central windcatcher. The third investigation classified three rooms into three different door positions: one-sided with a back door, left door, and right door to better understand the thermals and airflow effects in the space for winter and summer months conditions, namely January and July. The three investigation analyses were carried out to compare the annual maximum outdoor air temperature (OAT) with the indoor air temperature (IAT) for each case and select the room with the lowest temperature value as a baseline (see Fig. 2). Based on the previous investigation, finding the most effective windcatcher types to reduce the IAT for that specific location allowed selecting the room model with a one-sided windcatcher and small cross-Sect. 0.4m × 0.4m-Right Door (RM-1S-SC-RD) as a baseline because it was found to be the most cost-effective option.

However, other configurations regarding windcatcher design need to be investigated more deeply to find more temperature reductions by evaluating the annual and

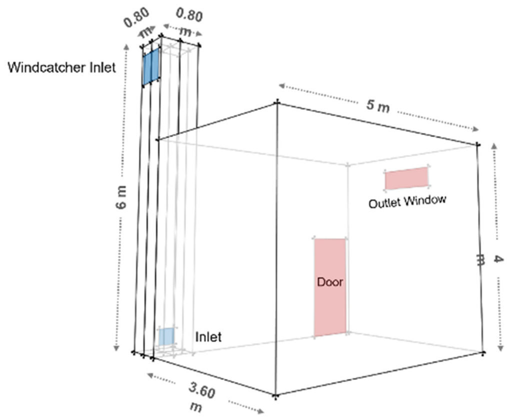


Fig. 2. Visuals of the simulated room model with a one-sided windcatcher and four small cross-Sects. 0.4m × 0.4m-Right Door (RM-1S-SC-RD). The diagrammed model was found to be the most cost-effective.

monthly maximum indoor temperatures. Also, all models in this step are assumed to have opened/closed room doors with opened outlet windows on the other side of the room to extract the outflow and drive the airflow from high pressure to low. RM-1S-SC-RD has a high potential to provide comfort, and simplicity would be appreciated in construction. Therefore, the subsequent step investigation of the windcatcher will include one model with different scenarios, including the multizone zones, floors, and raising the inlet distribution in the room from 0.6 m to 1.5 m. Evaluating the monthly (January and July) maximum IAT and analyzing the effects of natural ventilation potential takes place two single times representing winter (January 5th at noon) and summer (July 13th at noon) conditions, using the CFD tool to see the thermals and air profile distribution, air temperature, and airflow. Also, the investigations measured the LMA to evaluate indoor air quality and the relationship between changing old air to new.

3 Results and Discussion

3.1 Natural Ventilation and Wind Potential Data

The presented data in Fig. 3 show the maximum, mean, and minimum dry-bulb temperature (DBT). According to the Adaptive Comfort Model, the comfort zone area for that hot-dry location ranges between 23 °C to 31 °C [7]. The weather data clearly shows that the summer months in Jeddah from May to September have high OAT with an average range from 30 °C to 34 °C, and both April and October have fickle/unexpected weather. From November to March, the winter has warm weather ranging from 24 °C to 28 °C, including constant seaside wind throughout the year with an average speed of 3.5 m/s, demonstrating high natural ventilation potential. However, the OAT is indeed high most of the year, but the wind speed is also high most of the year, so, when OAT falls in the winter, the high wind speed provides comfort to occupants. The high wind speed with seaside direction and warm, moist air creates potential for natural ventilation in the winter months, particularly from November to March.

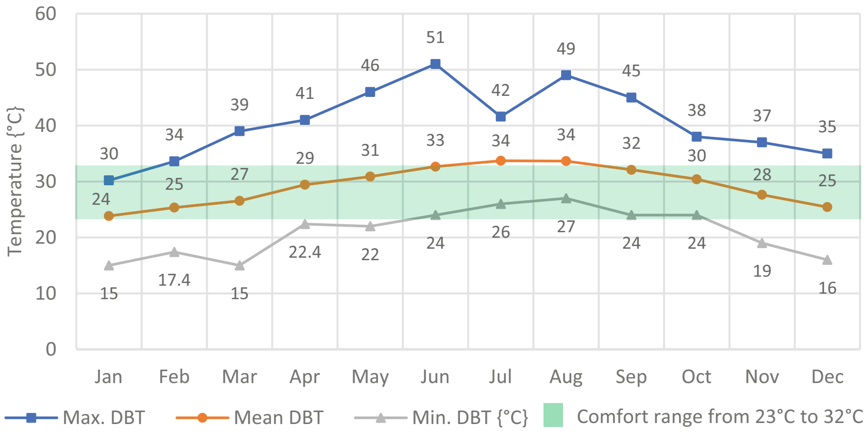


Fig. 3. Monthly comparison of the maximum, mean, and minimum conditions of DBT in Jeddah, S.A.

3.2 Windcatcher Configurations Investigation

The annual results of maximum IAT between opened/closed-door rooms in all models have a variety of temperature differences between the outdoor and indoor range from 5.4 °C to 6.2 °C for open-door rooms and from 9.2 °C to 10.1 °C for closed-door rooms. Overall, most integrated windcatchers alleviate the indoor thermal condition in the monthly evaluations and ensure a high range of ACH, higher than 8 ACH depending on wind speed. However, all the resulting IATs are very similar in all models; thus, the model with the most straightforward construction was selected to continue the following CFD investigations. RM-1S-SC-RD shows high potential to provide comfort with low IAT and has temperature reduction lower than the outdoor by 6.1 °C for open rooms and 10 °C for closed rooms. The following CFD investigations will highlight the rapid decrease in IAT and show the operative temperature (T_{op}) used to measure human thermal comfort based on a combination of room comfort parameters: air temperature, mean radiant temperature, and airspeed.

3.3 Daytime Effect on CFD Analysis

Further CFD analysis showed that integrating the windcatcher into the design always keeps the room's operative temperature below 31 °C in all cases. As can be seen in Tables 1 and 2, the closed room group reported significantly more temperature reduction than the other group, especially for the multiple floor model with a reduction of more than 6 °C in summer/July, which is higher than the comfort zone, but still a high reduction. Interestingly, in this table, temperature reduction happens only by integrating one architectural element, a windcatcher, in the design for natural ventilation. This study initially targeted only the winter in Jeddah and found reasonable results when using natural ventilation. However, the results also showed that natural ventilation might have high potential in summer because the operative temperature for all the models is still lower than 31 °C.

Table 1. Table showing outdoor conditions

Date/Time	Wind speed	Wind direction	DBT	**DPT**	**RH**
05/January at 12:00	3.1 m/s	360°(N)	25.7 °C	12.9 °C	45%
13/July at 12:00	4.1 m/s	330°(NNW)	37 °C	27.5 °C	59%

Table 2. Table summarizes the CFD results data for the indoor conditions during winter and summer for four different models with different scenarios.

Room model	Parameter	Scenario			
		05/Jan at 12:00		13/July at 12:00	
		Opened room door	Closed room door	Opened room door	Closed room door
RM-1S-SC-RD[a]	Velocity	≤ 0.6 m/s	≤ 0.4 m/s	≤ 0.6 m/s	≤ 0.4 m/s
	IAT	24.8 °C	24.5 °C	35.4 °C	32 °C
	T_{op}	24 °C	23 °C	30 °C	29 °C
	RH	48%	49%	64%	65%
	DPT	12.9 °C	13 °C	27.6 °C	27.6 °C
	LMA	≤ 5 min	≤ 10 min	≤ 5 min	≤ 11 min
RM-1S-SC-RD-ER[b]	Velocity	≤ 0.6 m/s	≤ 0.4 m/s	≤ 0.5 m/s	≤ 0.3 m/s
	IAT	25 °C	24.2 °C	32 °C	30 °C
	T_{op}	24.2 °C	23 °C	29 °C	28 °C
	RH	49%	49.65%	66%	65%
	DPT	12.9 °C	13 °C	27.6 °C	27.6 °C
	LMA	≤ 8 min	≤ 11 min	≤ 9 min	≤ 11 min
RM-1S-SC-RD-ER-MF[c]	Velocity	≤ 0.5 m/s	≤ 0.5 m/s	≤ 0.5 m/s	≤ 0.5 m/s
	IAT	26 °C,27 °C	24.2 °C,24.2 °C	31 °C, 32 °C	28 °C, 29 °C

(*continued*)

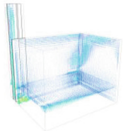
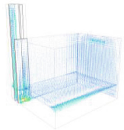
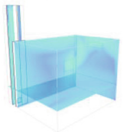
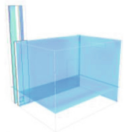
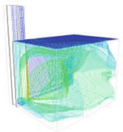
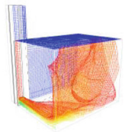
Table 2. (*continued*)

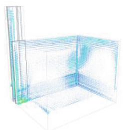
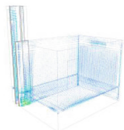
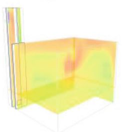
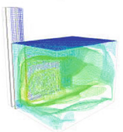
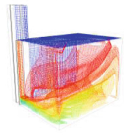
Room model	Parameter	Scenario			
		05/Jan at 12:00		13/July at 12:00	
		Opened room door	Closed room door	Opened room door	Closed room door
	T_{op}	23 °C, 23 °C	22 °C, 22 °C	27 °C, 28 °C	26 °C, 27 °C
	RH	49%, 49%	50%, 50%	65%, 66%	66%, 64%
	DPT	12.9 °C, 12.9 °C	13 °C, 13 °C	27.6 °C, 27.6 °C	27.6 °C, 27.6 °C
	LMA	≤ 9 min, ≤ 6 min	≤ 11 min, ≤ 7 min	≤ 8 min, ≤ 6 min	≤ 11 min, ≤ 8 min
RM-1S-SC-RD-1.5 m[d]	Velocity	≤ 0.5 m/s	≤ 0.5 m/s	≤ 0.5 m/s	≤ 0.5m/s
	IAT	24.8 °C	24.5 °C	32 °C	31 °C
	T_{op}	24 °C	24 °C	30 °C	29 °C
	RH	48%	49%	64%	65%
	DPT	12.9 °C	13 °C	27.6 °C	27.6 °C
	LMA	≤ 6 min	≤ 11 min	≤ 6 min	≤ 11 min

[a]Room model with one-sided windcatcher (RM-1 S) and small cross-section (SC) 0.4 m × 0.4 m-Right Door (RM-1S-SC-RD).
[b]RM-1S-SC" 0.4 m × 0.4 m-Right Door–Extra Rooms (RM-1S-SC-RD-ER).
[c]RM-1S-SC 0.4 m × 0.4 m-Right Door–Extra Rooms-Multiple Floors (RM-1S-SC-RD-ER-MF).
[d]RM-1S-SC 0.4 m × 0.4 m -Right Door–High inlet distribution of 1.5 m (RM-1S-SC-RD-1.5 m).
Note: Table 3 shows an example of one case, RM-1S-SC-RD, for the CFD analysis results

Additionally, there is a relation between IAT and the LMA; the temperature reduces when slowing down the local mean age of air. In other words, the IAT increases with lowers values of LMA and decreases with higher value of LMA. Moreover, from Jeddah's weather data, the OAT and wind speed are high, with an average of 29 °C and 3.5 m/s

Table 3. CFD analysis results for winter and summer at noon for opened/closed room door for the case of a room model with one-sided windcatcher and small cross-Sect. 0.4 m × 0.4 m-right room (RM-1S-SC-RD)

Winter condition, 05/Jan 12:00 PM		
Outdoor condition	Wind speed: 3.1 m/s · Wind direction: 360° (N)	DBT: 25.7°C · RH: 45% · DPT: 12.9°C
Winter	**Opened Room Door**	**Closed Room Door**
	Velocity: ≤0.6 m/s IAT: 24.8°C T_{op}: 24°C DPT: 12.9°C LMA: ≤5min	Velocity: ≤0.4 m/s IAT: 24.5°C T_{op}: 23°C DPT: 13°C LMA: ≤10 min
Velocity		
T_{op}		
LMA		

Summer condition, 13/July 12:00 PM		
Outdoor condition	Wind speed: 4.1 m/s · Wind direction: 330° (NNW)	DBT: 37°C · RH: 59% · DPT: 27.5°C
Summer	**Opened Room Door**	**Closed Room Door**
	Velocity: ≤0.6m/s IAT: 35.4°C T_{op}: 30°C DPT: 27.6°C LMA: ≤5 min	Velocity: ≤0.4m/s IAT: 32°C T_{op}: 29°C DPT: 27.6°C LMA: ≤11min
Velocity		
T_{op}		
LMA		

Velocity	0.00	0.15	0.30	0.45	0.60	0.75	0.90	1.05	1.20	1.35	1.50	1.65	**m/s**
Temperature	22	23	24	25	26	27	28	29	30	31	32	33	**°C**
LMA	0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	min

throughout the year, respectively, higher than Houston at 3.2 m/s and less than Miami at 3.9 m/s; hence, ensuring indoor air velocity of less than 0.6 m/s, helps to reduce the amount of hot outdoor air entering the indoor space in the hot-dry location. The acceptable indoor air velocity range for local air movement ranges from 0.3 to 0.9 m/s [20]. Therefore, allowing more air volume within high air velocity into the room raises the IAT due to the high OAT and vice versa.

On the other hand, keeping low air volume and low air velocity within a suitable range leads to better ventilation inside the room with the capability of lowering the daytime temperature in winter by 2 °C and 9 °C in summer, which keeps the room temperature within the comfort zone ranges of 23 °C to 31 °C. Figure 4 shows the data result from the simulation and proves that the wind enters the windcatcher through its openings, creating an LMA value of less than or equal to 5 min. Additionally, the CFD results showed no difference in IAT reduction or air profile distribution between low inlet distribution of 0.6 m higher than the room floor and a high inlet distribution of 1.5 m.

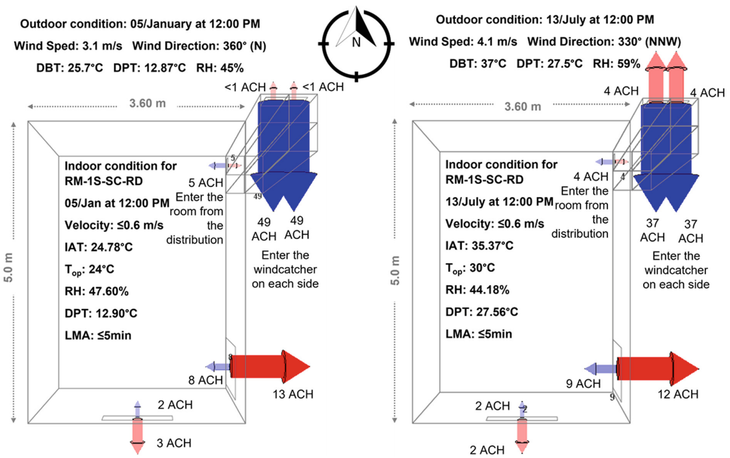


Fig. 4. Data summary of the simulated room model with a one-sided windcatcher and four small cross-Sects. 0.4 m × 0.4 m-Right Door as a baseline (RM-1S-SC-RD) during winter and summer conditions, 05/Jan at noon and 13/Jul at noon

4 Conclusion

This study investigated the thermal impact with the performance details of integrating windcatchers in modern house designs in a hot-dry climate, like Jeddah, KSA. The results indicate that the weather in Jeddah has a potential for natural ventilation from November to March because the average OAT ranges from 24 °C to 28 °C, the constant wind throughout the year has an average speed of 3.5 m/s, and the most dominant wind comes from the north side. Furthermore, the findings suggest that a one-sided windcatcher with a small cross-section of less than 3% of the total floor area is more effective in reducing the IAT than a large cross-section. The results data analysis highlights the importance of door position; the windcatcher inlet distribution to the room; door opening will be more effective if they are on the same wall side of the windcatcher. The following points emerged from the present windcatcher design configurations investigation:

1) The outlet window size should not exceed double the windcatcher inlet distribution size.
2) There are no differences in IAT reduction between 6 meters or 8 meters height of windcatcher.
3) There are no differences between a simple/straightforward windcatcher design and a windcatcher with an earth tube 3 meters below ground and around the room boundary.

Therefore, the simple windcatcher design was selected to continue the study because simplicity is appreciated in construction, with lower temperatures than the maximum outdoor by 6.1 °C for open rooms and 10 °C for closed door models. The evidence from this study suggests that the windcatcher has more potential with multiple floors than with one single floor. For example, the IAT reduction in winter/summer with one single floor ranges from 2 °C to 4 °C, but for multiple floors ranges from 5 °C to 7 °C, all rooms faced north based on the most dominant wind direction. Also, the CFD findings suggest that keeping low air volume and low air velocity in the room leads to better ventilation and lowering the daytime temperature in winter by 2 °C and 9 °C in summer. That keeps the room's operating temperature less than 31 °C in winter and summer, and the comfort zone area for that hot-dry location ranges between 23 °C to 31 °C. Overall, reducing the IAT and providing thermal comfort through the natural ventilation potential effect help minimize the use of air-conditioning systems in new houses in hot climates to save energy. This research can serve as a base for future studies or include it on building codes or energy efficiency guidelines for integrating windcatchers in new houses, in cities with climate conditions like Jeddah, to provide thermal comfort through natural ventilation. This study has investigated many design configurations for integrating windcatchers for new houses, but further work needs to be done to establish how the windcatcher strategy can work synergistically with other local traditional architectural elements strategies.

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Future of Thermal Insulation, Zero Carbon Options

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Abstract. This research is focused on the carbon assessment of thermal insulation. The building industry is now looking into not only reducing operational energy, but also embodied energy. First, a review was conducted of insulation types available in the American market. Materials were selected based on availability and market share. Then, a typical wall assembly for a house in the U.S. was defined and modeled using several types of the selected insulation materials. Location of the study set to Oklahoma and the baseline wall assembly was in compliance with IECC 2018. Life cycle analysis was performed in Tally to assess the conventional insulation types as well as a customized qualitative study of the low-carbon innovative materials. Results showed that Insulative Cork Board had the best performance among the types of materials. It had an extensive testing done for the final product with certification. The next contender for an innovative insulation is going to be the Mycelium. Mycelium is still a fairly new product to the market and there has not been any certification performed to ASTM standards. Among all the several materials discussed in this study, Insulative Cork Board was found to be far more effective to reduce carbon emissions into the environment, while still satisfying the code requirements for the wall assembly.

Keywords: Insulation materials · Building envelope · Carbon emissions · Life cycle analysis · Building innovations

1 Introduction

1.1 Introductions

Building insulations play an important role in the lifespan of a building. It improves the thermal comfort and wellbeing of the space's occupants all while reducing energy consumption due to heating and cooling, carbon emissions, and pollution. However, most materials that are used in the building's insulation are manufactured using mined and/or fossil fuel-based materials. These materials are by-products of oil and are being used in increasing quantities, which will eventually lead to problems associated with material depletion and its disposal during its end-of-life stages. One sustainable solution suggests the use of biodegradable materials that come from non oil-based products. There have been several attempts to develop biomaterials such as soy-based insulation, hempcrete or Airkrete, and rigid cork. In the next seven weeks, a comparative study

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is to be expected to document the use of mycelium-based insulation to both oil-based and non oil-based insulation types. The aim is to produce a comprehensive study over the mycelium as a competitive and sustainable solution and has the required properties that match the existing alternatives. The comprehensive study entails the comparative documentation of these following attributes: carbon emissions, cost, protective features (water and pest proof/resistant, fire resistant, and allergens), production and manufacturing, market shares, durability, acoustics and energy analysis. In order to produce a well-rounded report, a handful of materials were selected to analyze against the project objective. The non-renewable products (fiberglass batt, XPS - extruded polystyrene, and sprayed polyurethane) are all materials that have the highest market shares for oil-based insulation and will serve as a basis of expectation for the insulative properties in the renewable materials. Along with mycelium, the highest market shared materials that will be analyzed are soy-based insulation, hempcrete, rigid cork, and cementitious foam; all of which are utilized as lateral comparison.

2 Material Overview

2.1 Conventional Insulation Materials

Fiberglass Batt
Fiberglass is made primarily from silica spun into glass fibers that are held together with a binder. For years, urea-extended phenol-formaldehyde was the most common binder, but virtually all manufacturers now sell formaldehyde-free products. Most fiberglass insulation has at least 30% recycled-glass content. Low-density fiberglass may be less effective than many insulation types under very cold conditions due to its tendency to allow for air movement, but high-density products are available.

Extruded Polystyrene XPS
Extruded polystyrene (XPS) is thermoplastic, closed-cell foam insulation derived from petrochemicals (some of which are potentially hazardous). But XPS's excellent moisture resistance, high compressive strength, and low cost make it a very popular insulation material particularly for below-grade applications, including foundation walls and concrete slabs. XPS is now available with low-global-warming-potential blowing agents.

Spray Foam Closed Cell
Closed-cell SPF is typically installed at a density between 2.0–3.0 lbs per cubic foot and achieves the highest R-value of any foamed-in-place insulation. It can be used in place of XPS as an insulation for an exterior foundation, as long as there is proper drainage. While the blowing agent known as HFC-245fa is non-ozonedepleting, it is very potent for greenhouse gas, with a high global warming potential (GWP). Other blowing agents, such as HFOs (hydrofluoroolefin) have a much lower GWP with a higher R-Value, compressive strengths with the approval from Building Green. Closed-Cell SPF is installed in 2" layers at a time due to its exothermic curing process.

Spray Foam Open Cell
Compared to closed-cell SPF, open cell products use significantly less material, making it less expensive. It remains flexible and less likely to crack with the seasonal movement

of the building. However, open cell insulation achieves a much lower R-value and is not as effective at stopping moisture flow. This means that open-cell insulation cannot be used below grade or in high-moisture applications. Some low-density SPF products are formulated using other oil bases in place of petrochemicals.

Cellulose
Cellulose Batts is made from recycled paper (Newspaper) by hammer milling but also requires other fibers, binders, and borate-based and/or ammonium sulfate flame retardants. The newspaper is treated with chemicals, such as boric acid, to slow the spread of fire.

Conclusion of Conventional Material
There are several types of commonly used insulation materials for walls including cellulose fibers, extruded polystyrene, fiberglass batt, spray foam insulation both open cell and closed cell. This section was meant to briefly introduce the application of conventional insulations materials and their properties. By comparing the conventional insulations together by looking at a summarization of the product, the study can determine the insulation and performs better in terms of performance. These performance attributes varied anywhere from the thickness of the wall to acquire the R-value, safety features, compressive strength, manufacturing process and key ingredients. Of the five analyzed components, closed-cell extruded polystyrene has the best R-value per inch coming in at 7.1 per inch, however it has a high carbon footprint per square foot in comparison to the other conventional materials. This is not as high as the extruded polystyrene board that is more than 600 kgCO2eq/sqft. All the conventional materials were easy to find information for as the companies were required to seek out certifications based on the ASTM testing and EPD declarations.

2.2 Innovative Insulation Materials

Soy-Base Spray Foam
A high-performance, versatile spray foam insulation designed for residential construction. Its unique formula incorporates recycled plastic bottles and renewable oils to create high-performance, closed-cell spray foam insulation. This polyurethane insulation combines multiple control layers into a single application. Heatlok is developed with 14% renewable and recycled content and is the ideal choice for residential construction.

Cementitious Foam (Airkrete)
An inorganic, foamed magnesium-oxide cement insulation, Air Krete, is the foamed-in-place insulation material of choice for people with chemical sensitivities. There is no off gassing from this foamed-cement insulation, and it requires no flame retardants to remain noncombustible. However, the product requires very careful installation by company-trained installers to ensure proper performance. The cured foam is quite friable, does not function as an air barrier, and remains a very uncommon niche product.

Insulative Cork Board
Cork is a versatile material that has been used for many years and is very well known in architectural applications as well as day-to-day applications. The cork comes from

the bark of the Quercus Suber and is formed into a semi-rigid board that can be used as an insulative panel that comes in different thicknesses. It will not lose R-value over its lifetime unlike XPS which gradually degrades due to off-gassing. Since cork has a high vapor permeability than foam, there is a reduced risk of moisture issues in the wall assembly that can potentially extended the structure's lifespan.

Hempcrete
Hempcrete is a biocomposite material that is a mixture of hemp hurds, lime, sand, and pozzolans, which is used as a material for construction and insulation. It is easier to work with than traditional lime mixes and acts as an insulator and moisture regulator. It lacks the brittleness of concrete and does not need expansion joints like concrete does. The resulting product is a lightweight material that is ideal for most climates, and it combines the insulation and thermal mass into one.

Mycelium
Mycelium insulation board is an R-4-per-inch rigid insulation material that is made from intertwining mycelium (rootlike filaments of a fungus) that are grown in agricultural waste materials (primarily seed hulls) under controlled conditions. The mycelium forms a foam-like material that insulates reasonably well. The mixture can also be used with any mold to form bricks, panels, packaging, etc., meaning that the applications of mycelium are endless. This product as an insulative material is still new, therefore, there is not as much data for certifications and life cycle analysis (LCA).

Conclusion of Innovative Materials
There are several types of insulation materials for walls that are new and/or innovative to the market including soy-based spray foam insulation, hempcrete, mycelium, cork board, and cementitious foam. This section was meant to briefly introduce the application of innovative insulations materials and their properties. By comparing the innovative insulations together by looking at a summarization of the product, the study can determine the insulation and performs better in terms of performance. These performance attributes varied anywhere from the thickness of the wall to acquire the R-value, safety features, compressive strength, manufacturing process and key ingredients. Of the five analyzed components, insulative cork board is the best in terms of renewability, carbon absorption and certifications. however, the next contender for an innovative insulation is going to be the mycelium insulation. Mycelium is still a new product to the market and there has not been any certification performed to the ASTM standard making it difficult to produce a solid conclusion based on qualitative information alone. While the conventional insulations were easier to research and calculate for, it was fun finding the information for the innovative insulations. It brought up questions such as: "who or what actually certifies an insulation material?" This guided the study nicely, even if the innovative insulations were project-project certified.

2.3 Utilized Programs

Tally
Tally utilizes BIM data present in a Revit model to perform a life cycle assessment of the project based on the quantities of materials used. Tally calculations covers a building from

"cradle to grave," following the materials production stage to the end of the building life, giving a broad spectrum of the total carbon impact. Tally is very thorough in disclosing data assumptions for conventional materials and presents specifications for the user to select from. This means that Tally requires specific inputs, therefore, materials need to be selected with that in mind. The specifications make this program a tool to utilize specifically for design development with the refined details are being integrated. For this study, Tally was easy to utilize due to the focus on one material in the wall assembly, however the other layers were defined to the degree of having valuable data outputs for the overall wall system. For simplicity, ceilings and floors were omitted and the interior was assumed to be finished with a gypsum wall board. These simplifications put the emphasis on the envelope itself so specific data points could be excluded from the analysis.

EC3
EC3 used the tedious data inputs from Tally and processes it into an organized visual of carbon flows based on the materials present in the assembly. The resulting chart shows what materials are demanding the most carbon.

3 Energy Simulation

3.1 General Information

This section compares different insulation technologies discussed in the previous section based on their attributes. For this purpose, a basic wall assembly was created to produce LCA data for the conventional insulation. This acts as a reference "house" for the innovative materials. By utilizing the IECC 2018, the comparison baseline is created for needed to explore and compare. For more information about the IECC 2018 codes used please view the appendix (Table 1).

Table 1. Wall assembly.

Location	Oklahoma
Climate zone	3A
Wall dimension	4'-0" wide x 9'-0" tall
Wall thickness	3 ½" to 7 ¼"
Stud spacing	24" O.C

3.2 Material Properties

Attributes Table to Compare Insulations
This study was initially approached with an excel sheet that was utilized to compare the characteristics and attributes of the insulations in one place. This table also displays two materials that were later removed due to a lack in information. This table takes a very general look at the attributes and just gives numbers or a simple yes or no.

Table 2. Comparatives for insulation.

	Brand	R-value per inch	Carbon emissions	Water resistant	Pest resistant	Fire resistant	*Density lb/cft*
Fiberglass batt	Owens	4.06	2.18124 $kgCo_2/M^2$	< 5% ASTM E96	ASTM C1338	ASTM E84 UL723	0.116
XPS – Extruded	Dupont	5	9.03 E1 $kgCo_2$	1.5 ASTM E96	ASTM C1338	ASTM E84 UL723	0.15
XPS - Extruded	Owens -Foamular	5	2.19 $kgCo_2/M^2$	ASTM C578 Type IV	ASTM C 1338	ASTM E84 UL723	0.15
Spray foam (Closed cell)	Demilec Huntsman	7.1	N/A	ASTM E96	ASTM C 1338	NFPA 285	2
Spray foam (Open cell)	Demilec Huntsman	3.8	N/A	ASTM E96	ASTM C 1338	NFPA 285	0.45
Cellulose	Greenfiber	3.7	N/A	ASTM C1338	ASTM C 1338	Extremely Flammable	0.519
Soy-based insulation	Demilec	7.4	> 0.5–4.9 $kgCo_2/M^2$	ASTM E96	ASTM C 1338	ASTM E84 NFPA 286	2.1
Hempcrete	Hempitecture	3	−2454.21 $kgCo_2E/M^2$	< 5% ASTM C1104	Yes	Class b s1d0 EN Standard	7
Hempcrete	Hempecosystems	3.1	−2454.21 $kgCo_2E/M^2$	< 5% ASTM C1104	Yes	Class b s1d0 EN Standard	7
Rigid cork insulation cork board (IBC)	Corktherm	3.61	−1.91 $kgCo_2/M^2$	0.5 kg/m^2 EN1609	Yes w/Treatment	Euro Class E EN 13501–1	7
Cementitious foam	Airkrete	3.9ASTM C518, 6 per DLS report	D5116 carbon negative	ASTM E96	ASTM C 1338	ASTM E84-81A	5
Mycelium	Ecovative designs	4	Carbon negative	Yes	Yes w/Treatment	Low with no Silica added	59–552 (kg/m^3)

Cost For Insulation

To further utilize the information that was found on the insulation and as an extended comparative, this excel sheet was used to compare the cost per square foot and the cost for the R-Value per square foot. The sheet takes the given price from a construction material supplier whether it was for one board or measured coverage. If it was a measured coverage the total price was divided by the area that was given by the company. This gave the price per square foot at 1” thick. This price was then multiplied by required thickness [Table 3] of insulation to meet the R-Value from the IECC 2018 code.

Table 3 Cost for Insulation

-	Brand	Cost Given	/	Coverage sqft	=	Cost per SQFT	*	Thickness of Insulation	=	Cost for R-Value / sq ft
Fiberglass Batt	Owens	38.32	/	48.96	=	0.783	*	-	=	$0.783
XPS - Polystyrene Extruded	Dupont	32.98	/	32	=	1.030625	*	4	=	$4.12
XPS - Polystyrene Extruded	Owens - Foamular	23.25	/	32	=	0.727	*	4	=	$2.91
Spray Foam (Closed Cell)	Demilec Huntsman	1.50 @ 1in thick		-	=	1.0 / 1 in	*	2.82	=	$2.82
Spray Foam (Open Cell)	Demilec Huntsman	$0.54 per sqft @1"		-	=	0.54	*	3.421	=	$1.85
Cellulose	Greenfiber	$3.43 for 19 lb	/	22.7	=	0.151	*	-	=	$0.15
Soy Based Insulation (Closed Cell)	Demilec	3.00/ 1in		-	=	3.00 sqft	*	2.703	=	$8.11
Hempcrete	Hempitecture	54.99	/	19.98	=	1.25	*	6.45	=	$8.06
Hempcrete	Hempecosystems	54.99	/	19.98	=	1.25	*	6.45	=	$8.06
Rigid Cork	Corktherm	1.79		1	=	-	*	5.54	=	$9.92
Cementitious Foam	Airkrete	1		1	=	1.00	*	5.13	=	$5.13
Mycelium	Ecovative	1.71	/	1	=	1.71	*	5	=	$8.55

3.3 Wall Structuring

Wall Assemblies
To represent the most typical case of residential wall system, the commonly used 2 in. × 6 in. wood-stud wall is selected for simulations. The OSB sheathing layer and interior layer are kept the same for each case to control variable. The exterior finish layer that is applied is a wood siding layer and a brick veneer layer. These are to two most common facades that is applied to residential structures in the United States. Different types of insulation materials are selected for the insulation layer with properties described in Sects. 2.1, 2.2, and 3.2 respectively. A section of the modeled walls is shown in Fig. 2. and Fig. 3. The base line for the wall structure is defined by the IECC 2018 code for residential applications and it should be noted that any improvement in the performance of the insulation can be directly quantified. The simulated cases are named in correspondences to the different insulation materials used in the wall models (Fig. 1 and Table 4).

