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Mitigating Climate Change

Proceedings of the Mitigating Climate Change 2021 Symposium and Industry Summit (MCC2021)

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Editors

Mitigating Climate Change

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To those who work together to perpetuate planet Earth

Preface

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MITIGATING CLIMATE CHANGE
2021

To paraphrase Mother Teresa concerning our complementary abilities, “I can do things you cannot, you can do things I cannot; together we can do great things,” together we can forge a better tomorrow. Mitigating Climate Change 2021 brings together twenty-five experts of differing specialties from around the world to advance our collective endeavour to turn the tide of significant human-caused environmental damage. To defeat the impact of changing climates, mitigation alone is not enough; we must adapt and, for this, effective adaptation strategies are needed. Reader delineates the details of this comprehensively in Chap. 1, “Defeating the Impacts of Changing Climates.” Further capitalization of solar is an essential step forward. An outstanding challenge with solar cells is low efficiency. It is comforting to see continuous progress on this front. In Chap. 2, “Comparison of Critical Performance Characteristics of Perovskite-Based Flexible Solar Cells,” Sua and Balo disclose the assessment of the collection of parameters needed for the accurate assessment of solar concentrator cells. Even more challenging, in terms of electricity conversion efficiency, is the current thermoelectric generator. There are, however, many applications where the usage of thermoelectric generators is beneficial and, more so, as their efficiency continues to improve. Maduabuchi et al. present a unique combination of a solar thermoelectric generator and a compound parabolic concentrator in Chap. 3, "Electro-thermal and Mechanical Optimization of a Concentrated Solar Thermoelectric Generator." Solar energy sustains life on Earth and this abundantly available clean energy must enter every sector to resolve our environmental challenge. Transportation ranks high on the list in terms of both energy usage and environmental pollution and, thus, Chap. 4, "Green Technology: Application of Solar Energy into the Transportation Sector for Global Energy and Environmental Vulnerability" by Hossain, is dedicated to it. Renewable energy is critical to the mitigation of climate change. As such, furthering of wind energy is a given. Bashir and Khan communicate, in particular, the latest advances in wind energy, in Chap. 5, "Renewable Energy Sources: A Study focused on Wind Energy." Note that energy storage strategies are an essential complement to progress in renewable energy such as wind. A good intention will remain as a good intention unless there is financial backing. Accordingly, "Financial Optimization in the Renewable Energy Sector" is presented by Gökgöz and Erdoğan in Chap. 6. The idea is to match supply and demand better, and this has a lot to do with appropriately regulating the electricity market. The Turkish electricity market is chosen as an illustration of the working of their optimization models. Money alone as a driver would not go far; proper policies must also be established. Leech and Schuelke-Leech argue that crises can bring forth immediate action in Chap. 7, "Policy Responses to Climate Change: Lessons from Covid and Other Historical Crises." It is time for a generational mobilization, replacing our entitlement habits in this age of consumption with environmentally sustainable ones. Policies are needed to realize this fundamental shift, that is, accountable and consistent politics. Good health care is imperative for a sustainable tomorrow. What better message can the health care sector convey than being green and environmentally friendly herself? This is the topic of Chap. 8, "An Energy-Efficient Green Design and Modelling of a Health Clinic located in a Cold Climatic Zone." In this chapter, Balo et al. demonstrate the utilization of building energy modelling and building information management in running a health clinic in a cold region. Thermal comfort, including indoor air quality in elderly care centres, is described and examined by Seduikyte et al. in Chap. 9, "Study on Thermal Comfort in Elderly Care Centres." Specifically, they investigated an elderly care centre in Kaunas, Lithuania using computational fluid dynamic simulation. Mechanical ventilation with underfloor heating is found to be the solution. Dental is a very significant part of health care and, thus, dental implants are the topic of the final chapter, "Evaluating Alternatives in Dental Implant Materials by SWARA and Grey Relational Analysis." Mahmat et al. disclose the use of multi-criteria decision-making methods, SWARA for choosing the most important criteria for choosing dental implant materials and implement Grey Relational Analysis, based on the chosen criteria, to select the most suitable dental implant materials.

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David S.-K. Ting
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Acknowledgements Complementary efforts are essential in mitigating climate change and in compiling this volume, Mitigating Climate Change 2021 in the midst of the pandemic. We are most grateful to the twenty-five experts who compiled the ten timely chapters and the equal number of anonymous experts who reviewed the various versions of the manuscripts. DT is indebted to his grammar angel, Dr. Jacqueline A. Stagner. The editors are unaware of a team that is more efficacious than the Springer Nature team, led by Anthony Doyle and Jayanthi Krishnamoorthi. Most of all, completing this undertaking during the daunting pandemic was only made possible by the enduring grace from above.