4 Testing and Results

4.1 Conventional Data

To analyze the conventional materials, Tally was used to create diagrams representing each type of insulation under this category. Tally's database had the selected brands information available to study the lifecycle analysis of each material within a wood stud

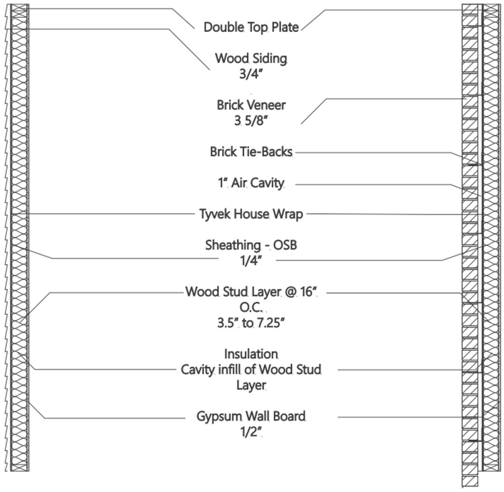


Fig. 1. a) Wall section with wood siding b) Wall section with brick siding

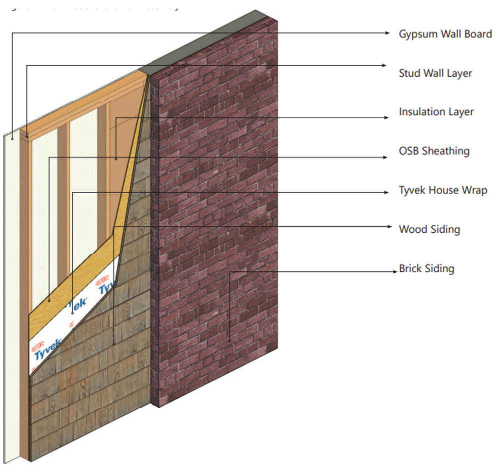


Fig. 2. 3D model of wall assembly

wall with typical wood siding or brick siding. Each result gave three diagrams like the image shown below:

Each set of data given determined what portion of the product had the greatest impact in terms of carbon emissions by lifecycle stage (left), division (center), and material (right). The lifecycle stage diagram breaks down which portion of the material's life has the most global warning potential within a vertical bar chart and pie chart. By division takes the lifecycle stage further and breaks it down into components based on finishes, thermal and moisture protection, and wood/plastics/composites. Lastly, the final diagram takes the broken down components even further from the previous chart and displays what material within the insulation is causing the most output. The data for obtained for

Table 4 IECC 2018 Thickness of Wall

-	Brand	Total R-Value	/	R-Value per Inch	=	Thickness for R-Value	Wall Stud Frame
Fiberglass Batt	Owens	20	/	4.06	=	4.926108374	2 × 6
XPS - Polystyrene Extruded	Dupont	20	/	5	=	4	2 × 6
XPS - Polystyrene Extruded	Owens - Foamular	20	/	5	=	4	2 × 6
Spray Foam (Closed Cell)	Demilec Huntsman	20	/	7.1	=	2.816901408	2 × 4
Spray Foam (Open Cell)	Demilec Huntsman	20	/	3.8	=	5.263157895	2 × 6
Cellulose	Greenfiber	20	/	3.7	=	5.405405405	2 × 6
Soy Based Insulation (Closed Cell)	Demilec	20	/	7.4	=	2.702702703	2 × 4
Hempcrete	Hempitecture	20	/	3	=	6.666666667	2 × 8?
Hempcrete	Hempecosystems	20	/	3.1	=	6.451612903	2 × 8?
Rigid Cork	Corktherm	20	/	3.61	=	5.540166205	2 × 6
Cementitious Foam	Airkrete	20	/	$3.90	=	$5.13	2 × 6
Mycelium	Ecovative	20	/	4	=	5	2 × 6

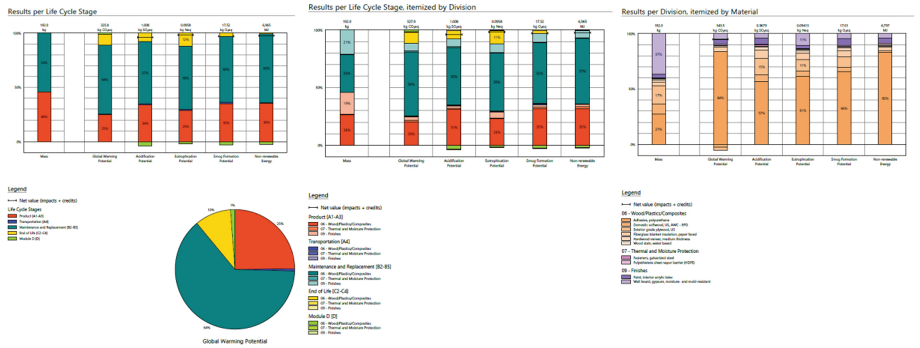


Fig. 3. Tally results

all brick wall assemblies was similar because the masonry brick and standard lime mortar produced the most carbon. This unfortunately overrode the data about the insulation due to the large amounts of carbon released during the production of the masonry products.

Fiberglass Batt
Wood Wall

Lifecycle Stage
Most impactful stage: Maintenance and Replacement
Conclusion: Fiberglass batt is one of the most common insulations used today in residential buildings, however once it needs to be replaced the removed product cannot be repurposed. Its embodied carbon is likely released as it ages and upon maintenance/repair will continue this cycle.

By Division
Most impactful stage: Maintenance and Replacement- Wood/Plastics/ Composites
Conclusion: Wood timber acts as a carbon sink on the front end, but if it is not able to be repurposed after the life of the building, it will likely release its stored carbon back into the environment.

By Material
Most impactful Material: Adhesive Polyurethane
Conclusion: Fiberglass batt is not the primary cause for the carbon impact on this wall assembly currently. The polyurethane adhesive that is being used contributes significantly to the carbon footprint in this case. Sustainable design, as shown by this data should begin at the design of the envelope.

Brick Wall

Lifecycle Stage
Most impactful stage: Product
Conclusion: Fiberglass batt is one of the most common insulations used today in residential buildings, the increase in global warming potential it likely because of the brick veneer. Its embodied carbon is likely released in larger amounts because of the manufacturing process for brick.

By Division
Most impactful stage: Maintenance and Replacement- Masonry
Conclusion: The masonry that added to the amount of embodied carbon in this wall assembly.

By Material
Most impactful Material: Generic Brick and Lime Mortar
Conclusion: Itemizing the wall assembly by the material, tally gave the results that 73% of the resulting global warming potential is marked up to the masonry in the envelope. Whereas the wood siding will absorb carbon to an extent, masonry just releases its own carbon into the environment.

Extruded Polystyrene XPS

Wood Wall Lifecycle Stage
Most impactful stage: Maintenance and Replacement
Conclusion: Fiberglass batt is one of the most common insulations used today in residential buildings, however once it needs to be replaced the removed product cannot be repurposed. Its embodied carbon is likely released as it ages and upon maintenance/repair will continue this cycle

By Division
Most impactful stage: Maintenance and Replacement- Wood/Plastics/Composites
Conclusion: Wood timber acts as a carbon sink on the front end, but if it is not able to be repurposed after the life of the building, it will likely release its stored carbon back into the environment.

By Material
Most impactful Material: Adhesive Polyurethane
Conclusion: Fiberglass batt is not the primary cause for the carbon impact on this wall assembly currently. The polyurethane adhesive that is being used contributes significantly to the carbon footprint in this case. Sustainable design, as shown by this data should begin at the design of the envelope.

Spray Foam Closed Cell
Wood Wall

Lifecycle Stage
Most impactful stage: Maintenance and Replacement
Conclusion: Fiberglass batt is one of the most common insulations used today in residential buildings, however once it needs to be replaced the removed product cannot be repurposed. Its embodied carbon is likely released as it ages and upon maintenance/repair will continue this cycle.

By Division
Most impactful stage: Maintenance and Replacement- Wood/Plastics/Composites
Conclusion: Wood timber acts as a carbon sink on the front end, but if it is not able to be repurposed after the life of the building, it will likely release its stored carbon back into the environment.

By Material
Most impactful Material: Adhesive Polyurethane
Conclusion: Fiberglass batt is not the primary cause for the carbon impact on this wall assembly currently. The polyurethane adhesive that is being used contributes significantly to the carbon footprint in this case. Sustainable design, as shown by this data should begin at the design of the envelope.

Spray Foam Open Cell
Wood Wall

Lifecycle Stage
Most impactful stage: Maintenance and Replacement
Conclusion: Fiberglass batt is one of the most common insulations used today in residential buildings, however once it needs to be replaced the removed product cannot be repurposed. Its embodied carbon is likely released as it ages and upon maintenance/repair will continue this cycle.
By Division
Most impactful stage: Maintenance and Replacement- Wood/Plastics/Composites

Conclusion: Wood timber acts as a carbon sink on the front end, but if it is not able to be repurposed after the life of the building, it will likely release its stored carbon back into the environment.
By Material
Most impactful Material: Adhesive Polyurethane
Conclusion: Fiberglass batt is not the primary cause for the carbon impact on this wall assembly currently. The polyurethane adhesive that is being used contributes significantly to the carbon footprint in this case. Sustainable design, as shown by this data should begin at the design of the envelope.

Cellulose
Wood Wall

Lifecycle Stage
Most impactful stage: Maintenance and Replacement
Conclusion: Cellulose is another common insulation type that is somewhat being phased out due to its health risk, and amount of maintenance of the product. Due to the cellulose fibers settling, it needs to be replaced so that the R-value may be maintained. Its embodied carbon is likely released as it ages and it will eventually cost more due to the consistent replacement.

By Division
Most impactful stage: Maintenance and Replacement- Wood/Plastics/Composites
Conclusion: Wood timber acts as a carbon sink on the front end, but if it is not able to be repurposed after the life of the building, it will likely release its stored carbon back into the environment.

By Material
Most impactful Cellulose
Conclusion: The breakdown of the wall assembly shows that the polyurethane adhesive and the blown-in cellulose insulation is what contributes the most to the overall global warming potential of this specific wall assembly.

4.2 Innovative Data

Qualitative Analysis of the Innovative Insulation Technologies Unfortunately, due to the limitations of the lifecycle analysis programs, there was not a similar way to organize the data for the Innovative insulations that were reviewed for this study. Instead, a qualitative analysis was performed using a point system that was inspired by the LEED points and accreditation system. To the Left (Top) the table shows the selected attributes of the insulations in the first column. This covers the basics for renewability, carbon emissions, safety features, market presence, and many more. The table then compares the attributes of the selected insulations from a scale of −2 to 2 and these are labelled as such (Tables 5 and 6):

Table 5 Qualitative Data for Innovative Insulations

-	Soy Based (Closed Cell	Hempcrete	Rigid Cork	Cementitious Foam	Mycelium
Carbon Absorption	0	2	2	2	2
Carbon Emissions	-2	0	-1	0	0
Fire Resistant	2	2	1	2	1
Water / Mold Resistant	2	2	1	1	-1
Pest Resistant	2	2	1	2	-1
Renewable	-2	2	2	-2	2
Recyclable	-2	-1	2	-1	2
Biodegradable	-2	1	2	-2	2
Availability	2	2	-1	1	2
Market Presence	2	1	2	-1	1
Skilled Labor Required	-2	-1	2	-1	1
Waste Production	-2	1	2	-2	2
Certifications	1	-1	-1	1	-1
Sound Absorption	2	2	2	1	2
Added Air Barrier	2	1	2	2	2
Total Points	3	15	18	3	16

Table 6. Point system for innovative insulations.

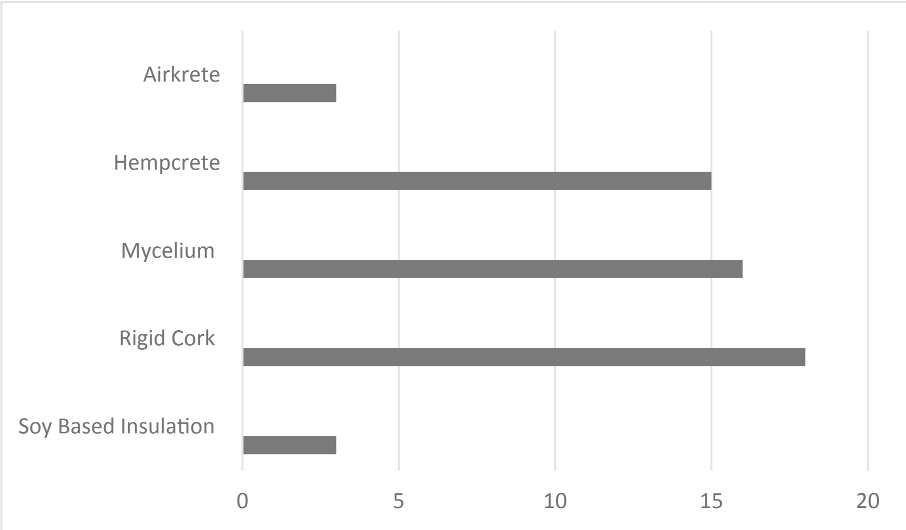
−2	Negative environmental impact and/or no
−1	Possibly but not proven
0	Not applicable/Not available
1	Yes, but does not have certifications
1	Yes, and has been certified by company

The Insulations were then measured according to whether the information was available, had a positive impact on the environment, had no information available, and had a negative environmental impact. The chart to the Left (bottom) then measures the insulations in comparison to each other based on the score that they received from the qualitative insulations (Table 7).

4.3 Ec3 Sankey Diagrams

EC3 used the tedious data inputs from Tally and processes it into an organized visual of carbon flows based on the materials present in the assembly. The resulting chart shows what materials are demanding the most carbon. These Sankey diagrams summarize all the energy transfers taking place in the lifecycle process of the wall assembly. The thicker the line or arrow, the greater the amount of energy involved (Fig. 4).

Table 7. Qualitative data for innovative insulations



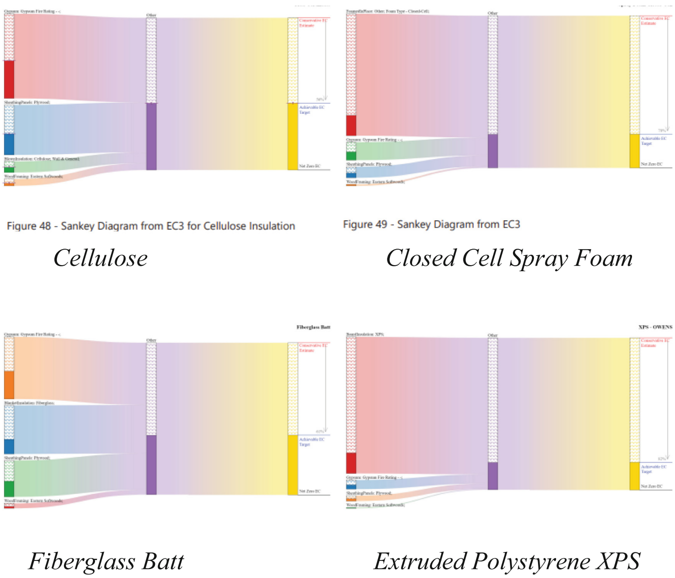


Fig. 4. Sankey diagram from EC3

5 Conclusions

5.1 Conclusions

In this study, the carbon emissions and characteristics of a residential wall assembly are studied by modeling two different wall assemblies in Oklahoma's climate zone 3A. A side-by-side comparative study was performed for different types of building insulation materials, which provide a better understanding and design alternatives for this field of study. The results show that insulation materials have a significant influence on the carbon footprint and overall performance of the building. Among all the types of insulation materials discussed in this research, ICB (Insulative Cork Board) is the best performing one regarding both carbon absorption, lightweight density, and thermal capabilities. Using ICB will allow for carbon to be absorbed from the built environment and still perform thermally while being the most sustainable material. The only negative is that the market is available more in the European area, however the United States would be capable of growing the Cork Oak in a simulated climate! The one issue with the study that occurred during the duration of the research was the limitations of the LCA data programs. A lot of the innovative insulations have not sought-after certifications and therefore are not in any of the cradle-to-cradle databases. This was a limitation that I specifically found with Tally. Tally's database does not contain the capability to access new forms of data outside of the initial library, nor does it allow for any customization of the materials in the program in order to manipulate the library for the specific needs of innovative insulations. Upon the suggestion from Tally's program manager, I sought to utilize Simapro 9, which is a high-end carbon analysis program that had the capability to utilize the data points. The negative parts of the program are that it is very difficult to navigate and required much more information for data input than I was able to pull from the innovative insulation companies. It made sense after a while; however the program does not give a diagram or organized graphic that can represent the information in an easy-to-read format. This drove the decision to study the conventional insulations through tally and the innovative insulations through a qualitative study that can be seen under Sect. 4.2. This does prove that our studies in a more sustainable insulation have a lot more work to do but there are large steps that have already been taken towards the future of our built environment.

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The Effect of Wind Tower Design Parameters on Its Daylighting Performance in a Tropical Hot and Humid Climate

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Abstract. The use of daylight in buildings is known to have benefits in both reducing energy consumption and improving human comfort and health. Wind towers are traditional architectural components used for providing natural ventilation and cooling in hot and dry climatic zones. To investigate this architectural component's daylighting performance, an experiment was designed to evaluate different wind tower configurations under tropical hot and humid conditions. A generic room was modeled, and a total of 18 configurations, with varying wind tower design parameters such as height, length, and placement were tested. The modeled room with the wind tower configurations was also tested in three different orientations. Daylighting simulations were performed using ClimateStudio (Solemma LLC) to examine lighting parameters such as illuminance levels under CIE overcast sky conditions, and a modified spatial daylight autonomy (msDA). Weather data from Puerto Rico was used to run the simulations. The obtained performance data is examined using linear regression statistical analysis and the correlations between the tested parameters and the daylighting performance are described. Results showed that the wind tower design significantly impacts its daylighting performance. The height had the most significant effect and contributed to most of the variance in the observed daylighting metrics.

Keywords: Wind towers · Daylighting · Daylight metrics · ClimateStudio · Hot and humid climate

1 Introduction

The use of daylighting has been associated with benefits in terms of energy consumption, human health, visual comfort, and visual performance. Peak daylighting potential occurs at peak electric load times. Since lighting can be 20–40% of a building's electric loads, minimizing electric lighting use during peak cooling times can reduce the peak electric load of a building by nearly this amount [1]. Researchers have suggested that health is improved when we are immersed in the daily fluctuations of light and are visually connected to views and outdoor conditions [2]. Daylighting has been associated with improved mood, enhanced morale, lower fatigue, and reduced eye strain. Some researchers have also pointed out that daylight is necessary for optimal visual performance. In terms of relative intensity, sunlight provides the most consistent and fullest

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spectrum of colors for the human eye [3]. Daylight provides high illuminance and permits excellent color discrimination and color rendering. These two properties mean that daylight provides the condition for good vision [4].

The considerable energy consumption attributed to buildings and the increasing requirements for healthier and more comfortable indoor environmental quality has led researchers and designers to consider different natural ventilation and daylighting strategies. Wind towers, also called wind catchers, are architectural components traditionally used in hot and dry regions to capture fresh air from outside and direct it towards the interior spaces. For centuries, this building element was able to produce comfortable conditions in harsh climates without the need for machinery or energy consumption [5]. Although it is not its main function, this roof-mounted device has also been considered by some researchers as a potentially effective daylighting strategy [6–9].

If properly studied and designed, wind towers have the potential to function as both a natural ventilation and daylighting architectural solution. However, the existing research on this component is limited in its applicability within the practice of architectural design. New research is warranted to assess whether wind towers can be used simultaneously as an effective natural ventilation and daylighting strategy in tropical hot and humid climates. The purpose of this study is to further develop the understanding of wind towers by investigating the effect of wind tower design parameters on their daylighting performance.

2 Background

Geometric and design parameters that affect the natural ventilation performance of wind towers have been identified. The height, the cross-section (plan shape and area), the shape of the roof, the internal partitions, the amount and placement of openings, and the use of louvers, dampers, and diffusers are determinant design parameters relating to the wind tower [5, 10, 11]. Research into the effect of external building parameters is less developed. In this area, only the building roof and upstream objects have been investigated [10]. Research on wind tower daylighting performance is considerably less when compared to existing work regarding their cooling and natural ventilation effect. The following paragraph presents a review of the investigations conducted to assess wind tower daylighting performance.

A sensitivity analysis was conducted by Pratiwi et al. [6] on the daylighting performance of wind towers used in a generic isolated room based on three design parameters; the number of gratings (a type of vertical louvers), the "chimney" (by chimney it is understood the wind tower opening) height and its interior surface reflectance value [6]. This analysis was performed by observing the effect of the tested parameters on the Average Daylight Factor (ADF) using the Honeybee tool in Grasshopper. The statistical analysis showed that the three design variables have a significant impact on the daylighting performance of the tested wind towers, the "chimney" height being the most relevant. It was found that by increasing the "chimney" height and the interior reflectance the daylighting levels are increased as well. Increasing the number of gratings in the tower opening reduced the daylighting levels. Other daylighting studies focused on field study measurements of existing wind towers [7, 8]. Subsequent experiments were carried out by varying the internal reflectance values of the measured wind towers. Tests with higher reflectance values were found to be the best in distributing higher illuminance levels. An additional study evaluated wind tower daylighting performance and compared it with two other daylighting systems used in the traditional architecture of the United Arab Emirates [7]. On-site measurements and simulations using Radiance were used to compare the three daylighting systems. This study is limited to a comparison of the wind tower performance with two other traditional daylighting systems. Thus, the wind tower design parameters were not evaluated.

Apart from the studies mentioned above, no other research was found on the topic of wind tower daylighting performance. This highlights the need for additional research in this area. The available knowledge on wind tower performance is not enough for it to be effectively implemented as a passive design strategy for both natural ventilation and daylighting. Parameters that have been identified and studied for their effect on natural ventilation have yet to be studied in terms of daylighting performance. It could be hypothesized that wind tower parameters not only affect its daylighting behavior but might also create conflicting relationships to optimize for both passive design strategies, such as obtaining better daylighting at the expense of natural ventilation, or vice versa.

3 Methodology

This study investigates a proposed one-sided wind tower used to cross ventilate a generic room in Puerto Rico. An experiment was designed to assess the effect of the wind tower design parameters on their daylighting performance. The influence of the wind tower parameters is observed in their contribution to the modified spatial Daylight Autonomy (msDA) and the mean illuminance levels (lux) of each configuration. Regression statistical models are used to evaluate the correlation between the wind tower design parameters and the obtained daylighting metrics.

3.1 Configurations Geometry

As shown in Fig. 1, the design parameters assessed in this study are the wind tower height, length, and placement relative to a rectangular room. Three variations in height and length were tested in regular increments of four feet (8’-0”, 12’-0”, and 16’-0”). The height of the tower is being increased but the opening height remains fixed at three feet (3’-0”) in every configuration. A 24’-0” by 30’-0” by 12’-0” feet room in which the wind tower was placed was modeled. The wind towers were tested being placed centered on the short side of the room (placement option A), as well as on the long side of the room (placement option B). Since the wind tower is a natural ventilation device, the outlet windows were modeled as openings without glazing. The space in placement option A included two windows ten feet and nine inches wide (10’-9”) by five feet (5’-0”) high, and a window to wall ratio (WWR) of 37.3%. The space in placement option B included two windows thirteen feet and nine inches wide (13’-9”) by five feet (5’-0”) high, and a WWR of 38.1%. The images in Fig. 2 illustrate the dimensions of the modeled test room.

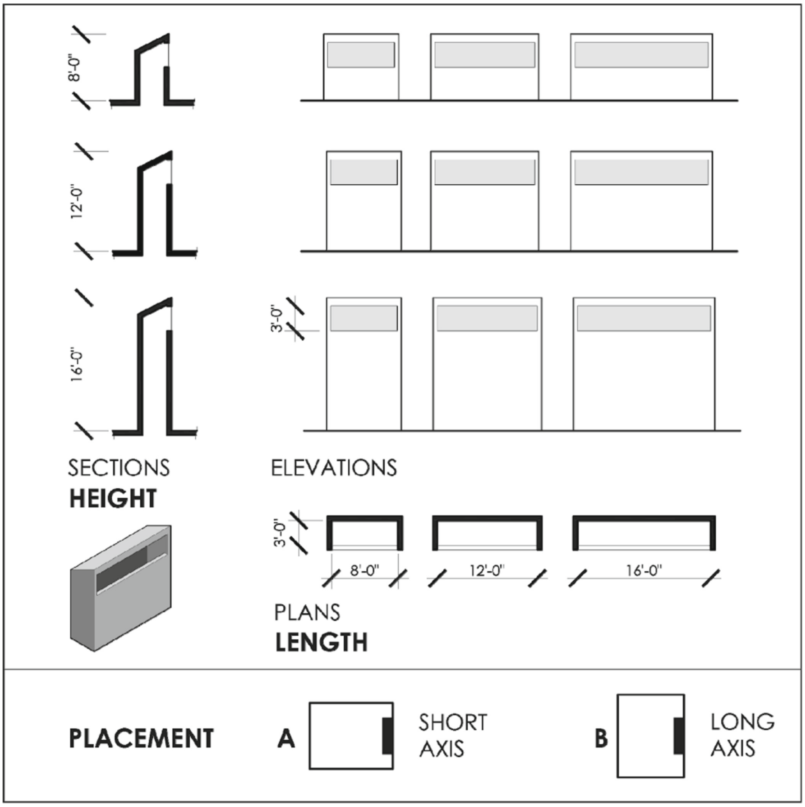

Fig. 1. Tested wind tower parameters

By combining the different variances in the wind tower design parameters, a total of 18 configurations were generated. The configurations were compared against two base models for each placement option without the wind tower. A conventional nomenclature was established to help identify each configuration. The configuration without the wind tower for placement option *A* was labeled **BASE MODEL-A**, and the model without the wind tower for placement option ***B*** was labeled **BASE MODEL-B**. Every model name contains the placement option of the wind tower (***A*** or ***B***), the height (***8H***, ***12H***, or ***16H***), and the length (***8L***, ***12L***, ***16L***). For example, model ***A-8H8L*** refers to the model with placement option A, with eight feet (8’-0”) high and eight feet (8’-0”) long wind tower. Figure 3 shows a matrix containing all the configurations and the base models with their respective names.

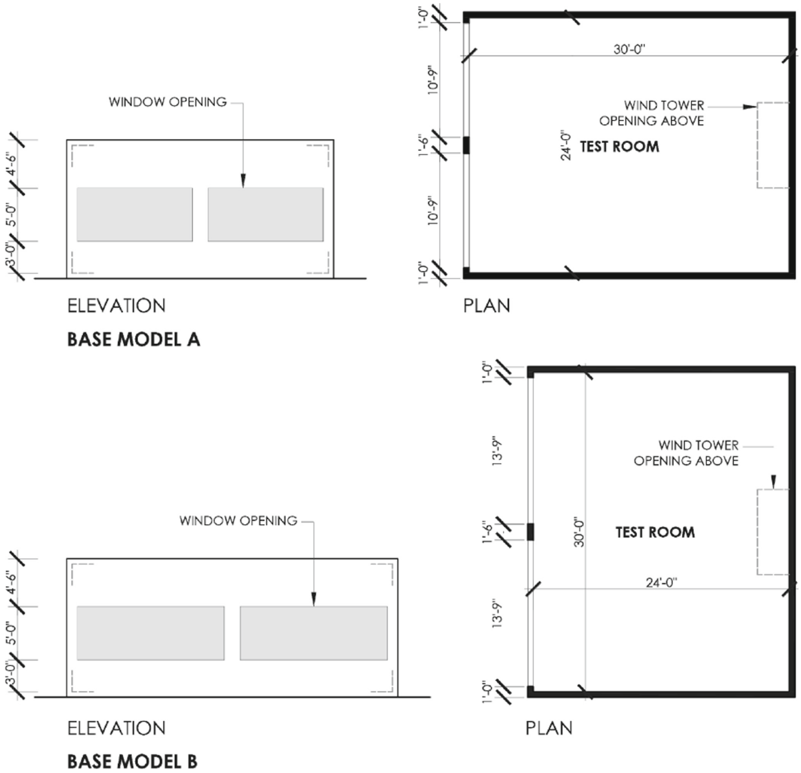

Fig. 2. Model test room dimensions

3.2 Daylighting Simulation

The daylighting simulations were conducted using ClimateStudio (SolemmaLLC) to evaluate a modified spatial Daylight Autonomy (msDA) and the illuminance levels on all room configurations. The conventional sDA metric used to confer LEED daylight credits is defined as the percentage of floor area where 300 lux is achieved for at least 50% of standard operating hours on an annual basis. Therefore, the ClimateStudio plugin for Rhino, through the Daylight Availability workflow, conducts a dynamic annual daylighting simulation from the input weather data with a Radiance-based engine to obtain the sDA value. The sDA metric in ClimateStudio was modified to reflect the floor area that achieves at least 300 lux for 99% of standard operating hours (8:00 am – 6:00 pm) on an annual basis, which represents an almost perfect daylight autonomy. For the msDA simulations, every configuration was tested at three different orientations. All configurations were simulated facing three orientations: N30°E, N60°E, and N90°E (see Fig. 4). These alignments respond to the prevailing wind directions of Puerto Rico. The variance in orientations also considers possible design limitations such as site geometry and orientation.

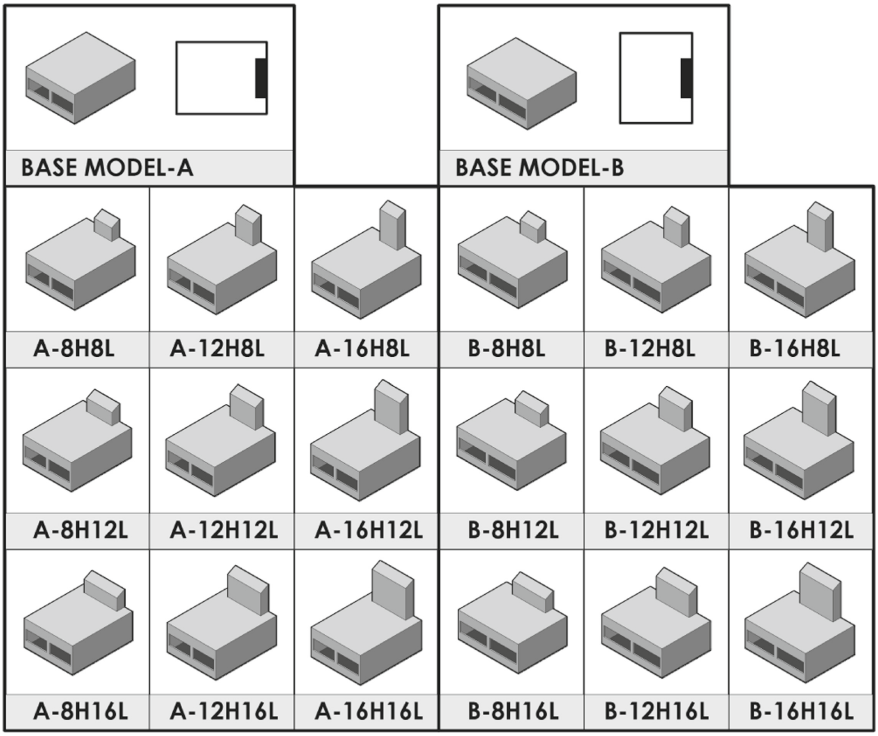

Fig. 3. Configuration matrix with model nomenclature

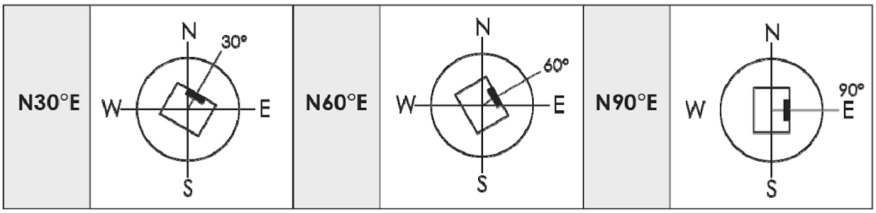

Fig. 4. Tested orientations for msDA simulations

The mean illuminance levels (lux) were evaluated under CIE Overcast Skies using ClimateStudio's Point in Time Illuminance workflow. The simulations were done at 12:00 pm on March 21. Overcast skies allow to evaluate the different configurations without considering the orientation and direct light entering the space due to the sun position under clear skies.

For both the msDA and illuminance level simulations the interior surface reflectance is 0.85 for ceiling, wind tower interior surfaces and roof, 0.6 for the walls; and 0.45 for the floor. The grid for the simulations consisted of 154 sensors spaced in 2 feet by 2 feet grid and at 2.5 feet height above floor level.

3.3 Data Analysis

To examine the obtained data a statistical analysis using linear regression was performed on an Excel sheet. The msDA percentage and the mean lux levels for each tested configuration were observed as dependent variables in the regression models. The model that considers the msDA value as the dependent variable uses height, length, and orientation as the independent variables. The wind tower placement options were considered in two separate regression models. The second set of regression models used the mean illuminance (lux) level as the dependent variable and only the height and length parameters as the independent variables. The influence of the parameters is observed in the Correlation Coefficient (CC), the R square, and the P-value of each correlation. The CC describes the strength of the relationship between the relative movements of two variables. It is a value between −1 and 1, whereas a value below 0 describes a negative correlation, and a value higher than 0 describes a positive correlation. A negative correlation refers describes a relationship where an increase in the independent variable causes a decrease in the dependent variable. In a positive correlation, an increase in the independent variable causes an increase in the dependent variable. The R square value represents the proportion of the variance in the dependent variable that is explained by the independent variable. The P-Value indicates the statistical significance of the results. The commonly used value of 0.05 is used as the threshold to determine statistical significance.

4 Results

The msDA results from the dynamic annual simulations under the three different orientations are shown in Figs. 5, 6, and 7. The results are shown in the percentage value of the msDA and floorplan view for every configuration, including the two base models. The floor plan view shows where the msDA achieving 300 lux during 99% of the operative hours on an annual basis was obtained. Figure 8 illustrates the mean lux levels obtained for every model. Although the illuminance levels were calculated for each data point within every configuration, the results are expressed as the mean value between the 154 data points. Each configuration is labeled according to the described nomenclature. The data shown in the graphs for the resulting msDA and mean illuminance levels were utilized to create the regression models.

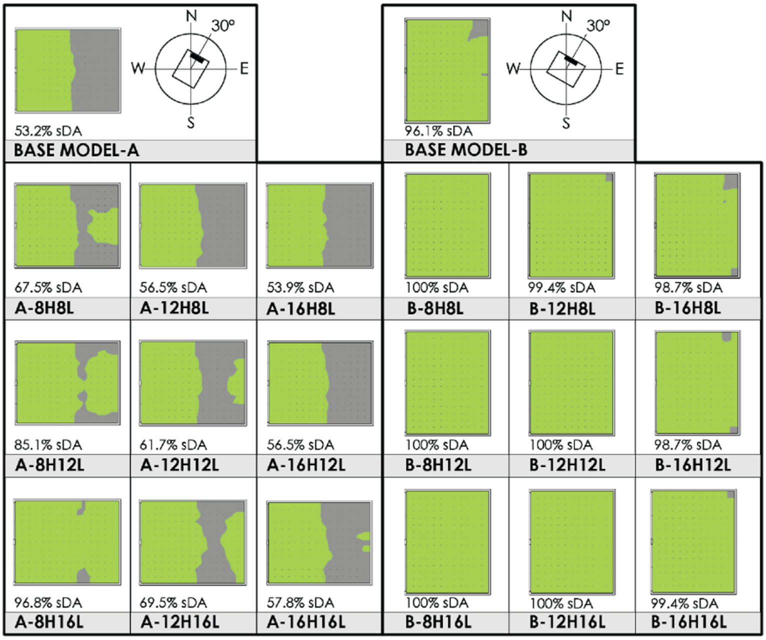

Fig. 5. msDA results for N30°E orientation. The green area shows msDA.

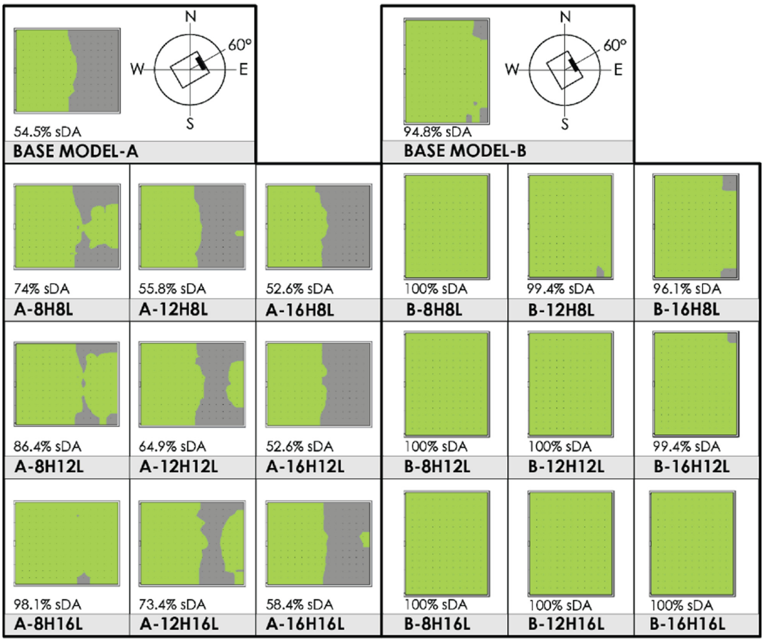

Fig. 6. msDA results for N60°E orientation. The green area shows the msDA.

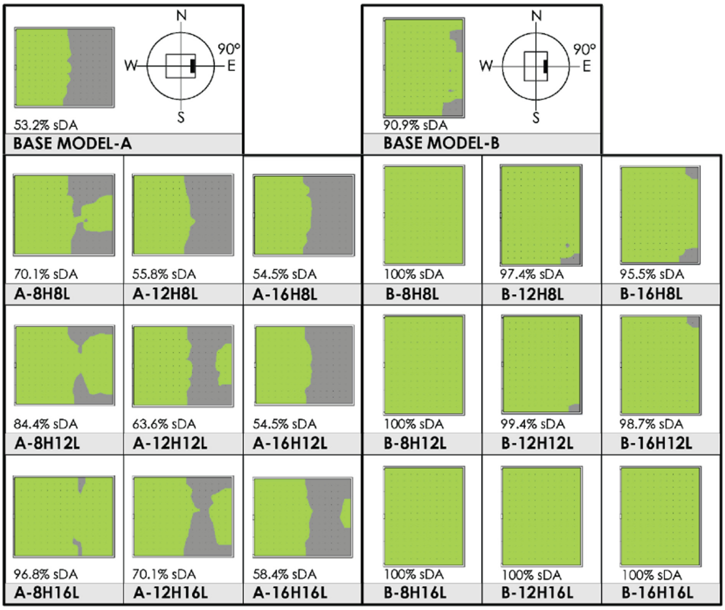

Fig. 7. msDA results for N90°E orientation. The green area shows the msDA.

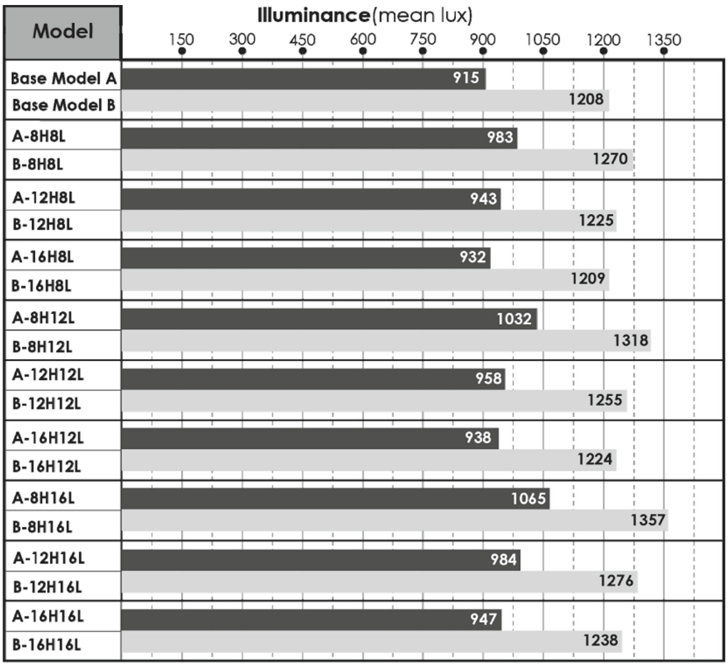

Fig. 8. Mean illuminance levels (lux) under CIE overcast skies

5 Discussion

The shorter and wider wind towers tend to provide higher percentages of msDA, meaning that they improve the distribution of acceptable daylighting levels throughout the whole room area. A trend in the data was observed whereby increasing the height of the wind tower led to decreasing msDA and mean lux levels. For example, in the models with placement option A, at a set wind tower length of 12 feet, an increase from 8 to 12 feet in height decreased the msDA by roughly 20% in all three orientations. The change from 12 to 16 feet height does not display a decrease as drastically, as only a 5–12% (across the different orientations) loss of msDA is observed across the different orientations. The length parameter follows a similar trend in reverse, as it appears that longer wind towers increase msDA. The models with placement option A with a 12 feet high wind tower display an increase of 5.2–9.1% msDA by increasing the length from 8 to 12 feet. Further increasing the length to 16 feet increases the msDA levels by 7.8–8.5%. The effect of the length appears more drastic in the shortest wind tower configurations, as increasing the length of the 8 feet high wind tower from 8 to 12 feet produces a 14.3–17.6% increase in msDA. This suggests that the height contributes the most to increasing or decreasing the daylighting performance of wind towers.

Table 1 Linear regression models output

sDA Linear Regression Models

A	CC	R^2	P-Value	B	CC	R^2	P-Value
Height	-0.827	0.683	1.08E-07	Height	-0.552	0.304	0.003
Length	0.441	0.194	0.021	Length	0.555	0.308	0.003
Orientation	0.009	8.50E-05	0.964	Orientation	-0.065	0.004	0.747

mean lux Linear Regression Models

A	CC	R^2	P-Value	B	CC	R^2	P-Value
Height	-0.828	0.686	0.006	Height	-0.819	0.671	0.007
Length	0.435	0.189	0.242	Length	0.499	0.249	0.171

The output from the linear regression models is shown in Table 1. In the models that consider the msDA as a dependent variable, the height parameter has a correlation coefficient (CC) of −0.827 and −0.552 for placement options A and B respectively. Therefore, the height parameter could be considered to have a strong correlation in models with placement option A, but only a moderate correlation in models with placement option B. The negative value of the CC describes a negative correlation, meaning that an increase in height produces a decrease in the msDA metric. The R square value indicates that the height parameter explains 68.3% of the variance in the msDA in the placement A configurations and 30.4% in the placement B configurations. The P-values for the height parameter are well below the commonly used 0.05 threshold, therefore these correlations are considered statistically significant. The length parameter displays notably lower CC values of 0.441 (placement option A) and 0.555 (placement option B), suggesting that this parameter has a moderate correlation with the msDA metric. These correlations are still statistically significant, with p-values of 0.021 and 0.003, although with a considerable decrease in significance in the case of the configurations with placement option A. The orientation of the models shows very weak and not statistically significant correlations, suggesting that their impact in a dynamic annual daylighting simulation is negligible in the tested positions. Orienting the wind tower opening within the tested range provides similar performance. The regression model using the median lux as the dependent variable shows a similar relationship with the height, with a notable difference in the P-value of the length parameter. In these regression models, the P-value of the length parameters indicates their relationship is not statistically significant.

There is a notable change in the CC and R values between Placement option A and option B in the msDA models. The shallower floor plan arrangement appears to mask the daylight distribution effect of the wind tower in terms of the msDA metric. These arrangements already had msDA levels above 90% in all orientations. The wind towers in the placement B options could only increase the msDA by no more than 5%−10% (depending on the orientation), as opposed to the A placement option, where the wind tower contributed as much as a 43.6% increase in msDA, in the case of the A-8H16L model. Therefore, wind towers do not make a considerable contribution to the msDA levels of the shallower floor plan arrangement. Nevertheless, the mean illuminance results (Fig. 8) show that even in an already well-lit floor plan configuration, the wind tower design parameters have a similar effect to those described for the placement option A configurations (in terms of illuminance levels), given that the shortest and longest wind towers provide the highest mean lux levels.

6 Conclusion

Wind towers are traditional passive cooling strategies used for natural ventilation that can also introduce useful daylighting levels in deep floor plans. The wind tower design parameters have a significant impact on their daylighting performance. The height parameter has the most significant contribution to the daylighting performance of the wind tower. Within the simulated tropical hot and humid climate, shorter and longer wind tower configurations improve the daylighting performance of wind towers. The analysis of the results suggests that studying wind towers in deeper floor plans allows for a better understanding of their contribution to the msDA metric. Analyzing both the msDA and mean illuminance levels in regression models provided a better understanding of the wind tower's daylighting contribution in the deep and shallow floor plan. Wind towers have a more significant daylighting contribution to deeper plan configurations. The findings from this work are limited to the tested conditions. More studies are needed to develop a more comprehensive understanding of wind towers as supplementary daylighting systems by including other parameters such as splayed-well sections, specular materials, multiple apertures, and louvers. Future work will assess the wind tower daylight performance by including additional daylighting metrics such as Annual Sunlight Exposure (ASE), Useful Daylight Illuminance (UDI), Daylight Glare Probability (DGP), and qualitative evaluations using HDR and false-color images. Parametric multi-objective optimization will be done to simultaneously assess the natural ventilation and daylighting performance of the wind tower design.

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Solar-Assisted Air Cleaning: Prospects and Potential Applications

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Abstract. Climate change presents numerous challenges to air quality in indoor and outdoor spaces. While the changing climate has brought poor air quality events—e.g., wildfires, heat waves—conventional air cleaning strategies can require significant costs in energy. Ironically, if this energy is supplied by non-renewable sources, the climate impact is worsened. Solar-assisted air cleaning is a possible solution. In one such scenario, updrafts created by incident solar radiation can be coupled with filtration systems to clean impacted air.

This presentation will review the potential applications for solar-assisted air cleaning, with particular focus placed on central updraft tower-type design, such as that employed at the Xi'an air cleaning tower. The feasibility and estimated performance of various designs will be presented.

Keywords: Air cleaning · Solar updraft tower · Solar thermal power · Pollution

Notation

α_a	Absorptance of absorbing PLATE in collector
A_c	Collector area
b	Beam air mass exponent, taken from [30] for a given location
C	Constant in collector heat loss formula, **Eq. 5**, as defined by Klein [32]
C_p	Constant pressure specific heat capacity
d	Diffuse air mass exponent, taken from [30] for a given location
ϵ_g	Thermal emissivity of collector glass
ϵ_p	Thermal emissivity of collector absorbing plate
f	Constant in collector heat loss formula, Eq. 5, as defined by Klein [32]
F'	Collector efficiency factor, calculated by **Eq. 6**
F_R	Collector removal factor
g	Gravitational acceleration constant
h	Planck's constant
H	Height of tower
$\overline{h}_c$	Convective heat transfer coefficient
I	Extraterrestrial solar irradiance
I_{bN}	Beam-normal irradiance
I_c	Irradiance received by the collector
I_{dh}	Diffuse horizontal irradiance

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m	Air mass
$\dot{m}_a$	Mass flow rate of air
Nu	Nusselt number
ν	Frequency of electromagnetic radiation
Pr	Prandtl number
Q_T	Rate of heat loss through the top of the collector
q_u	Rate of useful heat transfer
Re	Reynolds number
σ	Stefan-Boltzmann constant
T_a	Ambient temperature
T_{DB}	Dry-bulb temperature
T_{DTR}	Daily temperature range
$T_{f,in}$	Inlet air temperature
T_{MDB}	Maximum dry bulb temperature
T_p	Mean collector temperature
T_{RM}	Temperature range multiplier
τ_b	Beam optical depth
τ_d	Diffuse optical depth
U_c	Overall unit conductance from top of the collector to ambient air

1 Introduction

Climate change presents numerous challenges to air quality in indoor and outdoor spaces. Rising global average temperature can contribute to increased poor air quality events, such as wildfires or heat waves. Wildfire events carry a host of air quality implications; pollutants that can arise out of these events include particulate matter (PM, often quantified as particles with aerodynamic diameter smaller than 10 µm, PM_{10}, or 2.5 µm, $PM_{2.5}$), carbon monoxide, nitrogen oxides (including nitric oxide, NO), ozone, volatile organic compounds (VOCs), and polycyclic aromatic hydrocarbons (PAHs) [1–4]. Conventional air cleaning strategies, which include HVAC filtration and portable air cleaning devices, can require significant costs in energy. Ironically, if this energy is supplied by non-renewable sources, the climate impact is worsened.

Air pollution can also have major direct implications for human health [5]. A prime example has been witnessed in the period following the onset of the SARS-CoV-2 pandemic. According to an analysis by Aung and colleagues, a strong correlation exists between the incidence of ST-segment-elevation myocardial infarctions (STEMI) and the concentration PM2.5 [6]. In the natural experiment provided by the pandemic, we see that not only is increased $PM_{2.5}$ a risk factor for STEMI, but the inverse is also true: decreasing $PM_{2.5}$ in accompanied by a drop in the incidence of STEMI [6, 7]. While many Americans stayed home, industries slowed down, and cars, trucks, power plants, etc., generally burned a smaller quantity of fossil fuels, there were fewer heart attacks. Similar relationships between air pollution and human health can be found throughout scientific literature [8–10].

Solar-assisted air cleaning is a possible solution. Solar-assisted air cleaning involves the use of solar irradiation to activate a process whereby pollutants air are diluted, chemically reacted to yield less toxic products, or filtered from impacted air—that is, cleaning the air through ventilation, chemical oxidation, or filtration. In one such scenario, updrafts created by incident solar radiation can be coupled with filtration systems to clean impacted air. This study will review different solar-assisted air cleaning schemes, with particular focus placed on central updraft tower-type design. The feasibility and estimated performance of various designs will be presented.

2 Background

In this section, the various types of solar-assisted air cleaning schemes will be discussed. They are tabulated in Table 1. We begin by describing various concepts related to natural ventilation, continue with descriptions of designs involving photocatalytic oxidation (PCO), and conclude with a description of the solar updraft tower concept (also known as the "smog-free tower" [5]). Following this section, a case study evaluating the solar updraft tower concept is presented.

Table 1. Solar-assisted air cleaning schemes.

Air cleaning scheme	Mode of cleaning	Example
Natural ventilation	Ventilation (impacted air replaced with cleaner air)	Concordia University Eng. Building [11]
PCO	Oxidation of ambient pollutants	Milan Pavilion [12]
Solar updraft tower	Ventilation and/or filtration of impacted air	Xi'an tower [13]

2.1 Natural Ventilation

It can be argued that any wind current that provides natural ventilation to a building is due to solar energy, and so any application where wind-induced natural ventilation is employed could be deemed solar-assisted. We leave aside this category of natural ventilation and instead focus on those designs where solar thermal energy is directly harnessed—e.g., through fenestrations or solar collectors that directly heat indoor air—for the purpose of increasing natural ventilation.

Solar-assisted natural ventilation has been studied in a variety of applications for at least twenty years. Ding et al. proposed a system that utilized a chimney installed within an eight-story high-rise, which would not only provide natural ventilation, but also smoke control in the event of a fire [14]. Mouriki studied the natural ventilation performance of the Concordia University Engineering Building [11]. This system utilized a mixed ventilation mode assisted by a 15-story atrium that acted as a solar chimney. In general, when these types of systems are included in buildings, they require sufficient height to provide sufficient area to collect incident solar radiation and provide sufficient stack effect; they also tend to be coupled with one or more ventilation methods (e.g., fan assist) to account for intermittency of the solar resource.

2.2 Solar-Assisted Photocatalytic Oxidation (PCO)

PCO entails the use of a photocatalyst (e.g., zinc oxide, ZnO) that, under irradiation by photons of sufficient energy, catalyzes oxidation reactions on its surface [15]. A simple depiction of the process is shown in Fig. 1. Photocatalyzed oxidative materials have been used for indoor air cleaning, targeting bioaerosols, such as those carrying infectious virus particles, and VOCs; typically these air cleaning systems employ electrically powered light sources (e.g., UV-powered LEDs or bulbs) [16, 17]. But this study will focus on the potential for PCO air cleaning to use solar irradiation as the photon source. This can be accomplished for indoor air cleaning, with photocatalyst materials incorporated into a solar air heating system, for instance, or for outdoor air cleaning, with photocatalyst materials incorporated into building materials or coatings exposed to solar irradiation.

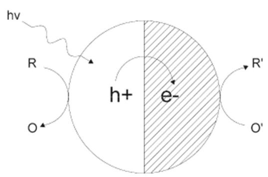


Fig. 1. Simple depiction of photocatalytic process on a semiconductor photocatalyst.

For indoor air cleaning applications, solar-assisted PCO has some potential, especially in light of the COVID-19 pandemic. Many common photocatalysts (e.g., ZnO, and titanium dioxide, TiO_2) possess a band gap greater than 3 eV, suggesting ultraviolet (UV) radiation is required to initiate the oxidation reactions that take place at active catalyst sites. In this case, an air cleaning system could entail a typical solar air heating system, where the absorber is made of photocatalyst. Many photocatalysts, while absorptive in the UV, are somewhat reflective in the visible spectral region. It should be noted, however, that many photocatalyst systems have been proposed that show activity in the visible region, as well [18]. For instance, Nakano et al. demonstrated the inactivation of different SARS-CoV-2 variants using a visible-light sensitive TiO_2-based photocatalyst [19].

In any case, when incorporating into a solar air heating system, the photocatalyst would likely need to be combined with a more visibly absorptive material. Concentrations recommended for building materials generally range from 1 to 5% [20], although an optimization is needed, balancing the needs for heat, air disinfection and/or VOCs reduction, and the costs permissible in materials (photocatalysts tend to be more expensive than typical absorber plate materials). A preferred design would have the absorber material be replaceable, or, if applied as a coating, have a coating that can be periodically reapplied—this would serve as a corrective action for catalyst fouling, and would extend the useful life of the air cleaning system. Moreover, substantial effort is required in design of the system: whereas solar collectors for indoor air heating (typically flat plate) are designed for optimal heating, solar utilization, and cost-effectiveness, additional considerations are introduced when adapting the system to air cleaning applications. For instance, the form factor of the system may be altered to increase mass transfer and/or oxidation rate, depending on a certain required minimum reduction in potential viral titer (based on known occupancy values and expected bioaerosol generation rates).

In the case of outdoor air cleaning, the photocatalyst can be incorporated into building materials and/or coatings—so-called "smog-eating buildings." For example, the Milan World's Fair Pavilion used TiO_2-concrete ("photocatalytic concrete) [12]. This strategy is most useful for nitrogen oxides (NO_x), though there is also the potential for reducing ambient levels of VOCs. An investigation by Lawrence Berkeley National Laboratory showed TiO_2 when used for this purpose had the potential to clean 100 m^3 of air per square meter per day (m^3/m^2-day) for NO_x pollution, and 60 m^3/m^2-day for VOCs pollution [20]. Importantly, it showed no efficacy for carbon monoxide (i.e., 0 m^3/m^2-day). These cleaning rates are fairly modest, especially when one considers the total volume of impacted air.

2.3 Solar Updraft Air-Cleaning Tower

The concept of an updraft tower for outdoor air cleaning was notably introduced by Pui and colleagues [21]. The concept on which it is based—that is, the solar chimney power plant—has been described in the literature since at least the 1970s, according to a study by Haaf et al. [22, 23]. Basically, the system consists of a large circular canopy, either glass or partially transparent synthetic film, that surrounds a central circular chimney. The canopy acts as a solar thermal collector and heats the air underneath; as the hot air rises through the chimney, it turns a turbine, generating power. Because the working fluid is ambient air, and heat losses from the collector and/or the ground can be significant, the overall efficiency of the systems are fairly low—approximately 0.2 to 2% [24]. The justification for the design is that the low efficiency can be compensated for by the relatively low cost of building materials and the straightforward operation of the system [22].

The idea to apply the solar chimney design to the problem of urban haze was first put forward by Cao et al. in 2015 [21]. The critical difference is the incorporation of filter banks in the path of heated air to allow filtration of $PM_{2.5}$; the turbine may be kept to generate power concurrently, although it is not necessary. Once the tower was installed in Xi'an, China, Cao et al. presented some preliminary performance data and numerical modeling, with included parametric analysis [25, 26]. A more recent proposal by Gong and colleagues involves an additional evaporative cooling system in an inverted U-type channel to allow air to be heated cooled (and potentially filtered) prior to returning to ground level [27]. The Xi'an tower is apparently the only installation of its kind currently operating for the purpose of cleaning outdoor air [5, 25, 26].

One weakness of this strategy is its dependence on appropriate filter selection and change-out frequency. The severity of the pollution dictates the level of adequate performance of the filter; an analysis by Stephens and colleagues shows that certain locations in China would require relatively high performance filters, with minimum efficiency reporting value (MERV) of 16 [28, 29]. Not only are these filters comparatively expensive, but they also tend to induce great pressure drop for equivalent filtration media velocities. In other words, we would expect lower clean air delivery rate (CADR) from a system using these filters.

The change-out frequency of the filters also poses a potential problem. For adequate filtration, filters must be replaced periodically, as particulate matter accumulates on the filter fibers. Generally, a used filter will exhibit somewhat improved single-pass efficiency, but substantially decreased air flow relative to newly installed filter. Changing out filters not only entails additional expense—cost of filters, cost of labor, etc.—but it also represents a potential source of pollution: the manufacturing of the filters will have some industrial footprint, as will the transportation of the filters to the end-use location, to say nothing of the disposal of the used filters.

3 Case Study: Xi'an Air Cleaning Tower

3.1 Model Development

In order to model the performance of the tower, it was necessary to specify ambient design temperatures and incident solar irradiance for Xi'an, China. The ambient temperature was specified using the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) fraction of daily temperature range data [30].

$$T_{DB}(t) = T_{MDB} - T_{DTR} \cdot T_{RM} \tag{1}$$

here, T_{DB} represents the dry bulb temperature, T_{MDB} represents the maximum dry-bulb temperature, T_{DTR} is the daily temperature range, and T_{RM} is the temperature range multiplier (taken from Table 6, p. 14.11 of [30]). Further, for the solar irradiance in the region, this study uses the ASHRAE Clear Sky Model [30].

$$I_{bN} = Ie^{-\tau_b m^b} \tag{2}$$

$$I_{dh} = Ie^{-\tau_d m^d} \tag{3}$$

here, I_{bN}, I_{dh}, and I are the terrestrial beam-normal, terrestrial diffuse horizontal, and extraterrestrial irradiance, respectively, τ_b and τ_d are the beam and diffuse optical depths, respectively, m is the air mass, and b and d are the beam and diffuse air mass exponents. It should be noted that the Clear Sky Model makes no predictions regarding adverse weather events, such as cloud cover or rain. Hence, the estimates obtained here will represent an upper limit to the expected performance of the air cleaning tower. Both the design temperature and clear sky solar irradiance are shown in Fig. 2.

This analysis models the canopy of the air cleaning tower as a flat plate collector. In fact, the actual installation had a slight tilt angle on the four sides of the square canopy (see, for instance, Cao et al. [26]), but the impact of this simplification is negligible, owing to the symmetric nature of the insolation about solar noon. The irradiance of interest would be I_c, or the useful irradiance received by the canopy. Shows this predicted clear

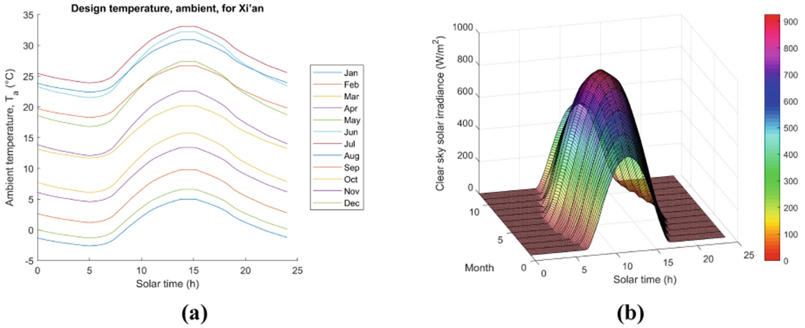


Fig. 2. Design temperature (a) and clear sky solar irradiance (b) for Xi'an, China.

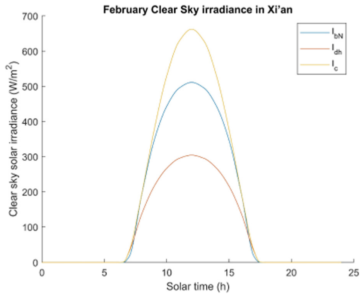


Fig. 3. Beam-normal irradiance, I_{bN}, diffuse horizontal irradiance, I_{dh}, and collector irradiance, I_c, for Xi'an in February, as predicted by the Clear Sky Model.

sky irradiance value, as well as that for beam-normal and diffuse horizontal irradiance, for Xi'an in the month of February (Fig. 3).

It is further assumed that the canopy is single-layer glass, the ground surface acts as an insulator, and that ambient air density is approximately constant. When approaching the canopy as a flat plate collector, one can employ the well-known Hottel Whillier Bliss equation to calculate the useful energy gain, given the heat removal factor and the collector heat loss due to radiation and convection from the top surface [31].

$$q_u = A_c F_R[\tau_c \alpha_a I_c - U_c(T_{f,in} - T_a)] \tag{4}$$

the collector top losses, U_c, can be estimated for multiple glass covers using the analysis of Klein [32]; here, assume just one glass cover, yielding the following equation.

$$Q_T = \frac{T_p - T_a}{\frac{C}{T_p}\left[\frac{T_p - T_a}{1+f}\right]^{-0.33}} + \frac{\sigma(T_p^4 - T_a^4)}{\frac{1}{0.95\epsilon_p + 0.05} + \frac{1+f}{\epsilon_g} - 1} \tag{5}$$

The air collector removal factor, F_R, can be calculated with the following equations [31].

$$F' = \frac{\overline{h}_c}{\overline{h}_c + U_c} \tag{6}$$

$$F_R = \frac{\dot{m}_a C_p}{U_c A_c}\left[1 - e^{-\frac{F' U_c A_c}{\dot{m}_a C_p}}\right] \tag{7}$$

It is also assumed that the inside surfaces of the canopy and ground are smooth, so the following equation can be used for the Nusselt number [31].

$$\mathrm{Nu} = \frac{0.0192\mathrm{Re}^{\frac{3}{4}}\mathrm{Pr}}{1 + 1.22\mathrm{Re}^{-\frac{1}{8}}(\mathrm{Pr} - 2)} \tag{8}$$

The average velocity of air rising in the chimney is determined with the following equation [33].

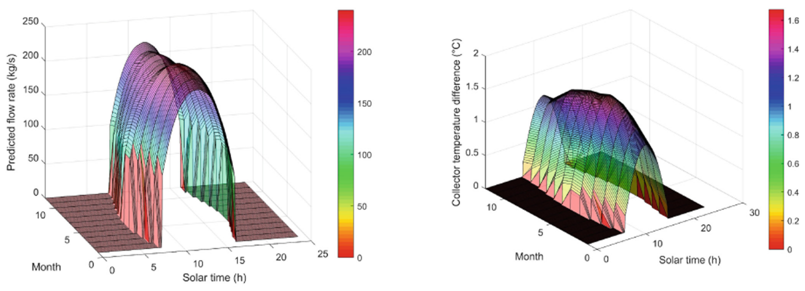
$$v_c = \sqrt{2\frac{\frac{\rho g H \Delta T}{T_a} - \Delta p_{losses}}{\rho}} \tag{9}$$

The transport properties of air were taken from REFPROP, developed by NIST [34]. The general computation strategy for this model is as follows.

1. Assume a mass flow rate of air through the tower
2. Solve for exit temperature of the collector section
3. Check validity of assumed mass flow rate

3.2 Results

To begin, the air cleaning tower was modeled without any pressure drop owing to filters. In this case, one can see that the average flow is 79 kg/s, or roughly 6 × 10^6 m^3/day. The temperature difference in the collector is very small, approximately 1.5 °C as a maximum, and the collector efficiency is very low. The predicted flow rate and collector temperature difference over one year are shown in Fig. 4.



(a) **(b)**

Fig. 4. Predicted flow rate (a), in kg/s, and collector temperature difference (b), in °C, for the *no filtration* case

Next, filters are included, and the attendant pressure drop, in the model. This would be reflective of the actual air cleaning system. It is important to note that no estimate is made of the effect of filter aging, whereby the pressure drop will likely increase over time with a concomitant drop in velocity and cleaned air flow rate. The predicted flow rate and collector temperature difference over one year are shown in Fig. 5. In this case, with filters included, one sees an average flow rate 9.2 kg/s, only 7×10^5 m^3/day. The efficiency of the system is still very low, but the collector temperature difference is slightly greater, owing to the greater residence time of the air in the collector zone.

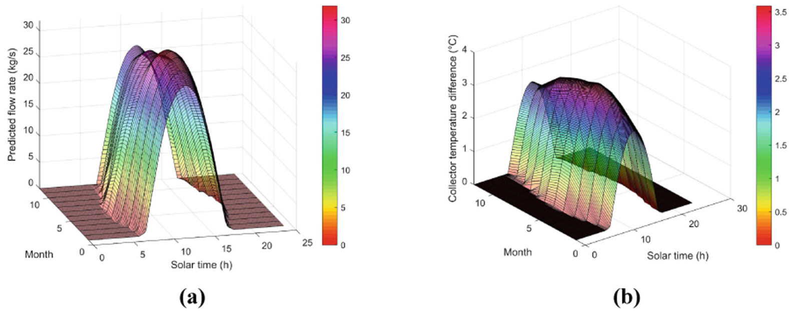


Fig. 5. Predicted flow rate (a), in kg/s, and collector temperature difference (b), in °C, for the *filtration* case

4 Conclusions

Solar-assisted air cleaning can be divided into three categories: 1) Natural ventilation of indoor air by thermal gradients caused by solar irradiance, 2) photocatalytic oxidation (PCO) activated by photons from solar irradiance, and 3) the solar updraft air cleaning tower. The first category, natural ventilation, only applies to indoor air. The second category, PCO, applies to either outdoor air, with photocatalysts incorporated into building materials or coatings (i.e., so-called "smog eating buildings"), or indoor air (e.g., with photocatalysts incorporated into a solar air heating collector). The final category, the solar air-cleaning tower, with which this study is primarily concerned, is specifically targeted toward cleaning outdoor air.

The analysis of the Xi'an solar air cleaning tower showed a potential for cleaning approximately 7×10^5 m^3/day of air, on average. However, the system showed very low overall efficiency. When comparing to solar chimney power plant designs, we can see some potential modifications for improved performance. Mullet described four different power plants; they all had chimney heights of 200 m or greater; they also had canopy diameters greater than the chimney height, in one case has much as ten times greater [24]. It can be seen directly from Eq. 9 that both the chimney height, H, and the collector area (which would increase the temperature increase, ΔT) will increase overall airflow as they increase. It seems the Xi'an tower suffers from its relatively small dimensions—a much wider canopy, especially if combined with a taller tower, would greatly increase the potential volume of treated air. Of course, being deployed in an urban area, where available real estate may be scarce, may render this impractical. It may be worthwhile to pursue a strategy of air cleaning towers on the periphery of an urban area for this reason.

Acknowledgements. This study was prompted by a webinar held April 10, 2021, *Emerging Trends and New Technologies on Indoor Air Purification (IAP)*, and the author gratefully acknowledges the support of the co-participants and organizers of that webinar, including Academy of Scientists for Industrial Research and Education (ASIRE), Panjab University, Indian Council of Medical Research (ICMR)- Centre of Innovation in Bio-Design, Chandigarh (India), and Molekule, Inc.

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Solar Thermal Heating of Existing Buildings

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Keywords: Passive solar · Solar thermal heating · Affordable solar heating for homeowners · Consumer absorption of passive solar retrofit · Bubble collector · Solar bubble

1 Introduction

Fifty Years of passive solar experience has resulted in my novel solar product patented in 2021, called **Universal Solar Thermal Cladding System.** When mounted on a sunny wall or roof it captures and circulates the heated air inside the building, enabling the building to substantially heat itself.

2 Materials and Methods

The Universal Solar Cladding System uses lightweight but structurally strong aluminum tubing that forms a framework mounted on the south, southeast and/or southwest sides of buildings. This framework supports two layers of 6 mil translucent polyethylene film that clips firmly into place against the building. A significantly more expensive clear film, ETFE is available. The film layers are then inflated using a low-wattage blower creating a tension structure. The resulting solar bubble collects thermal energy. The heated air is circulated into the buildings via windows, doors, or existing ductwork, often with the use of fans or blowers.

3 Results

ERDA, DOE and AIA awards and grants were received by my passive solar company in the 1970s. Passive solar was becoming popular until the 1985 demise of the Solar Tax Credit 1.0. www.solarroom.com - YouTube.

A. K. Ghosh and C. Rixham (Eds.): ASES SOLAR 2022, SPE, pp. 223–229, 2022.
https://doi.org/10.1007/978-3-031-08786-8_24

J. Douglas Balcomb, LANL's Solar Group Leader, was the DOE manager of our passive work. His 1992 book, Passive Solar Buildings, is the national survey. The engineering test data we generated and provided to Dr. Balcomb is still relevant. (Attachments Balcomb; Rogers).

(Fact Sheet below is the summary of the results of the DOE grants).

4 Discussion and Conclusions

Economic Justice vs Solar Availability: Affordability was a key requirement when developing our Universal Solar Thermal Cladding System. This "Solar Bubble" collector is made of high-tech, light weight, low-cost materials and is easily installed. The Bubble smiles at 80 mph winds. (Attachment Sears, Harr).

Challenges to passive solar adoption:

The first challenge is financial. I have had conversations with venture capitalists starting at the DOE's Venture Capitalist Conference in 1980. I was asked, "How do you monetize passive?" I was told, "Passive is Passé." Of course, DOE follows the money. Since the 1985 demise of Solar Tax Credits passive solar has survived only in up-scale home construction. Venture Capital tended to support Photovoltaics early on and later very expensive and ambitious Carbon Capture projects and Concentrating Solar Thermal power towers. All fine and good, but not a solution for the million of homeowners requiring an affordable carbon replacement option, or the millions of large warehouses and big box stores that could reduce carbon heating in cold seasons.

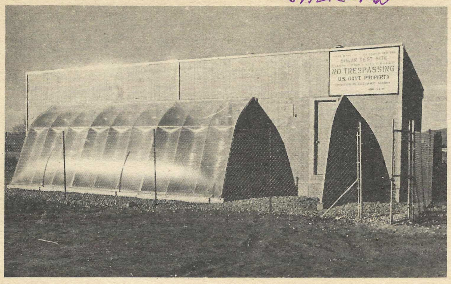
The second challenge is aesthetic: "Solar Bubbles" installed on homes and commercial buildings may not appeal to owners, but their heating effectiveness will.

Necessity Drives Invention: Today carbon replacement is an exponentially growing necessity. According to our and our patent attorney's research, ours is the only "Models and Tools" for the low-cost (passive) solar heating of homes and commercial buildings. (Passivesolarcladding.com – YouTube).

Appendix

Balcomb, Douglas

BALCOMB



SOLAR TEST SITE — The Solar Room test module is located near Ranchos de Taos on land donated by Kit Carson Electric Cooperative. Kit Carson also supplied the electrical power and meters for the solar test.

The Taos News

Thursday, December 29, 1977

Story and photos by Merilee Dannemann

Solar greenhouse tested

If you believe that a greenhouse solar heater will save energy and cut your heating bill, soon you'll be able to prove it.

The Solar Room Company of Ranchos de Taos is conducting a research project that will measure the effectiveness of Solar Room prefabricated greenhouses all through this winter season.

After about two weeks of operation, early results showed the greenhouse is way ahead in energy saving.

The project, which is federally funded and partly sponsored by Kit Carson Electric Cooperative, may be the first in the nation to monitor solar greenhouse performance in so scientific a manner. Los Alamos solar researcher Dr. J. Douglas Balcomb called it "one of the most significant passive research and development projects in the country."

Balcomb, who is official project monitor for the U.S. Energy Research and Development Administration, made his first inspection visit Dec. 15.

The experimental building, located near Ranchos, was built during the fall and started operation in late November.

It consists of four rooms of equal size, lined up next to each other. Each room has the same amount of exposure on the north and south sides. Unused storage rooms were built at both ends, so the two end rooms do not have more outdoor exposure than the others. Ordinary frame construction was used, except that double insulation was placed between each pair of rooms so they do not interfere with each other.

One room is the control, with no solar heater. A Solar Room greenhouse is stretched across the south side of the other three rooms.

One of those three is empty, with no heat storage. The second uses water storage, with water stored in quart jars under the floor. The last uses concrete slabs to simulate a massive concrete floor.

All four rooms have thermostats set to the same temperature. An electric heater turns itself on if the room temperature falls below a certain point. If the room gets too hot, a vent opens and an exhaust fan turns itself on — these actions simulate people in the house who would open a window if they were uncomfortable.

The electricity used for each room is recorded on a separate electric meter. The meter readings show exactly how much energy is used to maintain a constant temperature in each room.

After two weeks, the meters showed that the control unit required almost three times as much electricity as the solar heated room with water storage. When the meters were read Dec. 15, the control unit had used 164 kilowatt hours, the water-storage unit had used only 66 kwh. The solar unit without storage was in between at 97 kwh, and the concrete-block unit was close to it at 96 kwh.

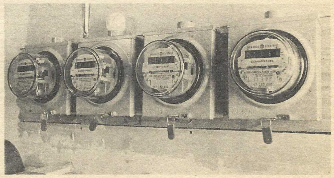
Solar Room Company president Stephen Kenin said he had expected the concrete-block unit to do better. He said he believed the problem was freshly poured and still curing — it is expected to hold heat better once it is thoroughly dried.

Dr. Benjamin T. Rogers of Rinconada, design engineer for the project, explained how heat storage helps the heat to be used more effectively.

The Solar Room is like a clear plastic bubble. If no windows or doors are open, it becomes quite hot in the daytime, just as a parked car becomes hot.

If a window or door into the house is kept open, the solar heat will warm the house in the daytime, but it could become too warm, depending on the size of the house. If it is too warm, the family will have to open a window to stay comfortable. Thus, part of the heat will escape to the outdoors and be wasted. But as soon as the sun goes down, the house will start to cool off. Heat from another source will be needed at night.

But if the hot air from the Solar Room flows past a storage medium, such as rock or water, some of the heat will be absorbed into the storage. When the air reaches the living space, it will be cooler because the storage has taken the heat. When the living space becomes cool at night, heat will radiate out of the storage, thus saving energy at night.



RESULTS — A row of electric meters tells the story of power consumption in the four test rooms.

Benjamin T. Rogers

WHAT IS A GREENHOUSE SOLAR HEATER? — A SIMPLIFIED ENGINEERING APPROACH

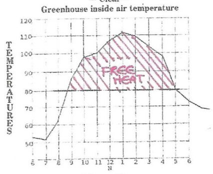
by Benjamin T. Rogers

What is a solar greenhouse? After all, in a sense, any greenhouse is a solar greenhouse. So, just what is a "solar" greenhouse? In this page we will try to explain, in non-technical language as far as possible, the Solar Room concept of a solar greenhouse and how it works.

The Solar Room is manufactured in the mountain country of northern New Mexico. The area characteristically sees more than 6,000 heating degree days each year. For comparison, the ASHRAE tables give Chicago 5,882 (city data); Anchorage, Alaska 10,864; San Francisco 3,001; and Dallas 2,363. But the heating load is only part of the story. For a solar greenhouse to handle the heating load there must be a balance between the solar energy that it accepts and the heat that it loses to the cold outside environment. So, like any solar heating system, the Solar Room system is location specific. A conventional greenhouse will accept a lot of sun energy through the south facing glazing, a little through the east and west glazing, and very little through the north glazing. So in a sense, it has one collecting area, two partially effective collecting areas, and one big loss area (the north side). The Solar Room system, applied to the south side of an existing structure, avoids the large north side losses and, being linear in configuration, maximizes the south collection area and minimizes the end effects. It also serves to insulate the south wall of the structure.

We will now take a simplified analytical look at a solar greenhouse. When the sun is shining, high temperatures will be experienced in the greenhouse. However, after sundown experience has shown that, in our climate, the Solar Room will maintain a temperature about 30° F. above the outside air temperature. A typical temperature record for 11/20/76 is reproduced. This is the inside air temperature with no heat being taken from the greenhouse. The mass of material such as soil, plants, water tubs, etc., within the space was typical of a simple home greenhouse.

SATURDAY, NOVEMBER 20, 1976
— Clear —
Greenhouse inside air temperature



Time — Hours
Overnight low ~ +20° F.
Max. Daytime Temp. ~ +56° F.
Located 36° 13' 12.4" North Latitude

In this case, if we had started to remove heat by circulating it into the house to which it is attached and continued until 5 p.m., and done it in a manner so as to hold the greenhouse temperature at 80° F., we would have maintained the difference between the greenhouse and the outside air temperature at very close to 30° F., during the entire 24-hour period (i.e. Delta T = 30° F.).

Now we will show the performance of one square foot of Solar Room glazing that looks out in various directions and estimate the gains and losses in each case. This is an approximation to illustrate the principles; the elegant method involves a large computer and a bunch of hour-by-hour weather tapes.

Heat loss/sq. ft. of glazing per day = Q_L

U factor of double glazing = 0.65 BTU/hr., sq. ft., deg. F

Thus:

$$Q_L = U \times \text{Delta } T \times \text{hrs/day}$$
$$= 0.65 \times 30 \times 24$$
$$= 468 \text{ BTU/day loss/sq. ft.}$$

We now tabulate the gains vs. the loss:

Direction	South	East	West	Roof
Gain BTU's	1437	454	454	772
(Loss) BTU's	(468)	(468)	(468)	(468)
Net	969	(14)	(14)	304

And our 30-foot long Solar Room would behave something like this:

South:	8 ft. x 30 ft. x 969 BTU's ...	232,560 BTU's PER DAY
East:	50 sq. ft. x (14) BTU's	(700)
West:	50 sq. ft. x (14) BTU's	(700)
Roof:	3 ft. x 30 ft. x 304 BTU's ...	27,360
	NET GAIN	258,520 BTU's per day

One of the reasons that a direct gain system such as the Solar Room is attractive involves its inherent efficiency. The efficiency of a typical flat plate solar collector drops off rapidly as the operating temperature rises, and high temperatures are frequently required to get usable heat to the point of utilization. The Solar Room operates at comparatively low temperature, and the heat is used at, or very near to, the point of collection. In one sense, the Solar Room is a solar collector that you get to live in.

Perhaps this little exercise has given you a better insight into how the Solar Room operates. We have kept the arithmetic simple and the results are very rough, clear day approximations.

We welcome requests for information. The more detailed the requests, the more detailed and technical our response will be.

Benjamin T. Rogers, engineer, was employed by Los Alamos Scientific Laboratories for 25 years. Recently retired, he is now consultant-engineer for LASA labs solar division, the Solar Room Company, and others. He is a director of the New Mexico Solar Energy Association.

Feeny, Robert S. Sears, Roebuck and Co.

SEARS, ROEBUCK AND CO.

ROBERT S. FEENY Store Manager

September 10, 1984

Mr Steve Kenin
Solar Resources, Inc
P O Box 1848
Taos, New Mexico 87571

Dear Steve,

Since I've had my "Solar Room" for three years, I thought it was time that I reported my complete satisfaction.

My wife and I are very happy since:

1. It has reduced winter heating bills by 60% (paid for itself the first year).
2. It has become a year-round hobby area (greenhouse). We have flowers all year.
3. It has added 312 sq ft of living area to our house.
4. It is delightful to be able to go out in December and sit in 80 degree temperature, when it is 25 degrees a few feet away.

The possibilities are as limited as the buyer's imagination, I can see it as a child's nursery, a hot tub enclosure, or just an area to read and/or relax.

My screen (for summer) is in excellent shape after three seasons. I am having to replace the plastic (also used three seasons) because icicles over the past three years, have punched many holes in the top and tape will no longer keep it air tight. The plastic has, otherwise, not deteriorated.

My Solar Room has been one of my best investments.

A very satisfied customer,

R. S. Feeny

RSF:dp

130 LINCOLN AVENUE SANTA FE, NM 505/983-6321

Harr, Kelvin S

July 16, 1982

HARR

Mr. Steve Kenin
Solar Resources
P. O. Box 1848
Taos, New Mexico 87571

Dear Mr. Kenin:

My two solar rooms have exceeded all expectations. They survived 80 mile an hour winds that blew down trees on my property. One unit keeps my two car garage shop useable all winter and the second unit provides significant heat input for the house. Last winter my heating bills were half that of anyone else in the neighborhood. I estimate my dollar savings to be in excess of $400 for the year.

I plan to relocate one of my solar rooms this fall to enclose a patio and hot tub. I expect no problems in moving the unit and am looking forward to a winter of hot tubbing. Also, tomatoes from the greenhouse have become a tradition for Christmas dinner.

Sincerely,

Kelvin S. Harr

Kelvin S. Harr
Senior Research Engineer
Golden Colorado

KH:sk

GOLDEN JUL 16 '82 COLO.

Solar Energy Research Institute
1617 Cole Boulevard
Golden, Colorado 80401

Mr. Steve Kenin
Solar Resources
P. O. Box 1848
Taos, New Mexico 87571

SERI
A Division of Midwest Research Institute

Fact Sheet

Fact Sheet

BUILDINGS GENERATE 40% of CO_2. Heating is a significant percentage

Solar Bubbles initiate a new solar category:

Solar Thermal Retrofit

"If you haven't installed Solar Bubbles by 2030, 'YOU HAVEN'T LOOKED UP'."SRK

Universal Solar Thermal Cladding, or "Bubble Collectors" for short, introduce a novel passive approach: SOLAR THERMAL RETROFIT
Bubble Collectors are constructed of hi-tech, lightweight materials, inexpensive and strong. Bubble Collectors are designed to heat existing buildings. Mounted on sunny walls or roofs they capture the solar radiation and circulate the heated air inside. Think **"Solar Tinker Toys."** Bubble Collector Kits come ready to assemble and fit on your cabin, castle or big box store.

Bubble Collector Structure & Configurations
A double layered membrane of clear ETFE glazing film or translucent Polyethylene film is stretched over a tubular aluminum structure configured to sunny wall or roof area(s). The membranes are then sealed at the building and inflated. The membranes become TENSION STRUCTURE BUBBLES.

This Solar Bubble Collector, 8'x30' = 240ft.^{2} was *DOE TESTED 11/20/76*
The following data is available from Buck Rogers, PE
232,560 BTU/day produced
969 BTU/1ft.^{2}/day
170 lbs. total weight of structure and polyethylene glazing
$600 direct costs
Utility Patent 2017, Universal Solar Thermal Retrofit:
PV space heating costs **10X** more than solar thermal space heating, significant percentage.

Bubble Collector marketing is based on teaching passive solar to young activists.
Many of Greta Thunberg's "Blah, Blah, Blah" kids, thousands of smart, environmental activists, including debtor students, would accept "green work" that teaches "replacing CO_2 heating with solar heating." Each kid would be providing an important fraction of the gigatons of CO_2 removal necessary before **2030**. Solar Thermal sales can provide significant carbon footprint reductions. Solar Thermal systems must become ubiquitous by 2030.

Clean Transportation

EV Expos and Enterprise Charging in Northern New Mexico

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Abstract. In Northern New Mexico a milestone is quietly being reached. There will soon be nearly 75 electric vehicle (EV) charging stations deployed and operational. These have been installed by various organizations to serve both the local and visitor populations at no cost. The source selection, installation, monitoring, maintenance and management of the EV chargers is described, along with analysis of the trends of charging sessions and energy use. Renewable Taos is working with the local utility to expand the enterprise and ensure the enterprise is fully operational and available.

Keywords: Electric vehicles · Enterprise charging · Source selection · Siting criteria · Operational experience

1 Northern New Mexico and the Enchanted Circle

Comprising the north-central third of the state, New Mexico's Enchanted Circle is considered the crown jewel of the state. Scenic roadways connect (clockwise) the communities of Taos, Village of Taos Ski Valley, Questa, Red River, Eagle Nest and Angel Fire, most being resort towns with heavy dependence on a tourism economy. There are four ski areas in the region, but the heaviest visitor traffic is in the summer months. Other than tourism, the main enterprise is agriculture. The area is mainly served by the Kit Carson Electric Cooperative (KCEC), with some contribution by two other rural electric cooperatives. It is important to provide EV charging facilities in this region for both business (tourism) and to a lesser extent, the local population. Some 80% of local EV owners are said to charge at home, at night [1], while tourists all rely on public charging facilities. It is this public aspect of EV charging that is the focus of this paper. Other applications, such as at fleet charging, theaters, shopping centers and multi-family complexes are not considered in this review, though still important.

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2 EV Chargers – Review of Three Levels

A quick review of the three levels of Electric Vehicle Support Equipment (EVSE), commonly called "EV chargers," is shown in Table 1. While most vehicles can use a standard J-1772 plug, others, such as Tesla have a proprietary connector and use an simple connector-end adapter to interface the car to the J-1772 cable. For highest speed charging (Level 3), Tesla has the Supercharger network, and for other EVs the CCS connector standard seems to be winning the popularity contest over the CHAdeMO connector standard [2].

Table 1. Types (Levels) of Electric Vehicle Charging Support Equipment (EVSE).

Level	Power source	Charge rate	Connector
1	Standard 120 V outlet, works with every EV, home or work	40 miles overnight 4 miles per hour	Standard 3-prong household AC plug
2	240 V source, up to 60 amps, "destination" or home/business, often free or low cost	25–40 miles of range per hour of charging	Hardwired or use a dryer/range/RV receptacle
3	480 V 3-phase power, public or fleet only, pay to charge	"DC Fast Charge" 0–80% in 30 min	Hardwired only

Other than a few home installations by early adopters, KCEC deployed the first EVSE in Taos. Some eight or so of KCEC chargers are directly wired into the behind-the-meter side of small photovoltaic (PV) solar arrays owned or providing power to KCEC. These locations included the KTAOS radio station, University of New Mexico Taos Campus, the Taos soccer/Eco Park, and at KCEC's main office. These are all Level-2 EVSE; both J-1772 and Tesla products. All are free to use, and most of the energy consumed is directly generated from these PV arrays. None of these initial deployments were centrally-located to downtown Taos, however.

3 The Taos Electric Vehicle Expos

Beginning in 2018, Renewable Taos, a 501c3 organization, began hosting educational EV Expos. There have now been three showcasing EVs and other modes of electric transportation including e-bicycles, e-motorcycles, and even electrified ATVs. All Expos also included a Speaker Program that has proved to be a popular forum for attendees to hear first-hand from EV owners on their experiences as well as related topics on energy efficiency, solar/wind/battery, transmission, and progress being made by the local utility. The first EV Expo included a ribbon-cutting ceremony for the first centrally-located EVSE in Taos, just a block from the central town plaza, adjacent to a large town park and the Taos Community Auditorium (TCA). Attendance has grown each year, with the latest EV Expo in 2021 drawing about 35 vehicles and 250 people. The EV Expos have been held in conjunction with National Drive Electric Week, sponsored by Plug-In-America, the Sierra Club, and other organizations. The EV Expos have been very popular and will continue in the foreseeable future.

4 EVSE Source Selection for Monitoring, Maintenance, Management

For enterprise operations, there are several important features: remote monitoring of status and usage, maintenance of units that have been damaged or had a failure and management for rate setting and other functions. Much of this is facilitated by the ability to have an internet connection to the EVSE, either via WiFi or hardwired Ethernet.

Because the Enchanted Circle and thus the extended service area is large, nearly 4,000 square miles, it is important to be able to get push notifications of equipment status via both SMS and email. For example, if the unit is off-line or reporting a fault condition, it can be determined immediately and a repair person dispatched. Other important status includes:

- Vehicle plugged in, vehicle has unplugged
- Vehicle charging start and end time
- Vehicle charge rate (amps)
- Charging delayed due to Time of Use (ToU) rates
- Energy consumption during charge
- Energy consumption cumulative per EVSE
- EVSE supply voltage, amperage, power and temperature
- Unit is offline, unit is back online
- Vehicle is not plugged in by a settable time of day

Useful EVSE management features include:

- Set charge current limit
- Set charge kilowatt-hour (kWh) limit
- Setting cost of charge by kWh, duration of charging
- Scheduling of charging by Time of Use and minimal state of charge (SOC)

- User/driver charge status and start/stop notifications via smart phone app
- User/driver charge session history and costs

These features are generally included in enterprise monitoring and management software packages, and licensed on a per-unit basis [3].

Although Renewable Taos presently monitors (and officially maintains) only five chargers at the Taos Community Auditorium and the Taos Public Library, there have been occasions to help maintain EVSE at other locations when failures occur. These repairs have been minimal. In two instances, cold temperatures has likely resulted in the breakage of the hook end of a J-1772 locking lever. Cold temperatures have also likely been the cause of broken plastic connector holsters. Some early products have had minor issues with the charge cable pulling out of the strain relief at the connector end. One other failure was traced to an improper crimp in a connector on a wire when installed by a contractor. However, these minor maintenance issues are only detectable by visual examination, not by monitoring via a network connection.

There have been instances when a unit is reported to be off-line (not reporting via WiFi) but not actually experiencing a problem. In these cases, the WiFi router was off-line and needed to be power cycled. While technically not an issue with the EVSE, it nonetheless required manual intervention. A method of automatically rebooting the WiFi router is suggested for remote sites. There are low-cost devices available that cycle power outlets at a set time on a daily basis, for example.

5 Siting Criteria

Certain siting criteria for EVSE are often overlooked. Because the focus of this paper is on Level 2, or "destination" chargers, locations where EVs are usually parked for one to four hours are highlighted. These locations include libraries, ski resorts, restaurant complexes, and central business areas. It is important to have restroom facilities and food/beverage access. This is often overlooked.

Installation is generally simple, with a 240 V circuit needed that can supply a 40 amp load. Additionally, an internet connection is needed for the product to reach back to central monitoring. This can be by hardwired ethernet or WiFi.

Of course, 24/7 accessibility is important, and at least two locations around the Enchanted Circle do not meet this criterion. Efforts are underway to relocate five chargers to more user-friendly locations.

Some hotels and small business centers are considering installing their own chargers, useful for overnight stays, and if you fancy a coffee and snack after shopping at the hardware store. In this instance, even an hour-long charge from a Level 2 EVSE will likely get you back home and would probably be free.

6 Taos Community Auditorium EVSE Operational Experience

The TCA chargers have been monitored for use since they were first installed in a Town of Taos parking lot adjacent to Kit Carson Park and the Taos Community Auditorium. There are three EnelX JuiceBox Pro40 chargers here, provided by Renewable Taos, Inc. There is no cost to use them, but a nearby sign suggests a donation of $3.00 per hour for the support of renewable energy initiatives in the region. Renewable Taos pays the electric bill for the users. Through March 2022, the cost of electricity has totaled nearly $7,000 for over 35 MWh of energy. This energy has propelled EVs an estimated 120,000 miles at roughly 300 W-hours per mile [4].

Months of operation:	33
Total Energy:	~ 35 million watt-hours (MWh)
Total Cost of Energy:	~ $7,000 including fuel adjustment, system charge, taxes
Cost of Energy only:	~ $3,900 exclusive of fuel adjustment, system charge, tax
Cost of Energy per mile:	~ $0.033 per EV mile
Cost of gasoline per mile:	~ $0.12 at $3.00/gallon and 25 miles per gallon

Figure 1 below shows the number of sessions and kWh per month since initial commissioning in September 2019. Some interesting points can be made. The effect of the COVID-19 pandemic can be clearly seen for March and April 2020 and onward. Charging sessions were essentially zero for that April, then it took a while to recover. Peak monthly sessions occurred in August of 2021 when summer tourism traffic peaks. Two months later, the energy consumption peaked at nearly 2.6 MWh. In the winter months, there are fewer charging sessions because downtown tourism is less; it is thought that more charging is now occurring at Taos Ski Valley.

The kWh per charging session has remained somewhat stable at an average of 13.9 kWh/session, peaking at 19.4 kWh/session for the month of June 2021. This is perhaps because of events in Taos such as festivals and more tourists staying in nearby hotels. Some cars park at these locations overnight.

7 Taos Ski Valley EVSE Operational Experience

There are now 16 EnelX JuiceBox Level 2 chargers in the parking lot at Taos Ski Valley. Monitoring of these units, most of which were only recently installed, began in late March, 2022. The chargers have been quite popular. They consist of three different models, providing charge rates of 32, 40 and 75 amps. Summary operational data is listed below.

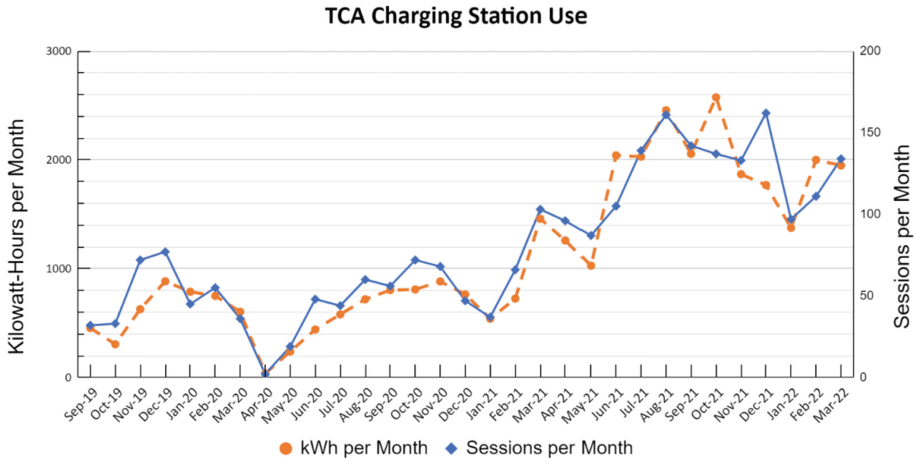

Fig. 1. Taos Community Auditorium EV charging station history since initial deployment and commissioning. The impact of the COVID-19 pandemic is clearly shown in early 2020.

Start date:	3/26/2022	
End date:	4/9/2022	
No. days:	15	
No. sessions:	268	Greater than 300 watt-hours (approx. one mile)
Total time:	541.5 hours	Total hours EVs being actively charged
Total energy:	4,047 kWh	Total kilowatt-hours used to charge EVs
Energy/session:	15.10 kWh	Kilowatt-hours per EV charging session
Duration/session:	2.02 hours	Time each EV charged, on average
Wh/mile:	300	Energy per EV mile (estimate)
Total EV miles:	13,490	Total miles (est.) provided by total EV charging
$/kWh:	$0.1107	Kit Carson Electric Cooperative commercial rate
$/session:	$1.67	Cost to Taos Ski Valley per EV session
Energy cost	$448	Not incl. fuel adjustment, system charge and taxes

8 EV Charging Across the Enchanted Circle

Across the Enchanted Circle and beyond to other rural communities such as Abiquiu and El Rito, the network of chargers is expanding. Within 12 months, it is anticipated that 75 or more chargers will be installed and operational. The table below lists the current deployment and planned installations (Table 2).

Table 2. Distribution of EVSE in North-Central New Mexico.

Enchanted circle, KCEC and others			
Qty	Town	Location	Connector type/Status
2	Angel Fire	Angel Fire Resort	DCFC with CCS/CHAdeMO, in planning
2	Abiquiu	Bode's General Store	DCFC with CCS/CHAdeMO
2	Eagle Nest	Village Hall	J-1772
2	El Rito	Northern NM College campus	J-1772
2	Ojo Caliente	Oliver's Store	J-1772
2	Peñasco	Sugar Nymph's Bistro	J-1772
2	Questa	Visitor Center/Library	J-1772
2	Red River	Convention Center	J-1772
3	Taos	Taos Community Auditorium (TCA)	J-1772
2	Taos	Taos Public Library	J-1773
2	Taos	Kit Carson Electric Co-op	One J-1772 and one Tesla
2	Taos	PPC Solar, Inc	One Tesla, one J-1772, public
2	Taos	Taos Eco Park	Tesla, limited access hours
3	Taos	KTAOS parking lot	Two Tesla, one J-1772, limited hours
2	Taos	UNM-Taos campus	J-1772 installed but not powered
3	Taos	Taos Mesa Brewing	Tesla and J-1772, closed until mid-2022
2	Taos	Central location TBD	DCFC with CCS/CHAdeMO, in planning
16	Taos Ski Valley	Parking Lot	J-1772
2	Taos Ski Valley	Blake Hotel	J-1772
5	TBD	On hand/storage	J-1772, location TBD
12	TBD	On order (KCEC)	J-1772
72	**TOTAL**		

9 Electric Rate Considerations for EV Charging

Much is available on the topic of Time-Of-Use rates, so this will not be an exhaustive analysis. KCEC, the local electric cooperative, as of this writing is nearing completion of an additional 22.5 MW of utility-scale PV solar with 32.5 MWh of battery storage located near the Taos Airport and in Angel Fire. This will be more than sufficient to meet the peak summer daytime load of about 40 MW. Because there is generally no need for summer air conditioning at this region's high elevation (Taos is at 7,000 feet), KCEC's peak load occurs in the early morning and evening hours of wintertime. Of course, battery storage will be used to smooth out the curve when demand is higher than generation, but because of the over-generation, this presents the opportunity for the utility to create a rate favorable to EV charging, instead of purposely derating or curtailing the output of some PV arrays.

A special Time of Use (ToU) rate could be enacted specifically for EV charging. This would likely require a separate meter at each location just for that purpose, instead of utility control of the EVSE directly, though this is a possibility. This is because as home, business and fleet charging proliferates, it would be difficult to standardize on the EVSE purchased by these entities, so it could become an integration nightmare. Simplifying to a utility-standard meter, with remote readout and even control, mitigates this issue. Other utilities across the US have incentivized home owners and businesses to use one particular brand of EVSE, however, so this remains an option.

KCEC has a ToU Rate Class (17) currently in effect [5], but it was last modified in 2016, before the popularity and necessity of electric vehicles was realized. This Rate was designed for applications such as electric thermal storage, electric baseboard heat, and electric water heating for individual residences and apartments. Under this Rate Class, a reduced cost of electricity is offered "off-peak" from 1:00pm to 4:00pm and from 9:00pm to 6:00am. To coincide with daytime peak solar generation, and in the event of over-generation potentially causing curtailment, a new Rate Class is being considered.

10 Conclusion

Renewable Taos supports the continued expansion of publicly-available EVSE across the Enchanted Circle, and will be working with Kit Carson Electric Cooperative to integrate monitoring, management and maintenance into their operational processes. As electric vehicles proliferate, and KCEC reaches or exceeds 100% daytime solar, Renewable Taos supports the development of a Rate Class favorable to members for electric vehicle charging.

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Strategy for the Assessment and Characterization of the Supply of Solar Power for Electric Vehicles in Residential Settings: Four Texas Cities

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Abstract. Electric Vehicles in the United States are predicted to reach parity with Internal Combustion Engine vehicles by 2035 which will require 200 TWh annually to meet their charging demand. To meet this demand without requiring the development of new fossil fuel power plants, roof mounted solar panels should be used where possible. This study presents a methodology for cities to assess local solar potential that is less resource intensive than comparable studies. Four cities in Texas were chosen for analysis with special attention paid to location, seasonality, and housing type. This study indicated that with modern technology and conventional usage, there was sufficient energy to meet demand in all four cities with only one exception. Additionally, location and housing type were significant indicators of a home's ability to meet electric vehicle energy demand.

Keywords: Electric vehicle · Solar analysis · Municipal analysis

1 Introduction

Increasingly, policy makers are interested in addressing the major components of climate change. Across all levels of government, various pro-environmental actions are being considered and businesses are following suit [1]. Currently, 29% of US carbon emissions come from the transportation sector [2], however, Electric Vehicles (EVs) charged with renewable energy offer a solution.

Yet implementation of a national electric fleet poses significant challenges, among others, the production of the necessary energy. US EVs are projected to reach 50% penetration by 2035 [3] and require as much as 200 TWh annually. To avoid building more fossil fuel power plants, at home solar should be utilized where possible. However, determining these locations can be costly and time consuming. As the transition to electric vehicles scales up, a low-resource tool that can be implemented across the nation will be needed to guide action, and examples will be needed to learn from.

Previous research has devoted considerable resources to the development of an accurate methodology to assess the potential for power generation from building mounted PVs in cities. Geographic Information Systems (GIS) form the foundation of many of

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these studies [4–9]. However, additional tools are needed. In some cases, GIS models such as r.sun are used to assess a location [8], but this tool can require more data than is readily available. Other times Lidar can be implemented to determine building characteristics [4, 7, 8]. While in many cases Lidar information is detailed and publicly available, it is not comprehensive for the entire nation with the same level of resolution making results variable based on data quality. Lastly, image recognition is a common practice where AI tools are trained to spot building shapes and occasionally roof features [6, 9]. This methodology has seen improvements; however, it requires high computing power to assess at the relevant scale.

All these methodologies produce valuable results but are resource intense requiring some combination of too much time, money, computational capacity, or training. This prevents these analyses from being conducted outside of very large cities, research institutions, or consultancies. As a result, policymakers in small and mid-sized municipalities may be ill-informed during the policy process. In this study I provide a methodology with low computational requirements that delivers specific information on locational solar potential. It uses publicly available GIS shapefiles to reduce the need to generate data and applies techniques to keep file size down. Using QGIS for analysis, it can be replicated across the country and by cities of varying sizes. The analysis can be conducted quickly to match the needs of the policy process. Additionally, it offers the ability to focus on specific building types. In this paper I present this methodology in addition to the results found when assessing and characterizing the solar potential in four Texas cities with respect to location, season, and housing type.

2 Data Selection and Methodology

Central to this methodology is the data powering it. I leveraged trusted publicly available data to maximize homogeneity across national implementations.

2.1 Data Gathering and Background

Microsoft's 2018 Building Footprint Project [10] forms the foundation of the analysis with comprehensive data on every building in the U.S. Since then, this project has grown to include other regions of the world and continues to grow. Microsoft used its own AI tool for determining building shapes and locations and was validated to be more effective than human drawn footprints. Every building in the US was captured and categorized by state and is available for download as a shapefile. These files are large so efforts to focus on the necessary region should be made (discussed in 2.2).

To determine the distribution of solar radiation I used the National Solar Radiation Database [11] (NSRDB) from the National Renewable Energy Laboratory (NREL). I used Direct Normal Irradiance (DNI) average values for each month as random weather events need not be included in macro-policy. Additionally, weather variation is probabilistically captured with monthly averages. These data are available in a raster format with a resolution of four kilometers. DNI, was measured in Watts per square meter and had to be multiplied by 24 h to get daily energy values.

Also available at the national level is vehicle miles traveled daily (calculated for each census tract) through the US Bureau of Transportation Statistics [12]. This was used to determine regional driving energy demand assuming no change in behavior from ICE to EVs.

Nationally, census tract demographics and shapefiles are available to define the regions of interest and to find tract population data. I used the American Community Survey information from 2017 to align with driving data and building data [13].

Lastly, zoning information was retrieved from municipalities to characterize buildings [14–21]. This attribute added to building footprint information allowing me to remove non-residential buildings and focus on housing. It was also used as the basis for neighborhood-type analysis allowing me to differentiate between Single Family (SF) and Multi Family (MF) homes. Single Family homes are defined differently by each city, but generally have medium to large lots with yards and space between one unit and the next. These are common in residential subdivisions and suburbs. Multi Family homes is a more diverse category ranging from duplex homes to high rise apartments.

After adding sufficient attributes to the building layer, calculations may be performed outside of QGIS.

2.2 QGIS Data Manipulation

Each data set from above is stored as a layer in QGIS. If not controlled for, these data will create a file too large for conventional computers to process quickly. To reduce the file size from these national sources to the area of interest, I used filtering and clipping. The steps outlined below are listed in no particular order but are grouped by parallel tasks.

DNI Vectorization. The only raster file is the direct normal irradiance layer from the NREL. I converted this to a shapefile that could be added as an attribute to the building footprint layer through two steps. I performed this for all 12 monthly average DNI values to characterize the solar potential throughout the year.

First, I used the Vector creation algorithm, Raster Pixels to Points. This algorithm creates a point feature in the center of every raster pixel with an attribute for that pixel's DNI value. Next, I converted this point to a polygon by adding a buffer half the radius of each pixel (2033 m). Adding Square corners will create a continuous surface with no gaps that can be used for joining later.

Reprojection. Each layer must be reprojected using the Reproject Layer algorithm, so they are in the same workspace. In my analyses I used EPSG 26914 for the Texas region, which also allowed analysis to be conducted in meters, the same unit as DNI.

Filtering. First, the filtering tool must be used on the city zoning layer to select residential buildings. The definitions of zoning codes that are common in zoning shapefiles can be found in city ordinances or on city planning websites.

Second, it is helpful to filter the census tracts to only those that overlay the area of study. In the case of smaller cities this can be done easily but with large metros the selection tool is helpful to visually select the tracts that overlay the city rather than manually inputting the GeoID – the identifier for census tracts. After selection, use the filtering tool to filter to selected census tracts.

Clipping. The building footprint layer is the largest layer and first to be clipped using the filtered city zoning layer as the overlay to define the city borders and find residential buildings. Next, the monthly DNI layers were clipped from its national coverage to the focus area. In some cases – in the exploration phase of the project – it may be helpful to keep the clip larger than the target area, in which case shapefiles for towns and cities may be beneficial clipping layers.

Joining. It is best to join attributes to the building footprints layer since this analysis was focused on buildings themselves. Use of the Vector algorithm, Join Attributes by Location with building footprints as the base layer and progressively add attributes. The geometric predicates were within and intersects to avoid dropping buildings on boundaries.

In the case of costal, cities like Corpus Christi, the DNI resolution may mean buildings exist outside of the DNI layers. Buildings closest to the jagged coast were not completely overlapped with solar radiation data, so I used the NN Join plugin to assign the DNI value nearest to that building. This is appropriate in areas where DNI does not vary significantly from pixel to pixel.

Adding Area Attribute. The final step is to add area attributes to the buildings. This is used to determine potential solar PV coverage as a scaling factor for DNI on residential units. Use the Add geometry attributes algorithm.

2.3 Methodological Assumptions

To advance the goal of producing a methodology with low implementation costs, assumptions may be made around power reductions that arise from imperfect energy generation. The first limitation on energy production is solar panel efficiency. The efficiency of panels has been rapidly rising [23] and is expected to continue to grow. Modern panels have efficiency ratings as high as 23%. However, over the course of the panel lifetime, this rating will decline. The value is also affected by temperature conditions and inverter limitations. To control for this, I used an efficiency rate of 20% for the lifetime efficiency of modern panels.

The next limiting factor is roof utilization. The proportion of roof that gets panels mounted is affected by obstructions like chimneys or architectural features. To control for this limitation, I assumed only 30% of the roof area would be used for power generation. This is based on what is suitable for most residential buildings [9].

The last factor impacting energy output was left out of the methodology to avoid the complicated tendencies of this type of analysis. That is, the power reductions that arise from sub-optimal roof angles for direct mount solar panels – common in residential settings. I call this the roof-angle coefficient (RAC). The RAC varies with a number of individual housing characteristics like the degree of southness of the roof as well as the latitude of the building. A detailed discussion of this limitation can be found in [22]. Because of the challenges of determining this coefficient for every building studied, roofs were assumed to have a constant RAC of 0.85. That is, standard residential angled roofs produce 85% of the energy an optimally sloped roof would produce all else equal.

For energy utilization, the vehicle efficiency is relevant. I calculated electric vehicles had an efficiency of 4.1 miles per kWh based on battery size and range calculations from four top EVs available in 2021. This data can be found in Appendix 2. This value was used to determine energy demand.

3 Results and Discussion

Appendix 1 presents summary values on the four Texas cities studied: Austin, Corpus Christi, Dallas, El Paso. These cities were chosen because they represent a descriptive cross section of the state in terms of location, population, and housing. Austin and Dallas are both major metro areas with a high population density. They also fall within the 'Texas Triangle', the central region of Texas where the majority of the population lives. This region has relatively homogeneous DNI characteristics. Corpus Christi and El Paso are at the edges of the state, on the coast and western border respectively. They have much lower population density and have populations roughly one third and two thirds of Austin.

To compare city statistics, I used DNI values from the month of April. This month was chosen as the basis for comparison because it represents an average DNI level for the whole year, and does not exhibit variations due to seasonal weather characteristics that are unique to any one area. Unless specified otherwise, the presented power and energy values are for the month of April.

In multiple cases – wherever the term neighborhood is used – I aggregated the data upward to the census tract level. This was done because population and driving statistics were unavailable at the individual building level. Thus, in the case of neighborhood analyses, the characteristics are averaged for neighborhoods that include both SF and MF homes. To categorize a neighborhood, I used a proportion of SF homes in the tracts. In tracts where the proportion of SF homes was greater than 60% I called these SF neighborhoods. Where it was less than 40% I called these MF neighborhoods. And when the proportion of SF homes was in between, I called these Mixed neighborhoods.

3.1 Locational Variation

My initial analysis was conducted at the state level. Graphing the state level DNI with cities overlayed showed the distribution of population across the state. Figure 1 shows DNI values as a color scale. The data is from the month of April which shows relative relationships well. DNI levels rise as you travel north and west. The development of the color scale with colors determined by the natural breaks (Jenks breaks) shows this trend. Additionally, with cities overlayed it is easy to see that the regions with the highest DNI do not have the highest population.

El Paso is the best equipped to provide renewable energy for electric vehicles. In Dallas, Austin, and Corpus Christi, the DNI level is much lower and is similar across the cities despite each representing a different region of the state – North, Central, and South/Costal Bend respectively [appx. 1]. This distribution of solar potential follows expected patterns and aligns with weather characteristics. The areas of high DNI are aligned with high aridity and low precipitation. Since the DNI values are calculated as monthly averages, weather patterns are an important factor in determining output. That is, Corpus Christi has more rainy or cloudy days during April than El Paso. In fact, El Paso averages just two rainy days for April [24], increasing the DNI values. But for a better understanding of DNI within cities, I assessed potential with respect to season.

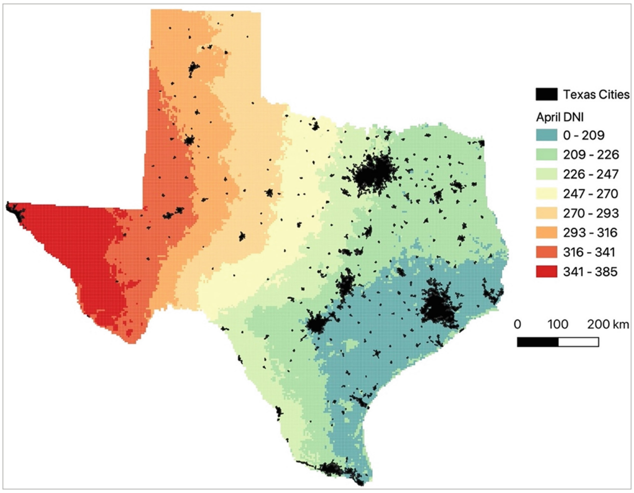

Fig. 1. Distribution of DNI and Cities across Texas

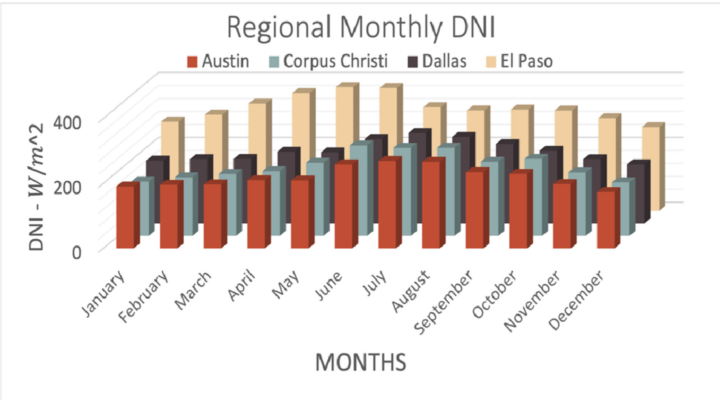

Fig. 2. Regional monthly DNI in four studied cities

3.2 Seasonal Variation

Time of year plays an important role in irradiation levels. The reduction in daylight hours and tilting of the earth causes winter to receive lower irradiation levels than summer months. On top of this, weather patterns tend to make the winter months cloudier than summer months. The month with the lowest DNI levels was consistently December, with an average of 39.5% less energy received than summer months. However, summer months did not show the same variation consistency across regions.

For Austin, Corpus Christi, and Dallas, the seasonality of solar performance followed an expected trend with maximums in either June or July. Figure 2 graphs the average DNI values for each city studied for all 12 months. El Paso is an outlier with a unique seasonal peak in May, and a significant DNI drop by July.

El Paso's odd summer pattern shows the importance of conducting solar analyses on many cities before policy decisions are made. The pattern is linked to the late summer rainy days that cloud the sky and reduce July, August, September, and October to the same DNI level as February.

Finally, the seasonal variability of DNI varies across the state. Austin and Dallas have lower variation throughout the year with ranges of 95 w/m^2 and 97 w/m^2 respectively [Appendix 3]. Corpus Christi showed a larger variation of 113 w/m^2 between months largely because of variation in weather patterns along the coast. El Paso had the highest monthly variation of 146 w/m^2 however, DNI variation is magnified by el Paso's large base values.

3.3 Ability to Meet Energy Demand

The locational and temporal variations are the foundation for characterizing solar. But the primary concern is whether the available energy is sufficient to power an electric vehicle fleet.

The Bureau of Transportation Statistics calculates daily driving averages at the tract level. Combining this with Census Bureau population characteristics, I found little variability between cities driving habits. Across the four cities, daily travel averaged 39 miles or 9.05 kWh per driving person. Given modern practical and technological limitations on energy production I found that in every case except for one, there was sufficient energy to meet driving demand from roof mounted solar panels.

Figure 3 shows the ability of residential charging stations to meet electricity demand throughout the year. This is based off average home size, population, and DNI values presented in Table 1. But the primary concern is whether the available energy is sufficient to power an electric vehicle fleet.

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Figure 3 shows the ability of residential charging stations to meet electricity demand throughout the year. This is based off average home size, population, and DNI values presented in Table 1.

Notably, at all times of year and in every city, energy demand is met, with the only exception being Austin in December. Austin and Dallas both barely meet demand during the winter but have excess energy during the summer. This means that the 30%

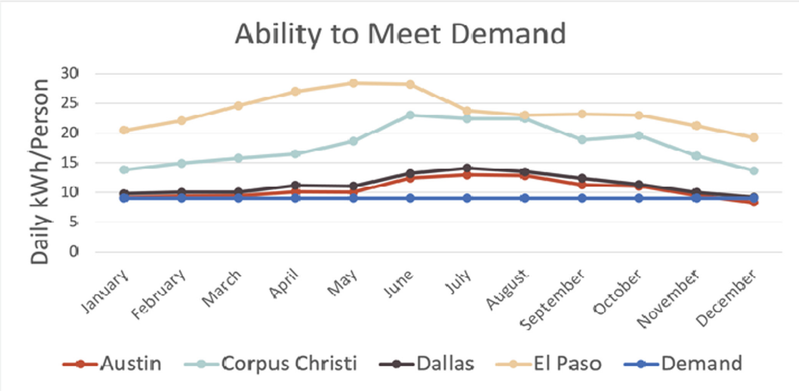

Fig. 3. Private charging station ability to meet demand through the year in Texas.

Table 1. Average building power characteristics by City

City	Avg building area	April DNI value	People per building
Austin	252 m^2	210	7.7
Corpus Christi	231 m^2	199	3.9
Dallas	295 m^2	221	9.3
El Paso	243 m^2	364	4.2

roof utilization rate assumed is the minimum roof coverage necessary to meet demand. But when electricity demand is higher during the summer months, these panels could provide extra energy to the grid or to meet personal electricity demands at home.

Corpus Christ follows the same seasonal trends as Austin and Dallas but is shifted upward due to lower population density. This difference makes Corpus Christi well equipped to meet its EV electricity demands. El Paso, like Corpus Christi, can meet electricity demands easily. In these two cities, moderate roof utilization is sufficient to meet EV needs and in summer may lead to lower energy bills as energy may be sold back to the grid.

Austin and Dallas have a much higher population per building due to the size of the MF residing population. Corpus Christi and El Paso have a higher percentage of SF buildings than Austin and Dallas. And where MF exists, it is still lower density than Austin or Dallas. The percentage of the population living in MF units is higher in Austin and Dallas than Corpus Christi and El Paso. As such, the available energy per person is lower, so the ability to meet demand is lower.

3.4 Housing Variation

Using zoning to classify buildings presents the opportunity to assess buildings by their housing type. While zoning codes have many classifications for housing, I simplified them to differentiate between Single and Multi Family buildings. The potential to produce energy from roof mounted PV panels is fundamentally limited by roof area. As such, potential energy per person and population are inversely related. Figure 4 shows the maximum potential energy per person organized by neighborhood housing type. SF homes have an average area of 241 m^2 and a per building population of 4.95 people. Conversely, MF buildings have an average area of 324 m^2 and a per building population of 17.73 people [appendix 4]. Neighborhoods with a mix of housing types have an average of 48% less potential power per person than SF neighborhoods. Similarly, MF neighborhoods average 55% the energy per person of SF neighborhoods.

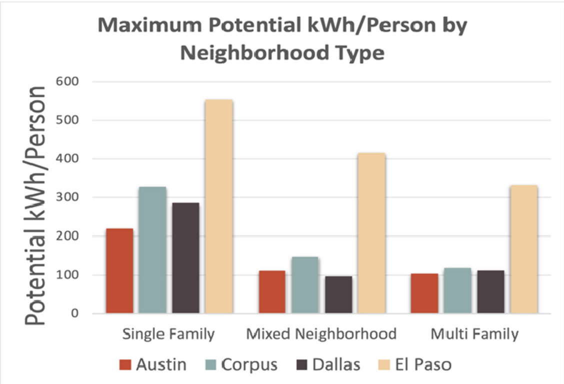

Fig. 4. Maximum potential kWh/person by neighborhood type

Building size and building population do not scale at the same rate since most additional population is added vertically. Roof area is relatively constant across all housing types, but building population is variable which leads to the variations in per person energy.

Fortunately, in urban settings, demand for energy is also less. People who live in urban areas are more likely to use alternative forms of transportation for daily travel than residents of Single Family homes, especially in suburban settings [12]. This difference in travel can result in as much as 2 kWh less electricity demanded daily. While 2 kWh represents a 22% reduction in energy use, it is not enough to offset the differences in energy production potential.

Since per person energy is the main concern for measuring a city's ability to meet EV electricity demand, special consideration in policy must be paid to these types of buildings to support their residents. As cities continue to experience growth, the relevance of supporting residents of MF buildings will increase.

4 Policy Implications

For informing policy decisions at all levels of government, this methodology has value. As I showed through the assessment of four cities, each area of analysis presented valuable insights. The power characteristics are poorly described by just one focus area, so this methodology should be used to detail a clear picture. The low implementation cost makes it possible to inform local policy with local characteristics.

As such, policies should be locationally specific. While insight can be gained from finding sister cities this analysis showed that even cities with shared characteristics like DNI values throughout the year, may have differences that will require unique policy.

Areas like El Paso should consider the high degree of variability alongside their high overall DNI levels, and areas like Corpus Christi should consider their high percentage of SF housing as they consider energy policy broadly.

Seasonality will also require consideration as policy makers consider what their goals are for roof utilization. For example, in Austin, there may be more need for public charging stations if it is not possible for widespread increases in per person output during the winter. Additionally, consideration of weather patterns should be a primary focus since electricity demand is independent of weather. That is, people still need to drive even if it is cloudy. In cases like these, storage and a diverse portfolio of generation options will be helpful.

Lastly, an intense focus should be paid to housing type. Housing type is a proxy for several cross-cutting demographic characteristics, so to implement equitable solutions, MF housing will need to be centered in policy decisions. For example, policy makers in Dallas could require that new constructions zoned as MF partner with SF zoned buildings to create a micro-grid to ensure all citizens have sufficient access to energy.

Implementing thoughtful policy will be an important step in advancing EV penetration and reducing climate risks.

5 Limitations

Ensuring this methodology is easy to implement for policy makers means there are limitations to the results. First, this methodology is highly dependent on the quality of input data, primarily zoning data, which has variable quality between cities. For example, buildings may get repurposed, or new ones may be built that do not match with original zoning. However, since this methodology is designed for stakeholders in city governments, the records for these types of building discrepancies should be relatively accessible. Further, it is possible for cities to lack zoning data. Famously, Houston lacks zoning, making this method inappropriate there.

Another limitation for very small towns is that census tracts may not have the resolution needed for municipal analysis – they may include buildings outside of the incorporated territory skewing building and population calculations. If this is the case, census tract may be replaced by blocks or block groups that have a much higher resolution to better align with incorporated boundaries.

6 Conclusion

This study presented a methodology with low implementation and computational costs to provide under-resourced policy makers a tool for policy decision making. Using national data, and publicly available tools, I was able to conduct detailed analysis with high resolution and impact potential on a conventional computer without reductions in data quality.

By characterizing solar potential for Evs with respect to location, season, and housing type, I found the analyzed population can meet their EV energy demand throughout the year with roof mounted solar PV units. This is despite population centers failing to align with the greatest solar potential. The high potential North and West Texas zones exhibit large fluctuations in DNI levels relative to their cross-state partners. Season significantly impacted ability to meet demand with winter months producing roughly 65% of the energy that summer months did. Additionally, variations in weather patterns play an important role contributing to the unique observations seen in West Texas. Yet, perhaps the most important factor in determining a housing unit's ability to meet its EV charging demand from roof mounted solar panels is the type of housing. While location exerts a basic force on solar potential, the makeup of city housing can change the availability of power for regions that otherwise would have similar potentials as MF housing has roughly 50 percent less solar potential per person due to higher population density. Where single family housing can easily meet its consumption demand, MF housing will struggle as long as their driving demand is the same. For future policy, this must be considered to create equitable outcomes.

7 Areas of Future Study

This study was limited in scope by focusing on building a methodology and deploying its analysis on four cities. In future research there is considerable potential in adding to the methodology with more detailed DNI data from the NREL. Adding time of day will be a valuable step in planning at the grid level.

Additionally, the MF category deserves significant attention. While SF homes are relatively homogenous, the variability in MF housing is high with buildings ranging from duplexes to 50-story luxury apartments. As city populations grow, the importance of understanding MF power characteristics will rise, so developing a set of best practices will be valuable. Additionally, MF housing has several cross cutting social characteristics that should be considered in tandem with solar potential.

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Appendix 1. City summary sata

Attribute	Austin	Corpus Christi	Dallas	El Paso
Location	Central	South	North Central	West
Population	956,310	325,584	1,188,884	690,764
Housing Units	176,127	99,804	233,170	177,907
Percent of Units SF	92.3%	90.0%	91.3%	86.2%
April DNI (w/m^2)	210.2	199.5	221.0	363.8
Daily Miles Driven	41	40.7	36.7	37.6
Daily Max kWh/Person	212.5	313.7	255.3	536.9

Appendix 2. Electric vehicle data

Top EVs	Range	Battery Size	Charge time (80% in 240-V)
Tesla Model 3	263 miles	50 kWh	6.5 h
Chevy Bolt	259 miles	65 kWh	6 h
Nissan Leaf	149 miles	40 kWh	7 h
Hyundai Ioniq Electric	170 miles	38.3 kWh	7 h

Appendix 3. Average DNI values for studied cities

City	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Austin	190.6	195.9	197.1	210.2	209.4	258.7	**269.4**	266.9	235.0	229.8	198.3	**173.8**
Corpus Christi	167.5	180.7	191.5	199.5	225.5	**278.9**	271.5	271.6	228.5	237.3	195.7	**165.7**
Dallas	193.8	198.1	198.9	221.0	219.0	260.5	**278.5**	266.5	244.7	223.8	197.9	**181.9**
El Paso	275.8	297.2	331.3	363.8	**382.2**	379.5	320.2	310.2	312.6	309.8	286.3	**259.0**

Appendix 4. Average DNI values for studied cities

City	Pop. in this type	Pop. Per building	Building count	Building size m^2	Daily roof MWh (April)	Energy demand (Miles)	$\frac{\frac{KWh}{Day}}{Person}$
El Paso SF	5,603 Avg 638,733 Tot	3.77 Avg	1,487 Avg 169,480 Tot	239.25 Avg	Type Tot:353,205 Building Avg: 2.08	37.91 Avg	553.0
El Paso Mix	5,065 Avg 25,326 Tot	6.89 Avg	924 Avg 4,619 Tot	272.09 Avg	Type Total: 10,524 Building Avg: 2.28	39.38 Avg	415.5

(*continued*)

(*continued*)

City	Pop. in this type	Pop. Per building	Building count	Building size m^2	Daily roof MWh (April)	Energy demand (Miles)	$\frac{\frac{KWh}{Day}}{Person}$
El Paso MF	4,451 Avg 26,705 Tot	10.23 Avg	614 Avg 3,682 Tot	295.01 Avg	Type Total: 8,879 Buildings Avg: 2.41	29.50 Avg	332.5
Corpus SF	4,607 Avg 308,698 Tot	3.42 Avg	1,457 Avg 97,639 Tot	229.31 Avg	Type Total: 101,086 Building Avg: 1.04	40.58 Avg	327.5
Corpus Mix	3,430 Avg 6859 Tot	9.52 Avg	332 Avg 664 Tot	236.62 Avg	Type Total: 1,003 Building Avg: 1.51	46.64 Avg	146.2
Corpus MF	3,342 Avg 10,027 Tot	10.12 Avg	432 Avg 1295 Tot	233.82 Avg	Type Total: 1,174 Building Avg: 0.91	38.83 Avg	117.1
Dallas SF	4,873 Avg 994,165 Tot	5.87 Avg	1,107 Avg 225,730 Tot	260.07 Avg	Type Total: 283,800 Building Avg: 1.26	37.94 Avg	285.5
Dallas Mix	5,385 Avg 48,462 Tot	24.56 Avg	256 Avg 2,304 Tot	370.48 Avg	Type Total: 4,695 Building Avg: 2.04	32.24 Avg	96.9
Dallas MF	4,432 Avg 146,257 Tot	26.33 Avg	218 Avg 7,194 Tot	487.07 Avg	Type Total: 16,409 Building Avg: 2.28	30.48 Avg	112.2
Austin SF	5,420 Avg 905,224 Tot	6.74 Avg	1,034 Avg 172,623 Tot	238.40 Avg	Type Total: 198,747 Building Avg: 1.15	41.34 Avg	219.5
Austin Mix	5,650 Avg 22,600 Tot	19.85 Avg	286 Avg 1,143 Tot	437.27 Avg	Type Total: 2,524 Building Avg: 2.21	32.91 Avg	111.7
Austin MF	4069 Avg 28,486 Tot	24.34 Avg	175 Avg 1223 Tot	479.55 Avg	Type Total: 2,968 Building Avg: 2.43	37.32 Avg	104.2

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EV Charging Impact on Transformer Loss of Life: A Case Study of Hong Kong 2035 Vision

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Abstract. Modern electric vehicles (EVs) are moving energy storage and load. Hong Kong announced the EV roadmap, in which by 2035, all internal combustion vehicles (ICV). With the recent speed-charging technology, the EV load will significantly bur-den a grid in a populated urban area like Hong Kong. This paper introduced an assessment framework with available data on traffic, grid equipment, and demographic to assess the impact and assist in maintenance decisions for grid transformation. By estimating the transformer loss of life coefficient, the framework allows an efficient assessment of the transformer fleet, which can be the future bottleneck. The result may assist the utilities in drawing a timely upgrade and maintenance priority decision.

Keywords: Electric vehicles · Power system · Transformer

1 Introduction

Nowadays, electric vehicles (EVs) are automobiles with extended batteries. Tesla Model 3 Long-range has already reached over 350 miles per charge [1]. The charging load will be a massive burden to the power grid with colossal energy consumption.

Hong Kong Government recently announced an aggressive road map and target of no import of diesel vehicles in 2035, suggesting most cars on the road will be EVs [2]. In 2022, there was only less than 5000 charging station in the city. Compared to 814 881 private cars currently registered, it would require significant resources on infrastructure to support the vision. The foremost priority for local utilities and policy-makers is supply reliability. This strategy leads to a relatively cautious and conservative approach during the energy transition. A comprehensive assessment framework would help the utilities better understand the impact of any additional grid burden and be more willing to unlock the grid potential.

Furthermore, asset management planning needs to address the grid reinforcement priority. The grid bottleneck and weak spot must be identified for future development. In the case of a highly concentrated and high-power load like EV speed charging, utilities may be reluctant to allow the connection without a full assessment of the impact.

To ensure a comfortable experience for EV drivers, the batteries and charging facilities must be able to cater to the speed of charging, which requires a high-power charger

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[3]. The recent speed charger is already reaching 250 kW. In western countries, home is where most charging stations are located [3]; the potential for adding fast charging loads to the residential grid is very high, hence a more significant impact on the residential area [4].

Subjects for analysis of the impact of EV charging on the grid can be listed as thermal load, voltage regulation, harmonic distortion levels, unbalance, losses, and loss of transformer lifetime [6, 7]. Smart charging is considered one of the solutions proposed [8–10].

This paper presents an impact assessment framework with a local traffic model, weather data, and charger model. 18 districts in Hong Kong were used to be the sample. The impact on the regional transformer was evaluated by loss of life and DGA analysis. The corresponding maintenance recommendation was included in the conclusion.

2 Methodology

To study the potential impact of the 2035 scenario, this paper suggests a method to construct a model using numbers of regional data combined with a transformer aging model. The model includes three main stimulations: carpark traffic, charging model, and transformer aging model. They will be explained in detail in the modeling session.

The calculation of transformer aging is a non-linear Arrhenius plot, which describes the temperature impact on the chemical reaction. The insulation aging depends on the previous degradation rate and oil temperature.

In this paper, the rate within every 5 min is obtained by linear interpolation. Then the model was repeated for the night peaks, defined as from 17:00 to 2100, for 365 days with the entire year of weather data. The average loss of life (LOL) will be combined with the DGA analysis result to evaluate the impact (Fig. 1).

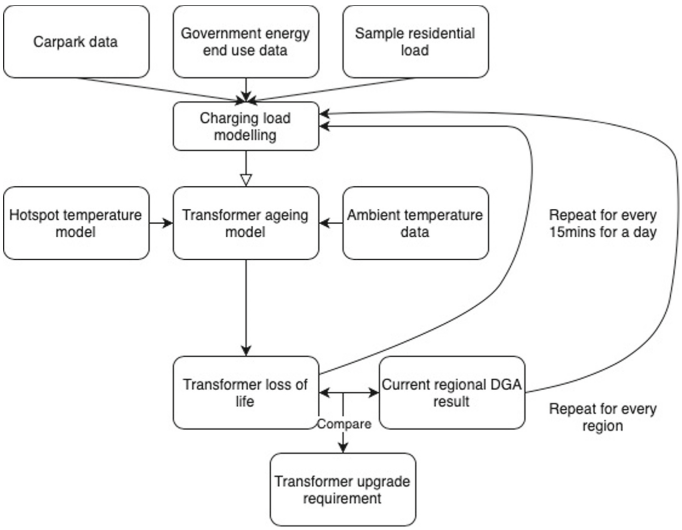

Fig. 1. Process flowchart of the stimulation

3 Modeling

3.1 Household Load Profiles

To simulate the household load in each house at certain times of the day without EV charging, we used a typical household load curve based on actual 24-h records of a residential ring in Hong Kong. The EV loading for the selected areas is aggregated on this load curve. An example of the load for households in Hong Kong on a weekday is shown below (Fig. 2).

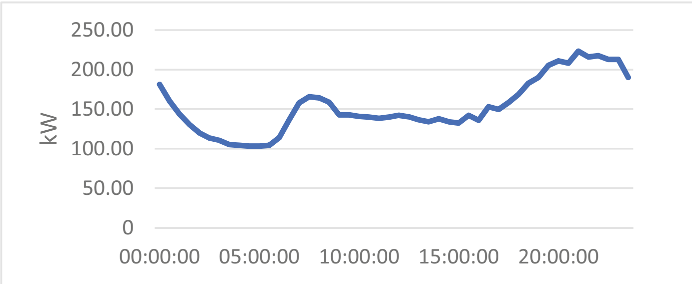

Fig. 2. Residential ring load curve used in the model

3.2 Transformer Aging Model

One of the significant problems of transformers faults due to demand-side like the residential load is the transformer aging. Transformer aging refers to insulation degradation, which is highly affected by temperature and humidity [11].

The model is to describe and quantify the effect of electric vehicle charging loads on the loss of life of transformers. So far, several thermal models have been proposed for power and distribution transformers. For oil-immersed transformers, moisture and oxygen have a limited impact on insulation degradation [11]. Transformer winding hot spot temperature (HST) is considered a key factor for transformer loss of life. In addition, ambient temperature and loading play the most crucial role [12].

The IEEE standard proposes an equation for calculating the aging rate of a transformer about hotspot temperature. This aging rate gives an evaluation of the loss of transformer insulation life [13].

The accelerated aging coefficient TrA = 1 suggests the temperature environment of 110 °C for insulation paper. [14] Due to the uneven temperature among different regions in the transformer, the hotspot region components suffer the most damage. Therefore, the winding hotspot temperature affects the aging rate.

Every 5 min, the load current generated by EV charging is calculated and added to the customer load. The results are then entered into a transformer thermal model. The manufacturer's ambient temperature data and transformer parameters are fed into the model. It would give the thermal properties and response of the transformer. The transient temperature during the 5-min interval is determined by linear interpolation. Each interval stands for the input and output of quick hot spot temperature. The model determines the transformer's life loss rate over a specific period.

The below equation is used to generate the loss of life rate as suggested by IEEE [13].

$$Tr_A = e^{(\frac{B}{T_\theta} + \frac{B}{T_{HT}})}$$

where T_{HT} is the Hotspot temperature, B is the transformer constant provided by the manufacturer.

$$T_{HT} = T_A + \Delta T_{HT} + \Delta T_{o/T}$$

$$you T_A \text{ is the ambient temperaure}$$

$$\Delta T_{HT} \text{ is the change in winding hottest spot temperature rise}$$

$$\Delta T_{o/T} \text{ is the change in top oil temperature rise}$$

$$\Delta T_{HT} = (\Delta T_{HTinitial} \times \left(K^{2m}\right)$$

$$\Delta T_{o/T} = (\Delta T_{\frac{o}{Tinitial}}) \times (\frac{K^2 R + 1}{R + 1}) \times \mathtt{C}$$

$K = \frac{Load}{} Rated\ Load, R = \frac{Rated\ Load\ Loss}{No\ Load\ Loss},\ m\ and\ C\ are\ empirical\ constant$ [13].

Below is the transformer model used in the study. The model is adopted widely in Hong Kong, and the manufacturer provides data.

Parking data will be based on sampling results of the Hong Kong real-time parking data. Total 1 of 49 carparks data are obtained. The raw data was recorded every 30 min. However, the information is not precise enough for the stimulation with the impact of speed charging.

The possibility distribution function is estimated through Kernel density estimation to sample the traffic model with better precision. The uniform estimator was used for the night peak. The window width is 45 min with 256 data points. The residential area carparks were selected for a focused study to illustrate the residential impact better.

The graph shows a substantial massive inflow of traffic in the evening and outflow in the morning. It is typically understood as the traffic of people going home after work. That's why the 5–9 period illustrated the study. As observed, the peak hour would be around 18:45 to 19:30. The model is only concerned with the inflow traffic of the carpark as that would be the main component of the charging load.

In the study, the charger model is the Tesla Model 3 Long Range SuperCharger V3. It is currently one of the most advanced chargers on the market. While Tesla overtook the Hong Kong EV market by over 90%, modeling the Tesla charger would give the best fit to the reality (Figs. 3 and 4).

3.3 Charger Model

The Tesla charger would be proprietary data. Because of the limitation, the charging curve and power were estimated through multiple reviews and testing because of the restriction.

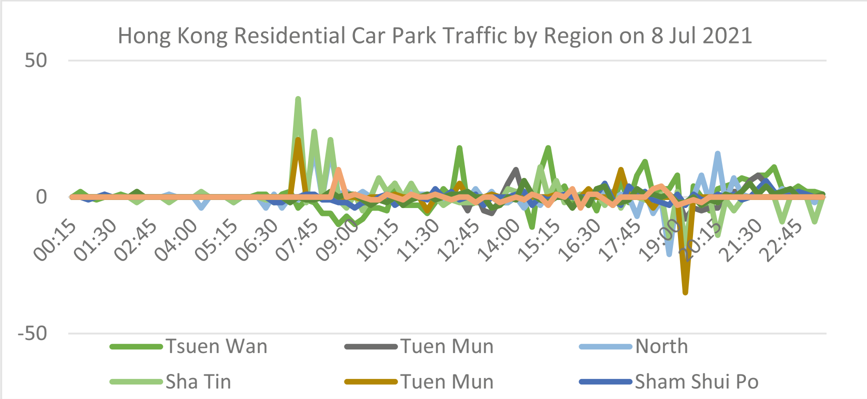

Fig. 3. The public residential carpark traffic data sample in the stimulation

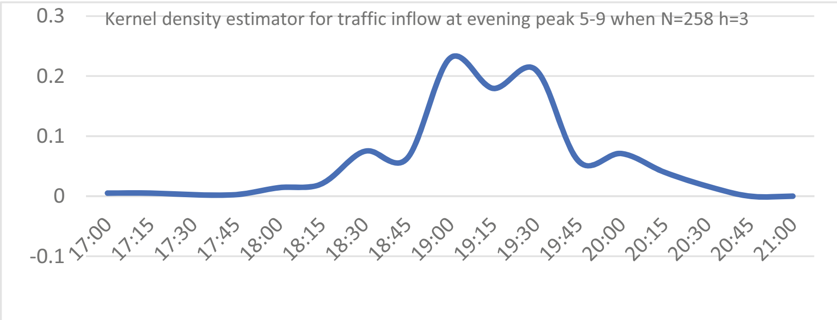

Fig. 4. The probability distribution function for the simulated traffic

To estimate the charging power concerning time, the equation generated the P(t) and hence the SOC versus time. The chart is based on the following formula

$$\int_{equalStart}^{End} P(t)dt = |SOC|_{0\%}^{100\%} = \int_{0\%}^{100\%} P(SOC)dSOC = 75 \text{ kWh}$$

When End = 61 min and Start = 0 min

Tesla announced, "…The V3 has a peak power of 250 kW. A Model 3 Long Range can charge up to 75 miles within 5 min". This would serve as the verification of the charging model.

For the battery to be charged up to 75 miles, i.e., 21.246% of the battery capacity, it took 4.3778 min under the 5 min criteria. Compared to available reviews done by other researchers, most charging times from 0%–100% fell to around 60–65 min which aligns with the model suggested in this paper (Figs. 5, 6 and 7).

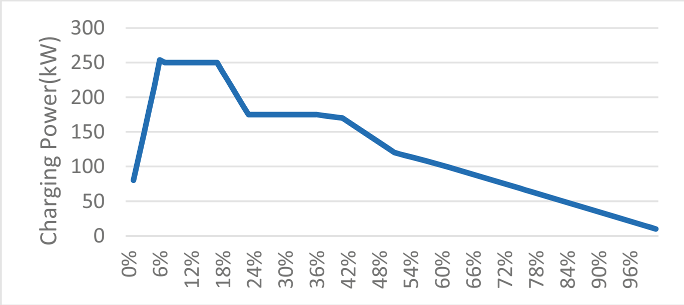

Fig. 5. SOC against Power of Tesla V3 charger

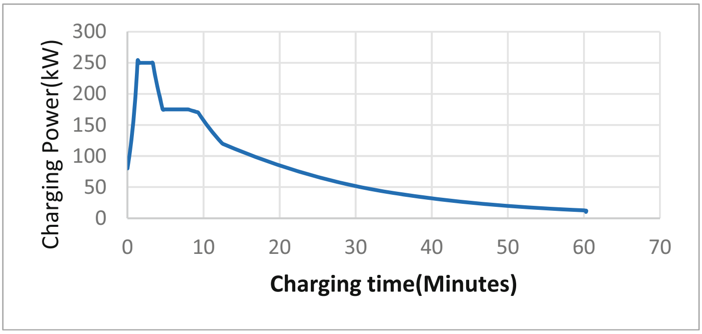

Fig. 6. Power against charging time of Tesla V3 charger

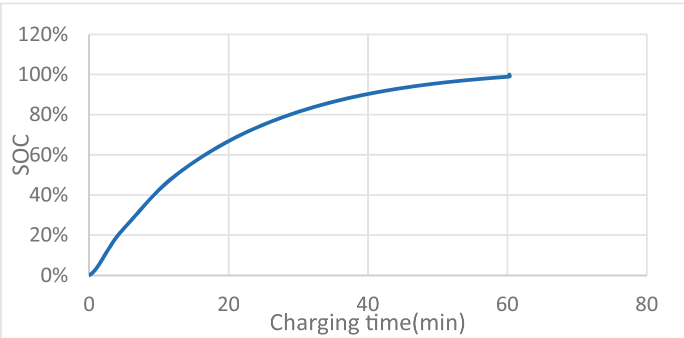

Fig. 7. SOC against charging time of Tesla V3 charger

3.4 Residential Area EV Charging Load Model

Combining the probability density function and the EV charging model generates the sample residential load curve. A regional constant is proposed in this paper to stimulate the corresponding impact on the various regions.

As you may see in the graph, the load starts climbing at 19:10 seven-fold in 10 min without any smart charging or coordination. The Tesla speed charging approach takes advantage of the low SOC and raises the power at the beginning of the charging cycle. As a result, when many EVs start charging simultaneously, the first 5 to 10 min of the charging cycle might incur a significantly heavy load (Fig. 8).

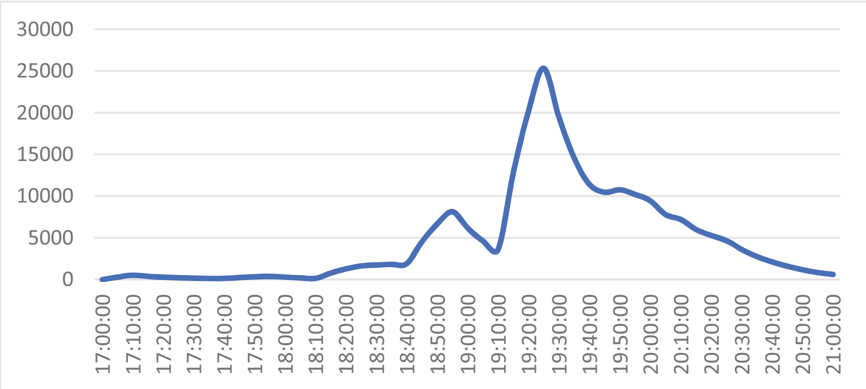

Fig. 8. The carpark loading in the model

3.5 Estimation of the Regional Impact

On predicting the regional EV energy consumption, it would take multiple assumptions. To isolate the impact of the residential pattern, only the total number of light-duty vehicles and corresponding parking vacancy are considered. In Hong Kong, 25% of gross energy was consumed on transportation in 2018. The 18% of it would be on light-duty vehicles and motorbikes typically used for the passenger. Currently, only 2% of them are powered by electricity [15].

On the other hand, within the 55% of gross Hong Kong energy consumption on electricity, 26% was residential use. From the above, it would give a fair estimation of the overall ratio of the energy use for residential household transportation and residential consumption [15].

$$Residential\ EV\ factor = \frac{Gross\ energy\ use\ on\ car\ and\ motorbike}{Gross\ Residential\ electricity\ consumption}$$

To stimulate the regional difference, another regional factor is proposed.

$$\begin{aligned} & \textit{Regional Residential EV charging factor} \\ & \quad = \frac{\textit{Number of light duty car parking lots in the area}}{\textit{Number of households in the area}} \\ & \quad \times \textit{regional constant} \times \textit{load scaling factor} \end{aligned}$$

The regional constant is an empirical constant representing the ratio of regional energy use on commercial versus residential. The load scaling factor is an arbitrary constant to scale down the load to avoid overloading the transformer. The overloading would severely damage the equipment, reduce the lifetime, and operate the protection, which is absolute to be avoided in any situation (Table 1 and Fig. 9).

Table 1. Stimulation parameter for districts in Hong Kong

District	Number of parking lots	Number of household (,000)	Ratio of parking slot over household	Constant (adjusted factor)
Sha tin	76069	239.3	0.31788132	0.54159889
Kwun Tong	53883	245.2	0.21975122	0.37440708
Eastern	53832	191.3	0.28140094	0.47944446
Kowloon city	52921	150.6	0.35140106	0.59870905
Kwai Tsing	48977	173.9	0.28163887	0.47984984
Tuen Mun	44202	181	0.24420994	0.41607929
Sai Kung	43575	157.4	0.27684244	0.47167779
Yuen Long	43513	225.3	0.1931336	0.32905659
Southern	42132	87.3	0.48261168	0.82226269
Central and Western	41490	92.1	0.4504886	0.76753212
Tsuen Wan	38549	112	0.3441875	0.58641875
Yau Tsim Mong	37658	128.4	0.2932866	0.49969498
Wan Chai	36185	70	0.51692857	0.88073102
Sham Shui Po	34034	161.5	0.21073684	0.35904859
Tai Po	30794	104.6	0.29439771	0.50158804
Wong Tai Sin	24733	145.7	0.16975292	0.28922112
North	24187	109.7	0.22048314	0.3756541
Islands	18056	69.9	0.25831187	0.44010583
Total	744790	2645.2	0.28156283	

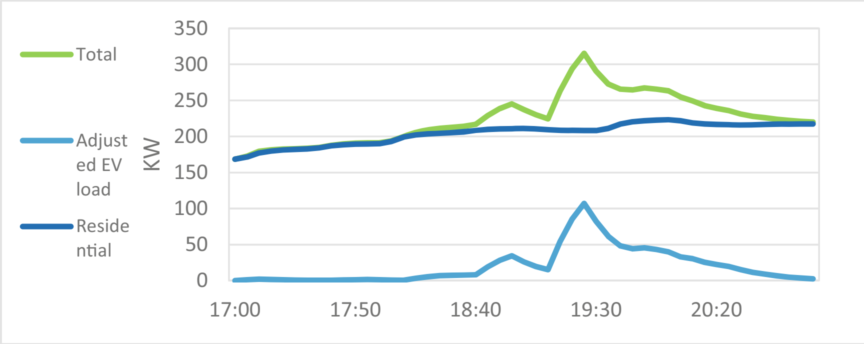

Fig. 9. Aggregated load curve used in the model

4 Results

4.1 Evaluation of the Current Regional Transformer Health

Solid insulation, DGA, and furan condition are typical ways to indicate the health condition of a transformer. The operating time of the solid insulation can be calculated based on the parts per million (ppm) of furan in the oil. Dissolved gas analysis (DGA) in oil applies a total gas equation with a table of range values for different dissolved gas content growth rates [13]. Transformer aging is calculated based on the number of years of operation and the use of accelerated aging coefficients due to temperature rise [14].

Of these three indicators, DGA results in the easiest way to assess the condition of a transformer in a non-invasive and practical manner. When insulation or transformer oil fails, some gas or moisture is released into the oil; the IEC standard identifies nine major critical fault gases.

For such cases, IEEE developed a criterion method for the risk classification, whether it remains in operation with combustible gas content in the transformer. The method takes the value for key gas concentration and the total dissolved combustible gas and divides them into four categories according to the maintenance urgency (TDCG) [11, 13]. Condition 1 means there is no issue with the transformer operation. Condition 2 suggests the alarming level of gas. There should be an investigation and a review of the gas level trend. Condition 3 suggests measures to be taken urgently toward the transformer. Condition 4 implies an immediate risk to the transformer operation.

To further access the transformer condition to draw asset management decisions, the Roger and Doernenburg ratios will be utilized to identify the situation [18]. The analysis may tell the partial discharge, arcing, fault, oil and insulation decomposition, and thermal issues. Through looking at some key gases' content and corresponding ratio, some conclusions can be drawn, especially since there might be potential EV load [19]. The thermal issue can be worsened if not enough attention is paid and with the extra EV loading. The uncontrolled thermal problem may potentially damage the insulation and mineral oil. The irreversible damage would reduce the lifetime and raise the potential of faults [20] (Table 2).

Table 2. Detailed DGA analysis for Wong Tai Sin Case

DGA result for sample Tx		Factors for Roger ratio and Doernenburg ratio analysis	
H_2	57.8018799	R1 (CH_4/H_2)	2.88492819
CH_4	166.754272	R2 ($C2H_2/C_2H_4$)	0.00400165
C_2H_2	0.03502056	R3 (C_2H_2/CH_4)	0.00021001
C_2H_4	8.75153351	R4 (C_2H6/C_2H_2)	7596.87491
C_2H_6	266.046814	R5 (C_2H_4/C_2H_6)	0.03289471
CO	368.741211		
CO_2	3651.35498		
O_2	80.9670792		
N_2	64928.1875		
TDCG	868.095764		
H_2O	3.18220305		

In Table 3, the DGA result for Wong Tai Sin is further analyzed through the Roger ratio decision tree utilized. The result is not conclusive see whether it falls into Case 4 or Case 5, which suggests an internal thermal fault below 700 C and above 700 C, respectively. But the result gives a general direction toward a thermal problem inside the transformer.

Table 3. Transformer Loss of Life and DGA analysis

Region	Average LOL per night peak	TDCG result	Roger ratio diagnosis result	Doernenburg ratio diagnosis result
Kwai Tsing	0.23	Condition 1		
Sha tin	0.11	Condition 1		
Kwun Tong	0.06	Condition 1		
Kowloon City	0.14	Condition 1		
Southern	0.54	Condition 1		
Sham Shui Po	0.05	Condition 1		
Tai Po	0.09	Condition 1		
Wong Tai Sin	0.04	Condition 2	Thermal problem	Oil thermal decomposition
North	0.06	Condition 1		
Control Group	0.02			

The Doernenburg ratio categories 3 cases for the specific gas ratio, thermal decomposition, partial discharge, and arcing. For the case of Wong Tai Sin, where R1 > 1.0, R2 < 0.75, R3 < 0.3, and R4 > 0.4, the result falls in the category of Thermal Decomposition.

5 Conclusion

The ranking of the loss of life rate suggests the upgrade priorities. From the result obtained, the Southern and Kwai Tsing ranked the highest in the loss of life rate, indicating the grid infrastructure in these regions suffered from the heaviest stress. During the grid reinforcement planning, the upgrade on these regions should be prioritized.

Given the urgency of the upgrade or reinforcement, the DGA analysis result is reviewed. While the South district transformer shows an increasing trend in TDCG value, it is still far lower than the alarming threshold of 750 ppm. It can be concluded that these two regions may need extra attention in the long term with more EV penetration.

Extra attention may be needed for the Wong Tai Sin Region. The TDCG has passed the 750 ppm, falling into Condition 2 defined by IEEE. The TDCG concentration continued upward momentum for a few years, suggesting the existence of internal issues. Internal thermal problem is also identified in the DGA analysis. The additional stress from the rising charging load may foster the heating of the transformer, risking further advanced insulation and oil breakdown and posing a significant risk to its operation. Another urgent action with the unit is highly recommended to avoid future failure.

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Education

Building a Diverse and Inclusive STEM Workforce: The JUMP into STEM Program

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Abstract. The JUMP into STEM program is a DOE-funded initiative jointly run by the National Renewable Energy Laboratory and Oak Ridge National Laboratory. Through this program, students from historically underrepresented backgrounds are engaged in the science of building energy-efficient infrastructure. Through program stages, students have opportunity to compete in challenges, competitions, and internship opportunities. We have conducted a study of past participants in the program. We find that 1) the program has been effective at engaging a diverse array of participants from a variety of backgrounds, including historically underrepresented backgrounds, and 2) the program has been effective at promoting career paths in STEM, and more specifically, in energy efficiency.

Keywords: Diversity · Equity · Inclusion · STEM education · Efficient infrastructure

1 Introduction

1.1 Background

JUMP into STEM is a student competition programed designed to inspire students from diverse backgrounds to apply their knowledge and creative skills to solve real-world problems in building efficient infrastructure [1]. It is funded by the Department of Energy (DOE) through the Building Technologies Office and by industry sponsors. It is orchestrated jointly by researchers at the National Renewable Energy Laboratory (NREL) and Oak Ridge National Laboratory (ORNL). Recently, Pacific Northwest National Laboratory (PNNL) has begun to contribute to JUMP into STEM as well.

The program is designed to engage students from a variety of underrepresented backgrounds. Across multiple phases of competition, students have opportunities to make their voices heard, to network with STEM (**S**cience, **T**echnology, **E**ngineering, and **M**ath)—professionals, and to engage in career development. The competition framework is illustrated in Fig. 1.

In the fall, students assemble into teams. Interdisciplinary teams, comprising of members from a variety of educational focuses and backgrounds, are encouraged. Together, team members submit a response to one of three energy-efficiency related challenges.

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https://doi.org/10.1007/978-3-031-08786-8_28

Fig. 1. Schematic of JUMP into STEM competition format.

From the challenge submissions, winners are chosen. Eligible challenge winners are invited to a competition. At this competition, they present their challenge submissions and network with researchers and industry professionals.

Eligible winners of the challenge competition are offered internships at National Laboratories. This provides valuable career development, networking, and training. It also benefits the national laboratories, as the interns bring their unique perspectives to the cutting-edge research projects they join.

1.2 Impact Tracking

Through the four years of the JUMP into STEM competition history, we have collected participant data, performed randomized participant interviews, and followed up with interviews to assess career outcomes for past participants.

2 Results and Discussion

2.1 Engaging a Diverse Participant Pool

JUMP into STEM emphasizes inclusion of underrepresented groups. These groups include, but are not limited to, those based on race, ethnicity, and gender. According to demographic data collected from student challenge submissions, internship applications, and follow-up interviews, the JUMP into STEM program is achieving inclusion of underrepresented groups at a very high rate compared to that which is usually seen in STEM programs [2].

From 2018 to 2021, just over 45% of student participants were from historically black colleges or universities (HBCUs) or minority serving institutions (MSIs). Furthermore, demographic information conducted during participant interviews suggests that the total number of participants from underrepresented backgrounds exceeds the number of students from HBCUs/MSIs. As indicated in Fig. 2, 71% of randomly selected interview participants were from underrepresented backgrounds.

Furthermore, among interview participants, 65% identified as women, far higher than the national average in STEM fields [3].

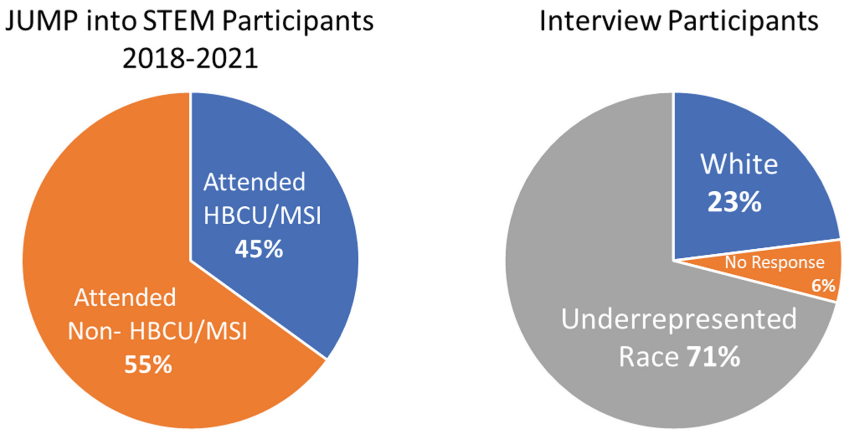

Fig. 2. Demographic data for JUMP into STEM participants.

2.2 Promoting Career Paths in STEM

More than 25 different majors and areas of focus are represented by JUMP into STEM participants. Each of these diverse focus areas has applications in energy and energy efficiency. However, these focus areas can be applied to many other focus areas as well. As the JUMP into STEM program encourages participants to enter the energy workforce, it was important to understand their career outcomes.

Based on follow-up interviews, 41% of JUMP into STEM participants currently work in fields related to energy or energy efficiency. As many past participants are still in professional training or educational programs, 18% are undecided. Fewer than 1/3 of past participants interviewed are working in unrelated fields. This is illustrated in Fig. 3. Thus, it is clear that JUMP into STEM participants are going into the energy infrastructure workforce at a higher than average rate.

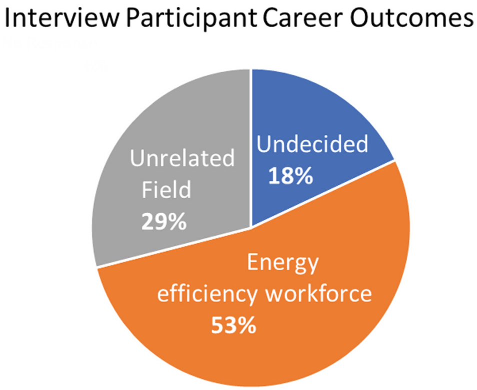

Fig. 3. Career outcomes for previous participants of the JUMP into STEM program who participated in randomly selected interviews.

3 Conclusion

Over the 4 years of the JUMP into STEM student competition program, it has successfully engaged a diverse array of participants. Furthermore, these participants have gone on to work in energy-related career fields. Thus, we conclude that the JUMP into STEM program has had, and is continuing to have, a positive impact on training, inspiring, and ultimately developing a diverse workforce for energy-related industries.

Programs like this are essential. It is critical that our energy infrastructure evolves in ways that meets the needs of the people it serves. Without engaging them in a fair and equitable manner, it is impossible to accurately gauge and ultimately meet their needs. Through programs like this, we can not only help students from historically underrepresented backgrounds succeed, but can also empower them to contribute to energy solutions in the future.

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Getting to Net Positive – An Architect's Perspective

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Abstract. The 70,000 sf Annie E. Fales Elementary School in Westborough, MA produces 10% more energy than it consumes, making it the first Net Positive public school in Massachusetts. Architect Gary Brock describes HMFH's work with the school and town leaders to establish this ambitious energy goal and manage the financial, political, and technical challenges that occurred along the way. During early design charrettes with mechanical and electrical consultants as well as experts in energy modeling, solar design, daylighting, and geothermal heating and cooling, the design team targeted an EUI of 25 and agreed on specific and measurable objectives for major systems, such as window to wall ratio, light power density, and daylight autonomy. Early cost estimates paired with energy models aided in systems choices and showed the owner that the increase to the Town's annual construction bond payment for ZNE provisions would be offset by yearly energy savings. The team continued to use energy modeling combined with cost estimates to ensure that value engineering did not impact the ZNE goal. The school is equipped with extensive data collection systems, allowing energy use and production data to be uploaded to a web-based portal. The district is currently developing curricula that will use this data for teaching about energy use and production to students at all grade levels.

Keywords: Zero net energy · Energy positive · Financing · Economic justice · Education

1 Establishing Goals and Owner Buy-In

Early in the design phase for the Annie E. Fales Elementary school, the design team was aware that there could be a good opportunity to design a zero net energy school building. For this project, we are defining zero net energy as producing on-site renewable energy equal to the energy used to operate the building annually. The ratio of interior gross square footage in relation to the area of the roof looked like it could be 2 to 2.5:1 meaning that the potential amount of electricity produced by photovoltaic arrays on the roof might be able to meet the potential energy needs for this particular building. It was in our minds early in the process to test the idea and pursue it if we could. We had to make a good case to the client in order for them to be willing to support the idea.

We have been fortunate in many ways for this project to be able pursue zero net energy aspirations and realize them. In addition to the advantage of great ratio between the roof

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area and the internal building area, the Owner was able to take advantage of a variety of financial incentives in Massachusetts that promote and support energy efficiency, renewable energy, and school construction. Our State has relatively high utility rates, which can also contribute to the economic case for low-energy, renewably powered buildings. A willing client is also very important.

1.1 The Early Conversations

HMFH worked with Westborough on a smaller project before this one, which helped us become more familiar with the town and their priorities and as we worked with them, we continued to learn more about the interests of the community. It was clear based on the evolution of their policies over the years that there was an interest and an effort to improve the sustainable attributes of their community. The following is a chronology of policies, developments of which had been occurring in greater frequency:

2010: Zoning for Solar Farms
2016: Greener Option with National Grid
2017: Green Communities Status (a state-based funding program)
2019: Climate Action Task Force
2019: Vote for municipal energy to be renewable by 2035

While community interest is important, there is also a need for a champion on the owner's side to be directly involved in the project. For this project, that was the Building Committee Chair and the town's Superintendent of Schools who were both big supporters of the effort. Also important is support from the facilities staff. Westborough had already demonstrated a willingness to implement technology that might be less common in similar municipalities. In 1998 they were the first municipality in Massachusetts to use deep, open-well ground source heat pumps for another of their elementary schools that had originally been designed as all-electric. That retrofit project saved the town $200,000 annually in energy costs over the course of twenty years. Fortunately, that history allowed their facilities staff to be open to new possibilities.

The Owner and the design team all needed to believe that this would be financially feasible. Given their experience working with the utilities and the development of solar farms in town, there were building committee members who were more comfortable than might be typical, understanding the potential savings that could be involved and the technical issues that come along with solar power. At the time of some presentations to the building committee, the town also happened to be discussing their town budget, which included discussions about energy costs. This is when the design team began to discuss with the building committee the potential savings associated with integrated renewable energy production offsetting purchased energy in relation to the long-term financial costs incurred by the town when it issues bonds for the construction project.

Typically, municipalities and other non-profits tend to implement a power purchase agreement (PPA) in order to install photovoltaic systems on their projects. This is usually because construction costs often push the limits of tight budgets. In the case of public-school construction, budgets associated with operational costs are often divorced from the construction budget, with different people and departments developing and managing them. PPAs avoid most of the initial upfront costs, lock in utility rates for an agreed upon amount of time at the expense of potential additional savings and renewable attributes (which are typically sold by the PPA entity).

Working with our consultants we analyzed three scenarios–two schools in addition to Fales–for purchasing and installing PV systems. For the other two projects, both ownership and PPA procurement methods were compared. For Fales, PPA was not reviewed at the time because a PPA entity was not involved at that point. For all three examples, the simple payback for ownership was similar, 8 to 9.7 years with Fales being 8.5 years. The potential for savings for Fales was higher because of the size of the system that would be considered (see Fig. 1).

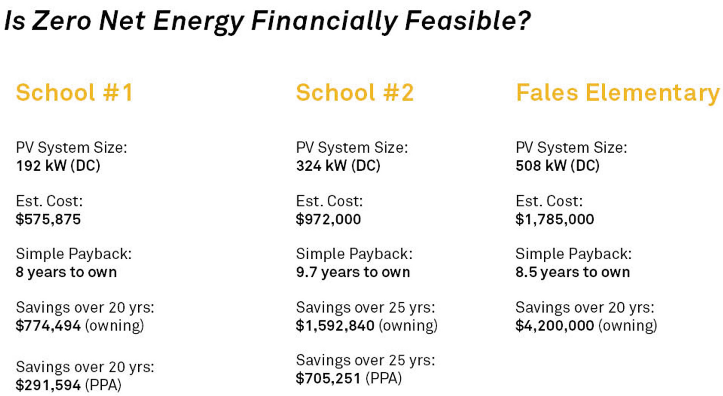

Fig. 1. Financial comparison–owning vs. PPA

1.2 Establishing Project Goals and Priorities

Once there was enough momentum for all to agree that it made financial sense to reach for a zero net energy goal, it was time to establish more specific goals and priorities to truly test the team's ability to get there with the design. Budgets had already been established but were revised based on the preliminary analysis that this could be less expensive for the community over time and was within their bonding capacity. Energy budgets were established. A target EUI was established of 27.5 kBTU/sf/yr. The owner and team decided to keep the building all-electric based on their experience with ground source heat pumps, and because they can be the most energy efficient method for heating and cooling in the northeast climate. Ownership versus PPA would continue to be evaluated with ownership being the goal if budgets could be met.

2 How to Get There

The team knew we would need to minimize energy consumption as much as possible to reduce the size of the PV system. We also knew we would need to maximize the amount of production on the roof of the building as much as possible, knowing that a roof-mounted system would be less expensive than one that is ground-mounted on this particular site. As we worked with our consultant team, we helped the owner and the design team understand which building systems had the most impact on total energy consumption and where we could prioritize efforts to impact consumption. An interesting observation for many was that plug loads were the largest individual component, consuming power at 32% of the total load. This becomes an important point later after the building is occupied. Occupant behavior can have a significant impact on achieving predicted energy consumption. Pumps and ventilation combined were just a little more at 35%. HVAC as a category represented 52% of the loads relative to everything else (see Fig. 2).

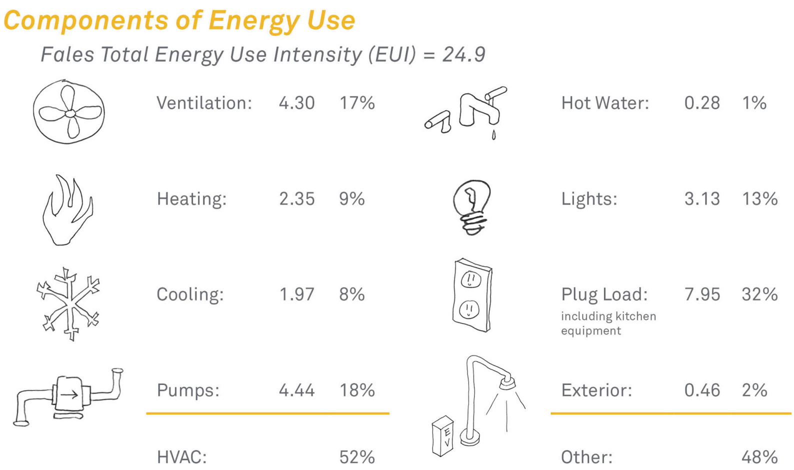

Fig. 2. Proportional energy consumption of Fales' building systems

3 Building Loads - Orientation, Massing, Thermal Envelope, and Daylighting

The potential locations where the building could be placed on the site were limited. The existing school building had to remain in place for use while the new facility was constructed adjacent to it. In order to maintain access to the site, allow enough space to drill wells for the ground loop associated with the heat pumps, and allowing space for the construction staging the new building had to be built to the west of the existing and partially buried into the hillside. Several massing options were evaluated with the goal to orient classrooms for north and south exposures as much as possible for better daylighting opportunities (see Fig. 3).

The building envelope is optimized to reduce heat loss and gains while balancing their impact with HVAC loads. Exterior wall and roof assemblies have R-values of R-30 and R-40 respectively. The exterior windows are high-performance triple-glazed uPVC units with U-values of 0.13, variable solar heat gain coefficients and daylight transmission based on orientation. Average window to wall ratio is 25% for the building (see Fig. 4).

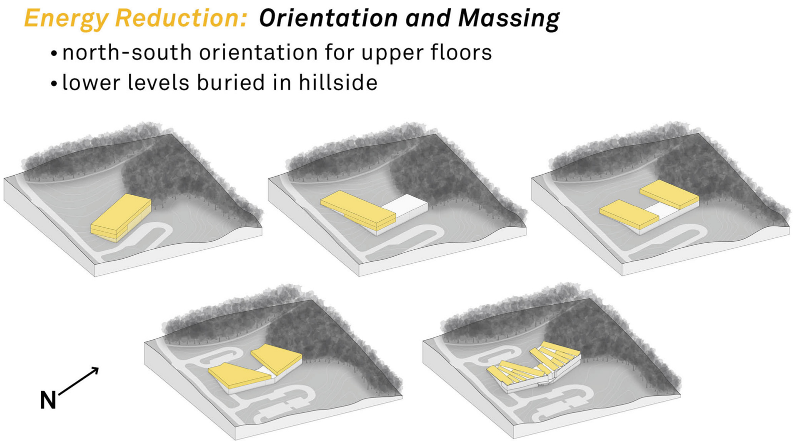

Fig. 3. Exploration of building massing and orientation

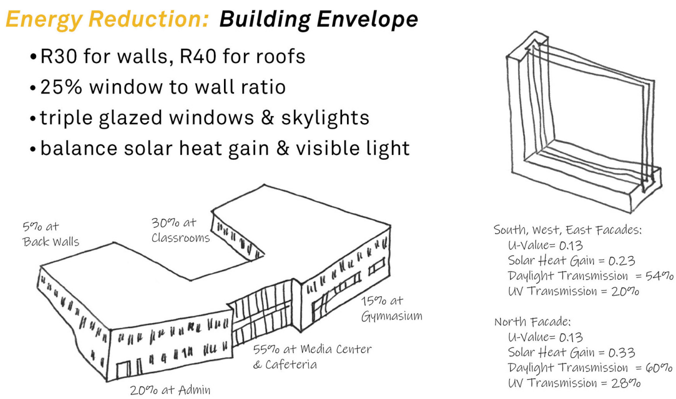

Fig. 4. Thermal performance of building envelope

Quality lighting, both daylighting and artificial, is an important feature to optimize for the benefit of students and faculty as they occupy the building. It is also another variable in the reduction of energy consumption. Because the building was bermed into the hillside, there was a need to utilize skylights strategically to bring daylight into spaces to balance the daylighting and bring it into deeper spaces without exterior exposures. We maximized daylight autonomy and minimized light power density, targeting an LPD of 0.43.

By utilizing a ground-source heat pump system and by installing air handling units within the building envelope, greater functional use of the roofscape is possible for more daylighting opportunities and to maximize the area for PV panels. In an effort to improve the daylighting and thermal performance, more clerestory windows were used in lieu of skylights. Clerestory windows enable better control of the daylight and much better thermal performance than typical skylight units (see Fig. 5).

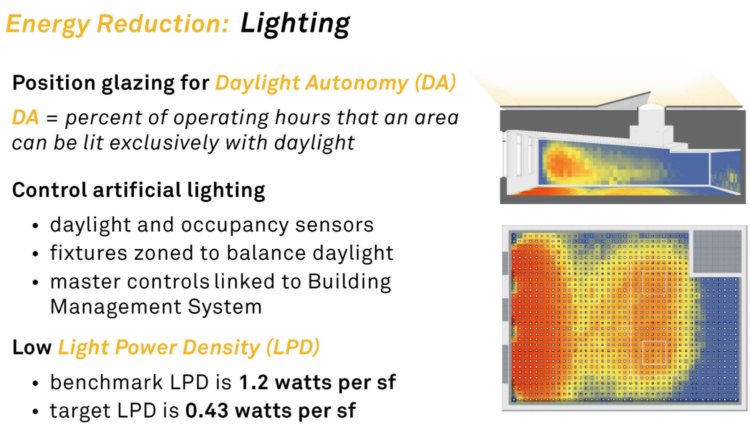

Fig. 5. Optimizing daylight autonomy

3.1 Energy Production

Based on the size of the building, the established goal of an EUI target of 27.5 and the addition of a 10% cushion to the estimate, the annual energy consumption was estimated to be 2,178,000 kBTU per year, or 638.154 kW-Hr/yr. Initial assumptions used 320 W per panel, requiring approximately 17.6 square feet each. This resulted in the need to provide space for about 32,000 square feet of roof area for PV panels (see Fig. 6 and Fig. 7).

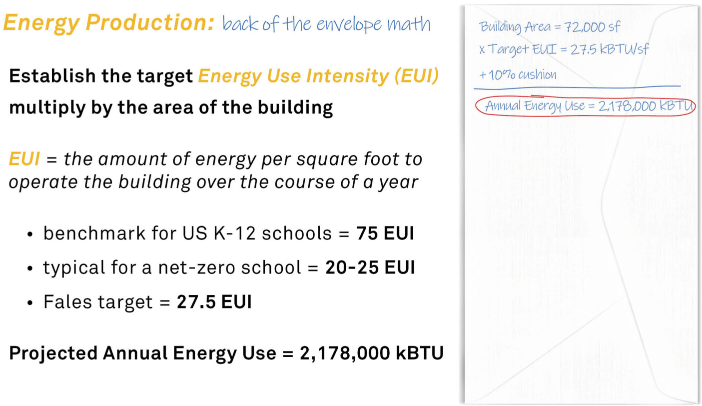

Fig. 6. Establishing an EUI target

Manipulating the roof geometry during design became an important exercise to both refine daylighting and maximize solar energy production. A sawtooth roof form allowed for the integration of clerestory windows and maximized roof area for PV panels. In addition, PV panel orientation could be optimized for improved production capacity.

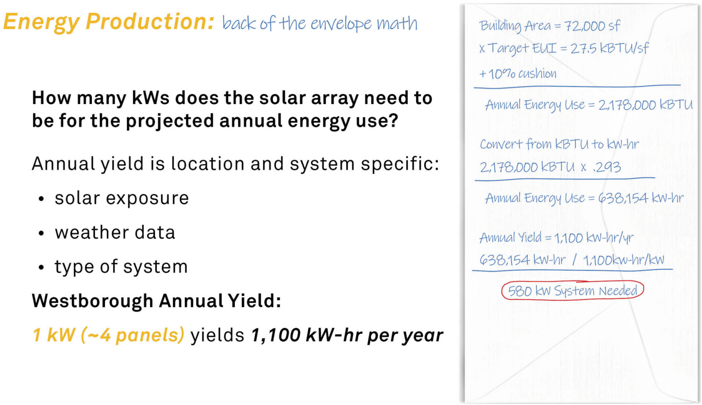

Fig. 7. Estimating PV system size

Radiance analysis allowed the team to evaluate which form and orientation was the most efficient (see Figs. 8, 9, 10, 11).

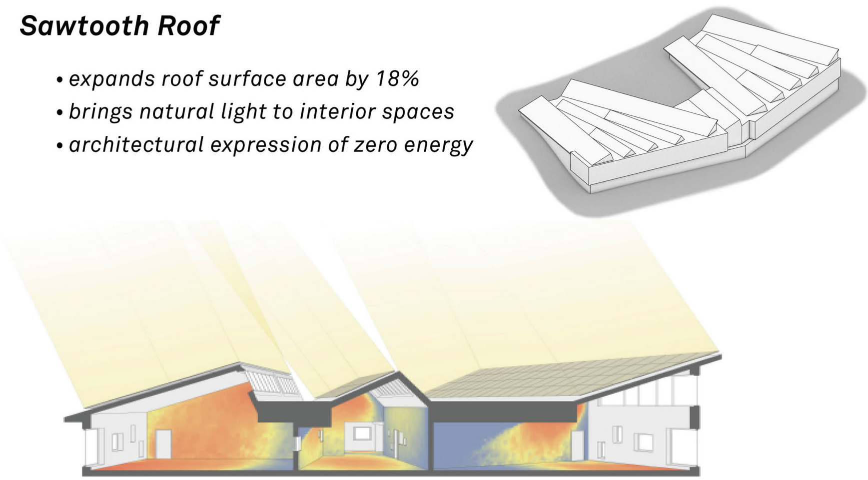

Fig. 8. Benefit of the Sawtooth roof form

Evaluating Achievement of the Goal. At the design development phase of the design process the team was anticipating the need for a 504 kW PV array that could produce 638,579 kW-hr per year. At the end of construction documents, the size of the array slighting increased to 508 kW which is estimated to produce 648,579 kW-hr per year. Through the refinements during the design process, the team was able to realize improved energy performance for the building while also maximizing the power production of the PV system. The availability of higher performing PV panels improved energy production while requiring less space to do so. The building is now anticipated to be 10% energy

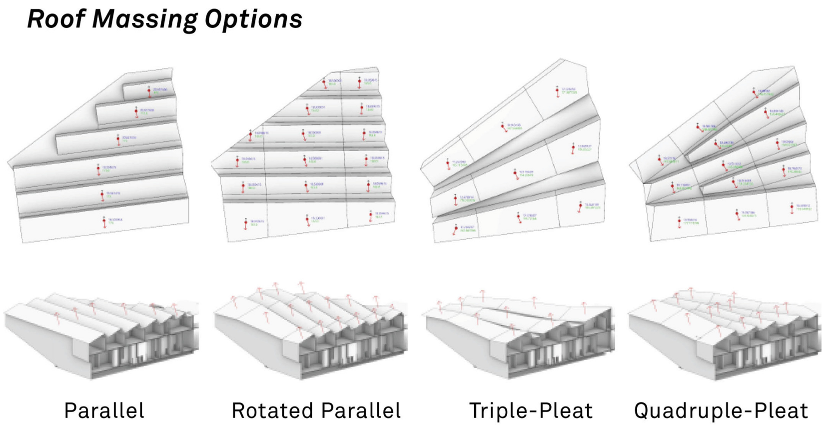

Fig. 9. Studies of different folds in the roof form

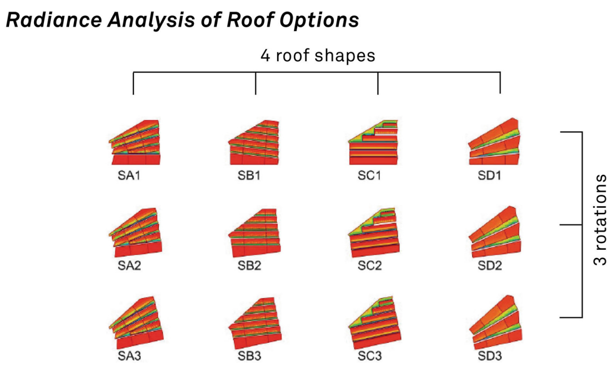

Fig. 10. Analyzing solar exposure on roof forms

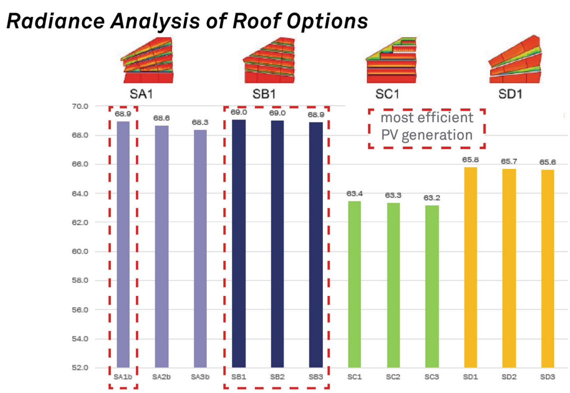

Fig. 11. Most efficient form for energy production

net positive (Figs. 12, 13, 14). Arrangements with the utility company will allow the town to apply the excess energy production to other municipal buildings in town, further improving their return on investment (Figs. 15, 16).

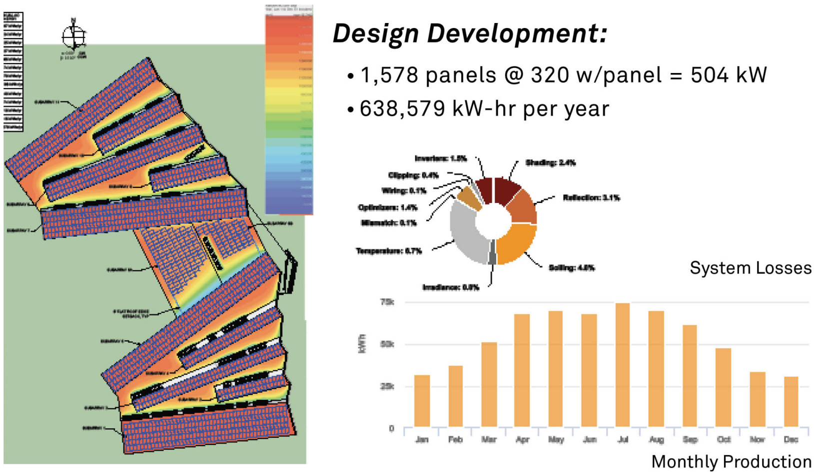

Fig. 12. Anticipated PV system sizing at DD

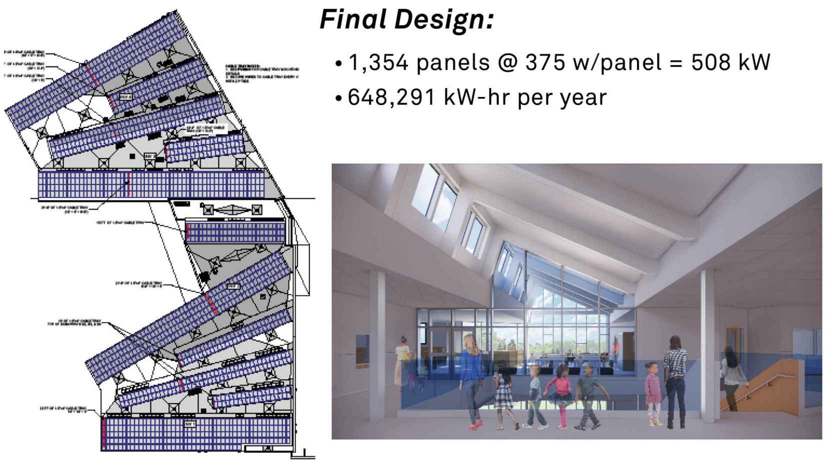

Fig. 13. Final PV system sizing

How did we do?

	Back-of-the-Envelope	**Final Design**
Energy Use Intensity:	*27.5 EUI*	**24.9 EUI**
Annual Energy Use:	*638,000 kW-hr*	**585,000 kW-hr**
Annual Energy Production:	*638,000 kW-hr*	**648,000 kw-hr**
Size of PV System:	*580 kW*	**508 kW**
Watts per Panel:	*320 W*	**375 W**
Size of Array	*32,000 sf*	**24,000 sf**

Net Positive - 10% more energy produced than used

Fig. 14. Assessing the goal

Fig. 15. Fales Elementary School during construction with existing school in foreground

Fig. 16. Annie E. Fales Elementary School main entrance

Diversifying the Solar Workforce Through Inclusive Apprenticeships

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Abstract. A recent study from the Department of Energy showed the US solar industry workforce will need to triple by 2035 to meet deployment goals. The solar industry has made progress in recent years as far as building a diverse workforce but more can be done to reach untapped talent pools to support future growth. Approximately 26% of adults in the U.S. have a disability, but only 29.1% are employed. In fact, 10.7 million more employable Americans could enter the job market if companies focus on disability inclusion. Apprenticeship programs provide participants with paid "earn while you learn" training through in-classroom instruction and structured on-the-job training with an experienced mentor. Apprenticeship programs designed to be inclusive of people with disabilities, and underrepresented groups more broadly, can be a low-cost way to help companies of all sizes to diversify their workforce, boost productivity, reduce turnover and absenteeism, enhance their brand images, and more—all factors that can increase a company's bottom line. The Partnership on Inclusive Apprenticeship (PIA), an initiative funded by the U.S. Department of Labor's Office of Disability Employment Policy, can support solar employers to advance and enhance inclusive apprenticeship programs.

According to the United States Energy and Employment Report (USEER) 2021, much of the clean energy sector experienced job losses during the COVID-19 pandemic, and the solar industry saw an 8% decline in jobs. (U.S. Department of Energy, 2021) In 2020, the industry began rebounding, bringing an influx of 560,000 jobs into the energy sector and a continued need for solar workers (U.S. Department of Energy, 2021). As the nation moves passed COVID-19 pandemic business hurdles, experts anticipate continued growth in solar jobs (U.S. Department of Energy, 2021)[1]. A recent study from the U.S. Department of Energy projects that the solar industry will employ between 500,000 and 1.5 million American workers by 2035 (U.S. Department of Energy, National Renewable Energy Laboratory, 2021).

Though increasingly optimistic about the future outlook, many industry leaders face major hurdles to recruit and hire experienced candidates to fill the growing number of clean energy jobs. As outlined in the USEER 2021 report, 88% of companies in the electric power generation sector reported: "It was either somewhat difficult (69%)

[1] Growth estimates precede the anti-dumping and countervailing duties circumvention trade case that, as of April 2022, sits before the Department of Commerce and has the potential to significantly reduce solar deployment in the years ahead, per industry forecasts (Pickerel, 2022).

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https://doi.org/10.1007/978-3-031-08786-8_30

or very difficult (20%) to find new employees." (U.S. Department of Energy, National Renewable Energy Laboratory, 2021) At the same time, the energy sector is "less diverse than the nation as a whole," and employers are seeking ways to build diverse, equitable, inclusive and accessible workplaces (U.S. Department of Energy, National Renewable Energy Laboratory, 2021).

Apprenticeship programs that are designed to be inclusive of people with disabilities — and underrepresented groups more broadly — can play a vital role in building out the solar industry's future workforce. This talent pipeline offers a cadre of trained and experienced job candidates with diverse skill sets, knowledge and abilities (Accenture, 2021).

1 Bringing in Diverse Talent Through Apprenticeship

About 26% of adults in the U.S. have a disability (US Centers for Disease Control, 2020), but only 29.1% of people with disabilities aged 16–64 are employed (US Bureau of Labor Statistics, 2022). People with disabilities can bring a wealth of untapped talent and diverse perspectives into the clean energy sector, filling jobs ranging from solar power installers to systems engineers and market analysts. In fact, 10.7 million more Americans could enter the job market if companies would expand their focus on full inclusion of workers with disabilities (Accenture, 2018). An apprenticeship program that is designed to be inclusive of people with disabilities can create a diverse talent pipeline of valued workers and help build a more inclusive solar industry.

Apprenticeship programs provide participants with paid "earn while you learn" training through in-classroom instruction and structured on-the-job training with an experienced mentor. Inclusive apprenticeship programs can help take apprenticeships a step further. These programs are specifically designed to be accessible to and inclusive of all trainee workers, including people with cognitive, neurological, physical, mental health and sensory disabilities. In turn, recruiting and hiring these career seekers can help to foster more diverse, equitable, inclusive and accessible workplaces.

Launching an inclusive apprenticeship program can offer a low-cost way to help companies of all sizes diversify their workforces, boost productivity, reduce turnover and absenteeism, enhance their brand images and more. All of these factors can drive a company's mission and yield key advantages for its bottom line.

2 The Value of Inclusive Apprenticeship

Creating an inclusive apprenticeship program can represent a low-cost way to build a diverse pipeline of solar workers. "The Value of Inclusive Apprenticeships," a recently published resource from the Partnership on Inclusive Apprenticeship (PIA), summarizes the crucial advantages that these programs can bring to companies (Partnership on Inclusive Apprenticeship, 2021), including:

Significant return on investment: In 2020, the average Registered Apprenticeship program yielded a 170% return on investment for North Carolina employers (NC Department of Commerce, ApprenticeshipNC, 2020). Companies that embraced best practices for employing and supporting more workers with disabilities in their workforce achieved

28% higher revenue, doubled their net income, and attained 30% higher profit margins on average (Accenture, 2018).

Lower turnover and reduced training costs: The vast majority of apprentices (89%) maintained their positions, helping their businesses achieve a strong 3-year retention rate (US Department of Labor, 2018). At four Walgreens locations, the three-year average turnover rate was 48% higher for team members without a disability as compared to team members with a disability, saving on recruiting and training costs (American Society of Safety Professionals, 2012).

A wider talent pool: As noted earlier, only 29.1% of working-age adults with a disability are employed, compared with 70% of working-age adults without a disability. Nearly 11 million Americans could enter the labor force and pursue jobs, including through apprenticeships, if companies embraced full inclusion of workers with disabilities.

3 A Path Forward: Steps to Creating an Inclusive Apprenticeship Program

For those companies with an interest in creating inclusive apprenticeship programs, these five steps can help organizations kick start the process and meet their goals to become more diverse, inclusive, equitable and accessible businesses:

Step 1: Explore

Interested companies can explore how apprenticeship programs can help prepare and train the future workforce by learning more about the value of inclusive apprenticeship programs and how the Partnership on Inclusive Apprenticeship is advancing career paths in the clean energy sector[2].

Step 2: Build

Interested companies can learn how to create an apprenticeship program or partner with an existing apprenticeship program[3]. Additionally, many states offer funding sources that can aid businesses in developing programs, providing financial support for solar workforce expansion, apprenticeship training, and work access for job seekers with disabilities. Employers can pursue several tax incentives and grant programs. Learn more about funding an apprenticeship program[4].

Step 3: Partner

Interested companies can consider developing a new partnership to create an inclusive program, which may include collaborating with industry partners such as apprenticeship intermediaries[5]. These intermediaries can connect apprentices and employers to help launch, grow and maintain apprenticeship programs. They are often run by industry associations, chambers of commerce, community and technical colleges, community-based organizations, labor-management partnerships and workforce development boards.

[2] See: https://inclusiveapprenticeship.org/the-value-of-inclusive-apprenticeships/.
[3] See: https://www.apprenticeship.gov/employers/registered-apprenticeship-program/build.
[4] See: https://inclusiveapprenticeship.org/the-value-of-inclusive-apprenticeships/#3.
[5] See: https://www.apprenticeship.gov/employers/registered-apprenticeship-program/build.

Step 4: Register

Interested companies can find out how to register an apprenticeship program with the U.S. Department of Labor or a state apprenticeship agency[6].

Step 5: Launch

Interested companies can begin an apprenticeship program by recruiting and hiring talented career seekers[7] while ensuring such a program meets their accessibility goals by reading "Designing Inclusive Apprenticeships: A Guide for Recruiting & Training Apprentices with Disabilities"[8].

4 Research Questions Lie Ahead

As PIA continues to make progress on advancing workforce development programs among solar energy stakeholders, the team will look to highlight lessons learns and create case studies of how such programs have taken shape. PIA will also appeal to the growing community of workforce development professionals focused on diversity, equity, inclusion, and accessibility for further insights on how to apply best practices for inclusion of underrepresented groups in the solar workforce.

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[6] See: https://www.apprenticeship.gov/employers/registered-apprenticeship-program/register.

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Solar Certification Programs: NABCEP vs ETA International

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Abstract. Most people who have made solar PV their career are familiar with NABCEP and the certifications they offer to the industry. But most members of the general public have no idea such a program exists.

Those who teach technical skills in community colleges and universities across the USA are aware of the Electronic Technicians Association International (ETA-I) and the certifications they offer. But many within the PV industry have never heard of ETA-I.

Founded in 1978, ETA® International (ETA) is a not-for-profit trade association that serves technology-related industries by providing accredited individual certifications. ETA has issued over 180,000 technical certifications covering more than 90 certification programs in a variety of technology fields.

Since 2010, ETA has offered certification to those designing and installing solar PV systems. Over the years hundreds of students have become certified through this program largely through community colleges

NABCEP® was established in 2002 with the mission "to support, and work with, the renewable energy and energy efficiency industries, professionals, and stakeholders to develop and implement quality credentialing and certification programs for practitioners".

While the mission of these two organizations are similar, their approach to the certification of individuals working in the solar industry is slightly different.

So what are the similarities and differences between the two programs?

What is the difference between a certification program and a credential, and why does it matter?

And where are these certifications required to install solar?

Keywords: PV certification · NABCEP · ETA-I · Accreditation

1 PV Industry Certification Programs

Both ETA-International (Electronic Technicians Association International as well as NABCEP (North American Board of Certified Energy Practitioners) are not-for-profit 501(C)(6) industry associations.

The prime mission of both organizations is to develop and promote individual certifications within their perspective industries.

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Individual (or personal) certifications are designed to provide an independent third-party attestation that an individual has demonstrated a minimum level of competence, education and/or experience in a given field, as determined by a committee (usually) of selected industry experts.

2 NABCEP Programs

The first NABCEP certification examination was offered in 2003, designed to test and certify solar PV installers. Since that time, NABCEP has added seven more specialized certifications (all within the solar PV and solar thermal industries). In addition, NABCEP also offers three entry-level "credentials" targeted at the solar PV, solar thermal, and small wind industries.

These certifications are focused on and marketed to the North American marketplace.

Certifications offered by NABCEP include:

- PV Installation Professional (PVIP)
- PV Design Specialist (PVDS)
- PV Installer Specialist (PVIS)
- PV Commissioning & Maintenance Specialist (PVCMS)
- PV Technical Sales (PVTS)
- PV System Inspector (PVSI)
- Solar Heating Installer (SHI)
- Solar Heating System Inspector (SHSI)

The eligibility requirements of each program vary slightly. For the purpose of this paper, we will focus only on the PV Installation Professional (PVIP) credential.

In order to be eligible to sit for the design and installation examinations, the applicant must provide extensive documentation that they have "performed in a decision-making role" in at least three (generally) solar PV installations larger than 1 kW within the two-years prior to application.

In addition, the applicant must also provide proof of completion of 58 h of solar PV specific training, as well as completion of 10 h of OSHA safety training.

Once approved, the applicant must obtain a 70% or better score on the written examination. The certification is then valid for three years and can be renewed for additional three-year periods by providing proof of continuing education.

The associate-level programs offered by NABCEP are designed as a "credential" rather than a certification. These are targeted toward individuals who have no experience in the industry but would like to demonstrate a minimum level of competence in the field.

These associate-level programs offered by NABCEP include:

- Photovoltaics
- Solar Heating
- Small Wind

No experience or hands-on skills demonstration is required for these credentials. The applicant must document a minimum of 40 h approved training in the specialty and obtain at least a 65% score on a written exam.

The credential is then valid for three years and can be renewed for additional three-year periods by providing proof of continuing education.

3 ETA International Programs

Founded in 1978, ETA International first developed industry certification programs targeted to the electronics industries (primarily radio and television repair and maintenance). Over the years, ETA-I has issued over 180,000 technical certifications covering more than 90 certification programs that include not only electronics, but fiber optics, low voltage cabling, biomedical as well as renewable energy.

For the purpose of this paper, the focus will solely be on the solar photovoltaic certifications offered by ETA-I. These include:

- Photovoltaic Installer - Level 1 (PVI1)
- Photovoltaics Installer/Designer (PV2)

The PVI1 certification is designed for individuals who are new to the industry. To be eligible to sit for the examination, the applicant must have completed 40 h of approved training, as well as have demonstrated a set of installation skills (such as connecting and testing solar panels, connecting disconnects and inverters, etc.) to the satisfaction of an ETA-approved certification administrator.

The applicant must then obtain a 70% or better passing score on a written examination.

The credential is then valid for four years and can be renewed for additional four-year periods by providing proof of continuing education.

The PV Level 2 program is designed for experienced solar PV installers/designers. The applicant must demonstrate experience, based not on number of systems installed but based on having completed a number of specific tasks. The applicant must also document 60 h of approved industry-specific training as well as completion of 10 h of OSHA safety training. In addition, the applicant must obtain the ETA Customer Service Certification.

The credential is then valid for four years and can be renewed for additional four-year periods by providing proof of continuing education.

4 Accreditation

In the United States there is no governmental oversight of the certification process (as is the case in many other nations). The process is largely voluntary and self-policing.

In an effort to help define what constitutes a quality certification program, the ISO (International Organization for Standardization) has published the *ISO/IEC 17024:2012,* *Conformity assessment - General requirements for bodies operating certification of persons.* This standard outlines the steps and processes a certification body should perform when developing and administering an certification program (from selection of the development team, psychometric processes in developing the question database, security issues, renewal criteria, etc.).

Just as with certification, which is designed to demonstrate (by an objective third party) that an individual has met a set of skills and experience deemed appropriate by the industry, a number of accreditation bodies exist that evaluate if the certification credentialing body has met the criteria as outlined in the ISO 17024 document.

Two such organizations active within the US are ANSI (American National Standards Institute) and ICAC (International Certification Accreditation Council). These accreditation bodies must in turn adhere to performance standards as outlined in I*SO/IEC 17011 – Conformity Assessment: General Requirements for Accreditation Bodies Accrediting Conformity Assessment Bodies.*

ETA International is accredited by ICAC. NABCEP is not accredited.

5 License and Certification Requirements

While certification is largely a voluntary process designed to demonstrate excellence within a specific industry, a state license is a government-issued document that provides proof that the business is legally allowed to operate in a specific state.

Many states require that solar PV installation be performed by a licensed electrical contractor. Some states require a general contractors license. A number of states have developed industry-specific solar PV licenses that are required to install systems. Still other states require no license at all.

While no state currently mandates that any individual or company hold a solar industry certification to perform work, at the local level, cities and counties may require such documentation. There is, however, no national database that tracks such narrow and specific requirements.

Some statewide solar incentive programs do, however, require that installers be industry certified in order to be eligible to participate - such as the Illinois Shines Program.

Where required, these incentive programs will accept either the NABCEP PV Installation Professional certification or the ETA-I PV Level 1 or PV Level 2 certifications.

The NABCEP associate-level credentials are generally not accepted as they are not considered certification programs.

Summary:

Despite years of growth, the solar PV industry is still in its infancy. As with any new enterprise, the rules of the road have yet to be firmly established.

Many states have chosen to simply incorporate the licensing of this emerging industry into existing structures (such as electrical or general contractor licenses). Some states have developed targeted licensing geared toward the solar industry, while still others have ignored it altogether.

But state licensing addresses only part of the problem. As the industry grows and matures, customers will increasingly seek some third-party credential when selecting a

PV installer/designer to help in assessing the quality of the firm or individual. Solar PV certification programs will in large measure fill this role.

The PV industry currently has two well established and quality credentials from which to choose. While they approach the task in slightly different ways, they both have demonstrated a commitment to providing affordable and relevant certification to the industry as it grows and changes over the coming years.

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An Energy Democracy Evaluation for 100% Renewable Energy Policies and Projects

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Abstract. This paper is an energy justice/democracy evaluation of the ten, proposed renewable energy policies and projects identified in my "Emerald City 100% Renewable Energy Plan" published in the American Solar Energy Society Solar 2020 conference proceedings. The terminology energy democracy is used interchangeably with energy justice as it provides a wider framework of analysis and better political currency for multiple policy and project approaches. These policies include unlimited solar net metering, community/cooperative solar, climate crisis recovery fees (alternative to carbon fees), on-bill utility financing, rebates, time-of-use rate reform, grid harmonization (with local community broadband), bans on natural gas lines, and local financing with green banks and green bonds. An additional discussion includes the overall energy justice impacts of projects including solar PV, local electrification, commercial wind, and the elimination of natural gas. Two evaluation methodologies will be used, the Energy Democracy Scorecard and the Energy Justice Scorecard.

Keywords: Energy democracy · Energy justice · Energy democracy for 100% renewable energy

1 Introduction

1.1 Distributed Abundance

Solar, wind, and other renewable energy resources are everywhere. While the energy density for solar and wind is less than fossil fuels there is a great abundance, distributed locally and regionally for all to share. Renewable energy is distributive and regenerative by nature, providing the basis and a foundation for energy justice and application of 21st century economic thinking as outlined in Kate Raworth's seminal work, "Doughnut Economics: 7 Ways to Think Like a 21st Century Economist" [1]. However, we are limited in our ability to apply these distributed and regenerative natural and inherent characteristics of renewable energy in a just and democratic manner without the proper policies and governance.

These renewable energy characteristics, policies and projects can be applied anywhere. For example, on the spring equinox, Barrow, Alaska has twelve hours of sunlight (as with all locations on earth) at a time when heating and other energy needs are significant. Northern USA humid continental cities have high air conditioning electrical

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needs in the summer when solar resources are nearly as good as anywhere on the planet, available to meet peak electric demands at a lower cost than conventional peak period power prices. Winter winds can heat these cities at a cost lower than natural gas, balanced with thermal and electric energy storage.

1.2 Technology

With solar and wind energy costs dropping over 80% and 50%, respectively, over the last ten years, they are the lowest cost energy, period. New low cost, bi-facial and single axis tracking solar arrays now provide more early morning and late afternoon electricity when demand is highest, at a lower cost than previously not considered possible. New large rotor diameter wind turbines on tall towers can capture enough energy to power a rural township from a single wind turbine, generating some energy 90% of the time, with capacity factors of 40% or more in moderate wind resource areas.

1.3 The Challenge

With these abundant regenerative renewable energy resources distributed rather evenly, with these new low-cost technologies, the question addressed here is how we implement policies and projects to distribute the economic, social, and environmental benefits on a just and equitable basis. Providing a localized equitable distribution of renewable energy is the critical next step needed to rapidly advance clean energy, addressing the climate crisis, with what I call the inside-out approach—community based renewable energy. As reported in a recent Lawrence Berkeley National Laboratory study "Queued Up: Characteristics of Power Plants Seeking Transmission Interconnection as of End of 2021" [2], "there is a clean energy revolution taking place in the types of electricity we are seeking, but there are massive institutional and structural barriers that are slowing down and prohibiting a lot of capacity from coming on-line." The study reports that there is enough proposed wind, solar and battery projects seeking interconnection to the US transmission system to bring the country to 80% carbon free energy by 2030. New renewable energy projects proposed to enter the grid via the Mid-Continent Independent System Operator (MISO), for example, have a two-to-four-year study and approval wait time, and for the most part such projects are not locally owned, or built to supply energy in the most just and equitable manner. Importantly, local community power projects inside the utility distribution grid are not required to have MISO studies or enter the MISO queue. Working with electric utilities inside the distribution grid (local grid), such as a municipal utility, 100% renewable energy supply can be achieved without transmission system delays. Therefore, it is critical to evaluate and propose policies and projects based on their ability to provide, local, just, and democratically distributed clean energy. To conduct this evaluation, two scorecards are applied, the Energy Democracy Scorecard [3] curated by the Emerald Cities Collaborative, and the Energy Justice Scorecard [4], by the Initiative for Energy Justice.

2 Policy and Projects Scorecards

Policies provide the foundation for distributing energy in a just and equitable manner. As distinguished Michigan energy attorney, John Pestle (ret) once said, "All energy choices and prices are based on politics and policy.

Ten policies are evaluated including:

- Unlimited solar PV net metering
- Community/Cooperative solar PV
- Climate crisis recovery fees (alternative to carbon fees)
- On-bill utility financing (efficiency, solar, storage, etc.)
- Rebates: (efficiency, solar PV, storage, EV, fuel switching, etc.)
- Time-of-use (TOU) rate reform
- Grid harmonization (via community broadband, "smart grid" initiatives, EV charging controls, etc.)
- Bans on new natural gas connections
- Green Banks
- Green Bonds

In addition, some project applications will be evaluated, including solar PV, electrification initiatives, distribution grid upgrades, energy storage, energy efficiency and issues in relation to solar and wind turbine sitting.

2.1 Energy Democracy Scorecard

The Energy Democracy Scorecard has four main categories, each with sub-categories that are scored from 0 to 7: Extractive (0–1), Better or NOT good or great (2–5), Energy Democracy (6–7). They are as follows:

- Social Justice
  - Environmental Racism: Health Impacts
  - Environmental Racism: Siting of Energy Plants
  - Indigenous Sovereignty or Recognition
  - Land Justice (Displacement/Gentrification)
  - Energy Burden
  - Poverty
  - Community Benefits
  - Right to Energy
  - Access to Renewables
  - Access to Efficiency
  - Transportation System
- Regenerative Energy Systems
  - Culturally Appropriate Energy Systems

  - Renewable Energy Generation and Procurement
  - Energy Source
  - Energy Resilience
  - Electricity Compensation
  - Transportation Use
  - Transportation Fuels
  - Valuation of Extractive Energy Systems
  - Water Systems

- Moral Economy

  - Wages
  - Workforce Training
  - Local Hiring
  - Worker Transition
  - Worker Cooperatives
  - Labor Stance
  - Inclusive Financing
  - Divestment
  - Community Wealth

- Co-Governance

  - Energy Ownership Structure
  - Public Governance Structure
  - Tribal Sovereignty
  - Grid Structure
  - Bailouts and Bankruptcy
  - Transparency/Accountability
  - Community Engagement

2.2 Energy Justice Scorecard

The Energy Justice Scorecard has five categories. Each policy is scored from 1 to 5. 1 (No), 2 (A little bit), 3 (Somewhat), 4 (Mostly), and 5 (Yes).

- Process: Have marginalized communities participated meaningfully in the policy making process with sufficient support?
- Restoration: Does the policy aim to remedy prior and present harms faced by communities negatively impacted by the energy system?
- Decision-making: Does the policy center the decision-making of marginalized communities?
- Benefits: Does the policy center economic, social, or health benefits for marginalized communities?
- Access: Does the policy make energy more accessible and affordable to marginalized communities?

2.3 Scorecard Results

The Energy Justice Scorecard has a more limited application for this study as it is primarily focused on marginalized communities. In a small semi-rural, northern Michigan resort community, population 15,000, there are not a significant number of marginalized citizens. There is a small portion of population consisting of Indigenous, African American and Latinos. Low-income and senior fixed income citizens represent the largest marginalized group—many living in multi-family rental housing. Affordable housing is one of the leading issues. Policies and projects which address local non-profit and governmental institutions and small business interests are vitally important. As such, the Energy Democracy Scorecard has more relevance for this evaluation.

Table 1 and 2 with the following matrix presents the results for the Energy Democracy Scorecard. The policy score averages 6.67 out of 7, and the projects score is 6.28 out of 7, ranking high in terms of energy democracy.

Table 1. Energy democracy policy and projects scorecard results

POLICIES	Raw Score	Number of Categories	Adjusted Score (Raw score/ # of Categories) 7 = Energy Democracy
OVERALL SCORE			
Social Justice	456	69	6.58
Regnerative Energy	249	37	6.67
Moral Economy	147	22	6.84
Co-Governance	249	37	6.70
TOTAL	1101	165	6.67
Scoring: Extractive (0 -1), Better but NOT Good or Great (2 -5), Energy Democracy (6 - 7)			

PROJECTS	Raw Score	Number of Categories	Adjusted Score (Raw score/ # of Categories) 7 = Energy Democracy
OVERALL SCORE			
Social Justice	472	73	6.45
Regnerative Energy	364	54	6.75
Moral Economy	336	61	5.50
Co-Governance	247	38	6.57
TOTAL	1419	226	6.28

(*continued*)

Table 1. (*continued*)

SOCIAL JUSTICE		
	Score	**Discussion**
Unlimited Net Metering	6.1	While unlimited solar net metering is available to all metered customers, without available financing, especially long-term on-bill financing, low-income and multi-family housing residents are limited in this opportunity. Unlimited net metering means unreasonable size caps are removed, and the net meter price is equal to the retail rate.
Community / Cooperative Solar	7	These projects receive a perfect energy democracy score because all citizens are eligible to participate with any amount of money, and at this scale (> 100 kW) provides more affordable solar energy.
Climate Fees	6.3	The climate fees adjust electric rates, higher on-peak, lower off-peak allowing all customers to manage their electric use to lower costs and provide competive off-peak energy, cheaper than natural gas.
On-Bill Financing	7	This policy receives a perfect energy democracy score due to the fact and any customer, low-income or high income, can obtain low interest financing for energy efficency and renewable systems (Solar, storage, etc.), with the loan paid off via their electric bill. No other credit requirements other than a history of electric bill payments.
Rebates	7	Rebates for energy effiency equipment, EV's, storage, fuel swithching, and solar PV are available to all. Therefore a perfect score of 7.
TOU Rate Reform	6.2	Time of use rates can help all consumers, but not all rate payers will be impacted.
Grid Harmony	7	Grid harmonization is organized and implemented by the municipal, citizen owned, electric utility, for the benefit of all citizens.
Natural Gas Ban	6.7	A ban on all new natural gas connections, in conjunction with more affordable and financed electrification, with/without heat pumps, does not burden utility consumers.
Green Banks	6	While green banks can provide targeted lower cost loans for solar, efficiency, etc. credit worthness can limit certain customers.
Local Green Bonds	6.4	Local green bonds would be sponsored by the city or electric utiliy, and could encompass multiple projects, small and large, large solar, commercial wind, grid upgrades.
Combined Total	6.6	
REGENERATIVE ENERGY SYSTEMS		
Unlimited Net Metering	7	Unlimited net metering means unreasonable size caps are removed, and the net meter price is equal to the retail rate. For larger customers an adjusted lower price may be offered. Solar PV receives a perfect score, as a generation system
Community / Cooperative Solar PV	6.7	All citizens are eligible to participate with any amount of money, and at this scale (> 100 kW) provides more affordable solar energy. However, the value of larger scale community solar may be reduced, in contrast to the net metering value utilizing a fair feed-in tariff.
Climate Fees	6.3	Climate fees do not directly generate renewable energy, but are a vehicle to RE generation. The climate fees adjust electric rates, higher on-peak, and lower off-peak allowing all customers to manage their electric use to lower costs providing off-peak energy, cheaper than natural gas.
On-Bill Financing	7	This policy receives a perfect energy democracy score due to the fact and any customer, low-income or high income, can obtain low interest financing for energy efficency and renewable systems (Solar, storage, etc.), with the loan paid off via their electric bill. No other credit requirements other than a history of electric bill payments.
Rebates	7	Rebates for energy effiency equipment, EV's, storage, fuel swithching, and solar PV are available to all. Therefore a perfect score of 7.
TOU Rate Reform	7	Time of use rates are a funding vehicle for other renewable generation sources.
Grid Harmony	6.7	Grid harmonization is organized and implemented by the municipal, citizen owned, electric utility, for the benefit of all citizens.
Natural Gas Ban	6	A ban on all new natural gas connections, in conjunction with more affordable and financed electrification, with/without heat pumps, does not burden utility consumers.
Green Banks	6	While green banks can provide targeted lower cost loans for solar, efficiency, etc. credit worthness can limit certain customers.
Local Green Bonds	7	Local green bonds would be sponsored by the city or electric utiliy, and could encompass multiple projects, small and large, large solar, commercial wind, grid upgrades.
Combined Total	6.7	

(*continued*)

Table 1. (*continued*)

MORAL ECONOMY		
Unlimited Net Metering	7	Unlimited net metering means unreasonable size caps are removed, and the net meter price is equal to the retail rate. This is a moral imperative.
Community / Cooperative Solar PV	6.4	These projects receive a high energy democracy score because all citizens are eligible to participate with any amount of money, and at this scale (> 100 kW) provides more affordable solar energy, however, there may be some issues with location and neighbor impacts.
Climate Fees	N/A	The climate fees adjust electric rates, higher on-peak, and lower off-peak allowing all customers to manage their electric use to lower costs and provide competive off-peak energy, cheaper than natural gas. Not a moral question.
On-Bill Financing	7	This policy receives a perfect energy democracy score due to the fact and any customer, low-income or high income, can obtain low interest financing for energy efficency and renewable systems (Solar, storage, etc.), with the loan paid off via their electric bill. No other credit requirements other than a history of electric bill payments.
Rebates	7	Rebates for energy effiency equipment, EV's, storage, fuel swithching, and solar PV are available to all. Therefore a perfect score of 7.
TOU Rate Reform	N/A	Time of use rates can help all consumers, but not all rate payers will be impacted.
Grid Harmony	7	Grid harmonization is organized and implemented by the municipal, citizen owned, electric utility, for the benefit of all citizens.
Natural Gas Ban	7	A ban on all new natural gas connections, in conjunction with more affordable and financed electrification, with/without heat pumps, does not burden utility consumers.
Green Banks	6.3	While green banks can provide targeted lower cost loans for solar, efficiency, etc. credit worthness can limit certain customers.
Local Green Bonds	7	Local green bonds would be sponsored by the city or electric utiliy, and could encompass multiple projects, small and large, large solar, commercial wind, grid upgrades.
Combined Total	6.8	

CO-GOVERNANCE		
Unlimited Net Metering	7	The very nature of a public power municiple utility is democratic, assuming the board and management are responsive to citizen needs. For this example, the board of directors meet in a public forum, with meeting documents provided in advance and the bi-weekly or monthly meetings broadcast live on the web. There is no limit to public participation. Unlimited net metering means unreasonable size caps are removed, and the net meter price is equal to the retail rate.
Community / Cooperative Solar PV	7	These projects receive a perfect energy democracy score because all citizens are eligible to participate with any amount of money, and at this scale (> 100 kW) provides more affordable solar energy. An energy cooperative is democratic in nature, with many co-equal participants, guided by typical cooperative by-laws.
Climate Fees	7	These rates are set by an elected or appointed board of directors with public presentations available to all citizens. The climate fees adjust electric rates, higher on-peak, and lower off-peak allowing all customers to manage their electric use to lower costs and provide competive off-peak energy, cheaper than natural gas.
On-Bill Financing	7	This policy is established by the local citizen utility board of directors with public discussion. This policy receives a perfect energy democracy score due to the fact and any customer, low-income or high income, can obtain low interest financing for energy efficency and renewable systems (Solar, storage, etc.), with the loan paid off via their electric bill. No other credit requirements other than a history of electric bill payments.
Rebates	7	Rebates are governed and established by the local utility management and approved by the board of directors in a public forum. Rebates for energy effiency equipment, EV's, storage, fuel swithching, and solar PV are available to all. Therefore a perfect score of 7.
TOU Rate Reform	7	Time of use rates can help all consumers, but not all rate payers will be impacted.
Grid Harmony	7	Grid harmonization is organized and implemented by the municipal, citizen owned, electric utility, for the benefit of all citizens.
Natural Gas Ban	7	A ban on new natural gas lines is a significant city wide decision requirint major input from all citizens with public hearings. A ban on all new natural gas connections, in conjunction with more affordable and financed electrification, with/without heat pumps does not burden utility consumers.
Green Banks	5	A new green bank must have a citizen board of directors with members represented by a range of citizens, low-income, non-profit organizations, etc.
Local Green Bonds	6	Approvals are necessary from government elected officials and utility board members, with public presentation, probably a vote by local citizens, authorizing the green bonds. Local green bonds would be sponsored by the city or electric utiliy, and could encompass multiple projects, small and large, large solar, commercial wind, grid upgrades.
Combined Total	6.7	

Table 2. Energy democracy projects detailed scorecard results

SOCIAL JUSTICE		
	Score	Discussion
Small Scale Solar PV	6.8	This project category has a high score as all customers are potentally able to install solar under the unlimited net meter program. The only limiting factor is site availability and financiablilty.
Large Solar PV >100	6.11	Large solar refers to community, cooperative and utility solar PV. If the systems are inside the distribution grid and citizen or public power owned they get higher social justice ranking.
Energy Efficiency	6.22	Other than a lower ranking for "energy source" efficiency ranks high for social justice, only limited by access to financing by lower income citizens.
Energy Storage	7	Energy storage gets a high ranking, in part as it can account for transportation use and transportation fuel, via battery storage.
Commercial Wind	6.33	Commercial wind gets a high ranking, especially with local ownership, limited by potential siting issues and impacts on land owners.
Grid Infrastructure	6.5	Grid infrastructure benefits all citizens on the local distribution grid.
Grid Harmonization	7	This provides benefits to potentially all citizens on the public power grid.
CHP Biogas	5.67	Assuming a regional source of biogas (green gas) is available and comes from a sustainable source (agricultural waste, process waste, wind fall, etc.) biogas combined heat and power generation provide quick responce electric generation and heat (with thermal storage) for certain high use district heat applications, such as hospitals and schools. Large energy storage that can be charged both from CHP and excess solar and wind energy to harmonize the grid is feasible.
Combined Score	6.45	
REGENERATIVE ENERGY SYSTEMS		
	Score	Discussion
Small Scale Solar PV	7	This project receives a high score since all utility customers are potentally able to install solar under the unlimited net meter program. The only limiting factor is site availability and financiablilty. This solar is most productive during peak period summer demand.
Large Solar PV >100	7	Large solar refers to community, cooperative and utility scale solar PV. As long as the systems are inside the distribution grid and citizen or public power owned, they meet a higher social justice ranking.
Energy Efficiency	6.71	Other than a lower ranking for "energy source" efficiency ranks high for social justice, only limited by access to financing by lower income citizens. The score is a bit lower due to the lower "energy source" category.
Energy Storage	7	Energy storage gets a high ranking, in part as it can account for transportation use and transportation fuel, via battery storage.
Commercial Wind	6.71	Commercial wind gets a high ranking, especially with local ownership, limited by potential siting issues and impacts on land owners.
Grid Infrastructure	7	Grid infrastructure benefits all citizens on the local distribution grid and is critical part of the generation system.
Grid Harmonization	7	This provides benefits to potentially all citizens on the public power grid, harmonizing the generation systems.
CHP Biogas	5.57	Assuming a regional source of biogas (green gas) is available and comes from a sustainable source (agricultural waste, process waste, wind fall, etc.) biogas combined heat and power generation provide quick response electric generation and heat (with thermal storage) for certain high use district heat applications, such as hospitals and schools. Large energy storage that can be charged both from CHP and excess solar and wind energy to harmonize the grid is feasible.
Combined Score	6.75	

(*continued*)

Table 2. (*continued*)

MORAL ECONOMY		
	Score	Discussion
Small Scale Solar PV	5.86	This project category receives a reasonably high score since all utility customers are potentally able to install solar under the unlimited net meter program and we can assume that electricians and installers are receiving workforce training and fair wages.
Large Solar PV >100	6.13	This category can receive a reasonably high score as it is assumed there will be local, cooperative and professioal installers receiving fair wages. As long as the systems are inside the distribution grid and citizen or public power owned they meet a higher moral ranking.
Energy Efficiency	5.38	This scores a bit lower due to uncertainties with wages, work force training, worker cooperatives.
Energy Storage	5.13	Energy storage gets a bit lower ranking due to uncertainties on wages, labor stance, and financing. It can be assumed, however, that skilled mechanical and electrical contractors will be engaged in the installation of energy storage systems, thermal and electrical.
Commercial Wind	6	Commercial wind gets a high ranking, especially with local ownership, limited by potential siting issues and impacts on land owners.
Grid Infrastructure	5.63	Grid infrastructure benefits all citizens on the local distribution grid.
Grid Harmonization	4.86	This provides benefits to potentially all citizens on the public power grid.
CHP Biogas	5	Assuming a regional source of biogas (green gas) is available and comes from a sustainable source (agricultural waste, process waste, wind fall, etc.) biogas combined heat and power generation provide quick response electric generation and heat (with thermal storage) for certain high use district heat applications, such as hospitals and schools. Siting Large energy storage that can be charged both from CHP and excess solar and wind energy to harmonize the grid is feasible. Siting the CHP systems 6 or more) around the city raises the main issue.
Combined Score	5.5	
CO-GOVERNANCE		
	Score	Discussion
Small Scale Solar PV	7	This project category receives a high score as the public power utility establishes such programs under the supervision of the board of directors with open to the public hearings, and public comment.
Large Solar PV >100	7	This category can receive a reasonably high score as it is assumed the the governing body, the board of directors, approves the large solar project pricing and interconnection terms.. As long as the systems are inside the distribution grid and citizen or public power owned they meet a high governance standard.
Energy Efficiency	7	Energy efficieny programs with incentives, on-bill financing and rebates have significant input via the utility board of directors public meetings.
Energy Storage	7	Energy storage programs and incentives will be organized by the public utiltiy management and approved by the board of directors in public meetings.
Commercial Wind	6.4	Commercial wind projects require numerous public meetings and community engagement--usually a two year study and permitting process, with dozens of public meetings and engagements. Two or more public hearings are typical in the planning and permitting process.
Grid Infrastructure	6.2	Grid infrastructuer projects and upgrads must be planned my utility management, budgeted and submitted to the public board of directors for approval in public meetings.
Grid Harmonization	6.6	Grid harmonization projects "smart grids" must be planned, budgeted, and submitted to the utility board of directors for approval in public meetings.
CHP Biogas	6.4	Planning and siting a roughly 35 MW distributed CHP project is a major undertaking requiring years of planning, siting and installation work, all which must be reviewed and approved in numerous stages and public engagement meetings.
Combined Score	6.57	

Table 3 and 4 presents the results for the Energy Justice Scorecard. Policy scores 3.58 and projects score 3.625 out of 5.

Table 3. Energy justice policy scorecard results

ENERGY JUSTICE SCORECARD - POLICY						
Scoring key: 1 (No), 2 (A little bit), 3 (Somewhat), 4 (Mostly), 5 (Yes)						
	Question					
	(1) Process: Have marginalized communities participated meaningfully in the policy making process with sufficient support?	(2) Restoration: Does the policy aim to remedy prior and present harms faced by communities negatively impacted by the energy system?	(3) Decision-Making: Does the policy center the decision-making of marginalized communities?	(4) Benefits: Does the policy center economic, social, or health benefits for marginalized communities?	(5) Access: Does the policy make energy more accessible and affordable to marginalized communities?	Combined Score out of 25
Unlimited Net Metering	3	4	2	3	5	17
Community / Cooperative Solar PV	3	5	4	3	5	20
Climate Fees	3	5	3	5	5	21
On-bill Financing	3	5	3	4	5	20
Rebates	3	5	3	4	5	20
TOU Rate Reform	3	4	3	3	5	18
Grid Harmony	3	4	3	3	5	18
Natural Gas Ban	3	4	3	3	5	18
Green Banks	3	4	3	3	3	16
Local Green Bonds	2	3	2	2	2	11
Combined Score						3.58

Table 4. Energy justice projects scorecard results.

ENERGY JUSTICE SCORECARD - PROJECTS						
Scoring key: 1 (No), 2 (A little bit), 3 (Somewhat), 4 (Mostly), 5 (Yes)						
	Question					
	(1) Process: Have marginalized communities participated meaningfully in the policy making process with sufficient support?	(2) Restoration: Does the policy aim to remedy prior and present harms faced by communities negatively impacted by the energy system?	(3) Decision-Making: Does the policy center the decision-making of marginalized communities?	(4) Benefits: Does the policy center economic, social, or health benefits for marginalized communities?	(5) Access: Does the policy make energy more accessible and affordable to marginalized communities?	Combined Score out of 25
Small Solar < 100 kW	5	5	5	3	5	23
Large Solar >100 kW	3	4	3	3	5	18
Energy Efficiency	4	5	3	4	5	21
Energy Storage	3	4	3	4	4	18
Commercial Wind	2	3	3	4	5	17
Grid Infrastructure	2	3	3	3	5	16
Grid Harmony	3	3	2	4	5	17
CHP Bio Gas	2	4	2	2	5	15
Combined Score						3.625

3 Conclusions

Energy democracy, defined by the Institute for Local Self-Reliance [5] (ILSR), "means both the sources and ownership of energy generation are distributed widely. Energy democracy means that the distribution of power generation and ownership, and access to governance of the energy system be equitable by race and socioeconomic status".

Eight core principles of energy justice have been advanced by Benjamin Sovacool [6]: availability, affordability, due process, transparency and accountability, sustainability, intra-generational equity, inter-generational equity, and responsibility.

Meeting these principles can best be achieved by community owned, public power agencies--municipal electric utilities. While these municipal utilities represent less than ten percent of the USA electric distribution, they can quickly advance equitable renewable energy as they are locally controlled and governed with citizen board oversight, have competent administrative, service and maintenance organizations, often with broadband services that can apply "smart grid" programs, and can be what Dr. Hermann Scheer calls the "Archimedes wedge" in his book "Energy Autonomy [7]" where small actions leverage great change. A municipal electric utility can advance electrification programs, and with appropriate rate reform and structures can out-compete natural gas, new natural gas pipelines [8] and petrol fossil fuels, while doubling or tripling its electric distribution, bringing significantly more energy revenues to the local public, distributing benefits equitably, lowering costs, while fully utilizing the capacity of the local electric distribution system.

One way to describe this conceptual approach is what I call "inside-out, up-side down, and underwater." This illustrates and highlights some of the key electric utility institutional and contractual barriers to change. It is understood that significant electric transmission and distribution infrastructure must be upgraded and adapted to accommodate new renewable energy generation. These upgrades should begin inside out beginning on the local distribution grid, from the end users (homes, business, institutions, distribution sub-stations), limiting the need for more transmission upgrades. This requires that traditional utility managers and boards use upside down thinking, a way of thinking that is very challenging for traditional utility managers. Instead of thinking about generation coming in from the outside, they should primarily think about generation from the inside. Manage for efficiency (negawatts), storage, local solar and wind energy, local smart grid systems, improving the distribution system to handle two to three times the electricity for electrification initiatives, out-competing natural gas, bringing exported natural gas revenues home.

One major impediment is electric utility contractual obligations with underwater coal and atomic power plants. Long term-contracts and bonds requiring a "take or pay" obligation saddles utilities and delay's local generation opportunities. Fortunately, many of these underwater coal and atomic plants are losing money and aging out, and as such owners are seeking ways to decommission them as quickly as possible. Optimistically, many will be shut down within the next few years, opening the grid to new renewable energy systems, locally and regionally.

Applying these energy democracy principles and implementing these policies can quickly leverage the implementation of local, equitable, and distributed renewable energy, accomplishing 100% renewable energy in a matter of years, not decades. We are in a race against time, and it is urgent to implement just and equitable policies for 100% renewable electrification, eliminating wasted time on building, replacing, and repairing natural gas lines, unnecessary transmission lines, new atomic energy, and the continued extraction of fossil fuels.

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Abstract Papers

Optimizing DER Deployment for Climate, Health, Resilience, and Energy Bill Benefits Using the REopt Model

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Abstract. Climate change, public health, and resilience to power outages are of critical concern to local governments, federal agencies, and the private sector, and are increasingly motivating investments in distributed energy resources (DERs). However, designing a solar-plus-storage system to co-optimize for climate, health, resilience, and energy bill benefits requires complex trade-offs. To address this need, the National Renewable Energy Laboratory has integrated climate and health impacts of grid-purchased electricity and on-site fuel consumption into the publicly-available REopt web tool and API—a techno-economic model that determines the cost-optimal DER system sizes and dispatch strategy. This presentation will provide an overview of the tool's methodology, datasets, and capabilities, including costing emissions into system sizing and dispatch and setting emissions reductions targets. Results of previous work will demonstrate the use of new emissions accounting capabilities by, for example, quantifying the impact of including climate and health costs on the optimal resilient microgrid configurations for a hospital, school, and warehouse across 14 U.S. cities.

Keywords: Distributed energy resources · Emissions · Climate · Health · Optimization · Solar-plus-storage

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Innovative Rooftop CPV Cogeneration System for Electricity, Solar Hot Water and Supplemental Building Heating

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Abstract. Homes and buildings have energy needs encompassing electric energy needs for lighting, electrically powered systems & appliances (e.g., ventilation system, kitchen appliances, laundry appliances) and electronic equipment; as well as heat energy needs for domestic hot water, building heating and in some cases swimming pool heating. Conventional rooftop solar panels have the advantages of simplicity and low cost, but typically harvest only 20% or less of incident solar energy converted into electricity. For home or building electric energy and heat energy needs to be more fully met from solar energy falling on available roof area, it would be highly beneficial to complement simple solar panels with rooftop cogeneration modules that harvest 60% or more of incident solar energy into electricity plus usable heat, if innovation could be applied to minimize complexity and cost of a rooftop cogeneration system. This poster presentation at SOLAR2022 (Albuquerque, NM, June 22, 2022) describes the design, analysis and prototype testing of such an innovative rooftop solar cogeneration system currently under development by RIC Enterprises. The particular configuration being developed is called 'SuperSurya' and features an innovative combination of design features aimed to keep complexity, weight and lifecycle cost of energy (LCOE) low while also addressing considerations of modularity, robustness, weather tolerance, reliability, maintainability and aesthetics. The design features incorporated include (a) a low concentration linear reflector subsystem using a framed membrane reflector surface covered by an inflation-supported transparent ETFE protective cover; (b) two-axis heliostatic tracking using a sun sensor, an azimuth control gearmotor and an elevation control gearmotor; (c) a high-efficiency monocrystalline CPV linear receiver; (d) a heat transfer subsystem using a heat transfer fluid flowing behind the linear receiver to cool the receiver while extracting usable heat energy at 75+ deg. C; and (e) a modular set of beneficial heat energy end-use subsystems for desired combinations of solar hot water, supplemental building heat including use of phase-change heat storage for night heating, and swimming pool heating.

This poster presentation summarizes design development, preliminary analyses, and prototype development and testing of a prototype of the SuperSurya rooftop solar cogeneration system. A roadmap to implementation and beneficial deployments is also included.

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Keywords: Rooftop solar · Building innovation · Cogeneration · Concentrating photovoltaics (CPV) · Tracking · Solar hot water · Solar swimming pool heat · Solar building heat · Solar thermal

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Machine Learning for Solar Power Forecasting in Puerto Rico

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Abstract. We study the contribution of machine learning (ML) methods to improve cloud propagation in short-term (subdaily) global horizontal irradiance forecasting for photovoltaic solar power management in Puerto Rico in the context of an ongoing project at the Cooperative Institute for Research in the Atmosphere (CIRA) funded by the National Renewable Energy Laboratory (NREL). We synthesize data streams including GOES-R geostationary satellite imagery, numerical weather prediction (NWP) wind and cloud forecasts, and ground-based observations to improve cloud and cloud-shadow forecasting, and hence solar power forecasts. One ML method explored is regression random forests, which allow flexible nonlinear dependencies of the forecast model on variables such as topography and synoptic conditions. Another approach is a multimethod one based on automated ML, as implemented in Python's auto-sklearn toolkit. The developed model is compared to the currently state-of-the-art mechanistic approach where NWP wind fields are used to propagate GOES-R clouds, which has difficulty capturing orographic and time-of-day effects on cloud location and thickness. We keep the same data pipeline as for the existing method, allowing the new approach to be dropped in to a container application that can run in a cloud computing platform and issue real-time forecasts.

Keywords: Resource assessment · Solar power · Supply forecasting · Meteorology · Random forest regression · Automated machine learning

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Cloud Segmentation and Motion Tracking in Sky Images

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Abstract. In this work, we present two different algorithms to aid in real-time weather predictions. This information can be used to inform the movement of a tracker or short-term power predictions. It is known that cloud cover causes insolation to become more diffuse; identifying clouds and predicting their movement can be useful in a variety of ways. This work presents a convolutional autoencoder (CAE) to identify clouds and a particulate tracking implementation to predict movement trends. The CAE model was chosen to integrate information from multiple traditional vision approaches to cloud segmentation, and a particle tracking approach is useful in areas such as Albuquerque, NM where clouds move in smaller fragments due to rapid variance in wind direction caused by the mountains. By combining neural networks and more classical technologies, the system becomes more robust and explainable then either image processing or pure neural network technologies, respectively. This work presents a vital piece of a single axis tracking control algorithm that is currently in development. Current tracking methods generally ignore local, intra-hour weather conditions, which leaves performance on the table that can be fixed with a low-cost, plug-and-play update to the controllers. At utility scale, this can lead to sizeable performance increases in the long-term. This work serves as a case study for machine learning analytics applied to practical PV problems.

Keywords: Sky image · Cloud motion · Deep learning

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Getting to Yes: Fostering Support from Solar from Neighbors, Local Governments, and Community Leaders

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Abstract. Neighbors and local stakeholders are often the loudest voices on solar projects, and the solar transition is facing numerous challenges at the local, community and neighborhood level from an array of different constituencies. These challenges arise in a wide variety of contexts but are often based on so-called "aesthetic" considerations. State laws vary widely as to the leeway afforded to various governing entities, from HOAs to local jurisdictions, to regulate and restrict solar development. This presentation will briefly summarize these laws, then address how to account for law, policy and public interactions to garner public support and political force from those who are in favor of solar – who say YES in my backyard. It will examine how to proactively ensure those opposed are heard and their concerns are addressed. Issues of economic justice, ensuring access to solar for all, and dispelling elitist views about the impacts of solar to a community will also be confronted.

Keywords: Covenants · HOAs · Solar neighborhoods · Community advocacy · Community planning · Solar design

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Author Index

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