Contents

Chapter 1
Defeating the Impacts of Changing Climates

Graham T. Reader

Abstract The Earth's climate has changed several times during the last million years, with many instances of glacial expansion often resulting in drought, famine, and floods. Our human ancestors adapted to these changes, mostly by geographic migration, but if they took no adaptive measures, or were unable to, they likely did not survive. After the last major ice age, the *Holocene* (the last 11,700 years of Earth's history) began and the gradually warming Earth enabled homo sapiens, especially those living in the geographic *lucky latitudes*, to develop agricultural food production and domesticate animals; two of the vital elements which led to the establishment of modern civilizations and societies. More recently, over the past 3 centuries, the global human population has increased by a factor of about 8 and it is forecast, by the United Nations, to increase by at least another 30% from today until the end of the twenty-first century. This recent era of population explosion coincided with an increase in the global consumption of fossil energy, which is now 1400 times greater than at the start of eighteenth century. There were positive outcomes from such energy use but, increasingly, there are concerns about the high possibility of damaging climate effects from fossil fuel emissions, such as Greenhouse Gases (GHGs). Subsequently, in addition to natural climate changes brought about by volcanic eruptions, disruptive solar activity, earthquakes, and periodic orbital cycle variances, anthropogenic (caused by human activity) influences must also be taken in account. Can adaptation alone address the vagaries of changing climates? It appears not, and there is a global belief that only the mitigation of GHG emissions will restore the Earth's inherent ability to accommodate changing climates. So, for the past two decades, global governments focused-on mitigation measures involving transitions away from fossil fuels to renewable energies. But will the mitigation of anthropogenic affects also reduce the impact of

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This Chapter is partly based on an extended abstract presented at the *Thriving Through Climate Change and Pandemic 2021*, Symposium and Industrial Summit, June 24–25, held at the University of Windsor, Windsor, Ontario, Canada, https://scholar.uwindsor.ca/ttccap/.

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natural changes on climate? Can we afford to overlook adaptation strategies until mitigation is successful? If not, what adaptation strategies will be needed to avoid local weather and climate disasters? Meaningful combinations of mitigation and adaptation to defeat the harmful impacts of changing climates do not appear to receive palpable financial support. Why not? These questions are discussed in this chapter.

Keywords Adaption · Climate change · Mitigation · Variability

1.1 Introduction

Changes in climate prior to the latter part of the twentieth century are normally attributed to natural causes, for example, varying solar activity, volcanic eruptions, earthquakes, and cryosphere melting. Humans adapted to these changes by such measures as migration, precipitation harvesting, flood prevention, and irrigation. Natural causes and climatic occurrences, such as the changing orbits of the Earth relative to the Sun (*Milankovitch* cycles), can have short-term, and sometimes long-term, impacts on climate, but usually the Earth eventually self-adjusts, albeit that glacial expansions, ice-ages, are more frequent than global interglacial periods when atmosphere and water temperatures rise, i.e., the globe *warms*. However, since the start of the industrial revolution, variously defined as 1750 Common Era (CE) or 1850 CE, the human population has rapidly increased, accompanied by similar growths in fossil fuel usage although, even today, biomass, especially wood, is still the fuel source used for cooking, heating, and lighting by between 33 and 39% of the global pollution [1–3]. All these hydrocarbon fuel sources produce Greenhouse Gases (GHGs) which have increased the *natural* global levels at a pace which the Earth cannot readily adjust to in the rest of this century, or, maybe, not even in the next [4]. Numerous scientific investigations since the 1990s have found that the GHG issue is the main cause of rapidly increasing surface and ocean temperatures as well as sea-level rises [5]. The ensuing analyses were, and continue to be, strongly focused on developing complex climate models which have the capability of accurately reproducing past climate observations and, therefore, if successful, can be used to predict[1] future climates with the same degree of precision and confidence. Of course, comparison between modelling results and actual observations can only be made after the future arrives and then becomes the past, nevertheless based on recent measured data it was reported that, despite continuing uncertainties, some models are getting better at projecting future trends [6].

In 1992, the United Nations Framework Convention on Climate Change (UNFCCC) chose to differentiate between changes in climate caused by natural forces and those associated with anthropogenic activity, by defining the impact of

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[1] Climate Scientists now tend to use the term projection rather than prediction.

the former as *climate variability* and the latter as *climate change*.[2] Modern changes in climate, using the same convention, are presumed to be caused by humans, especially from the emissions of GHGs largely generated by the combustion of fossil fuels. Subsequently, instead of humans finding ways to adapt to changes in climate by such measures as migration, precipitation harvesting, flood prevention, and irrigation, *mitigation* has become the approach to reducing the harmful effects of climate change. The focus being on reducing Carbon Dioxide emissions by energy use transitions to renewable and sustainable sources such as solar, wind, and water. The overall aim of mitigation being, not only to reduce anthropogenic impacts on climate, but also to eventually end them and, maybe, even reverse their effects. But can mitigation eradicate non-human climate variabilities? If GHG emissions are removed from the atmosphere will that prevent volcanic activity, earthquakes, cryosphere melting, extreme weather events, sea-level rise, and the orbital effects of Milankovitch cycles? The answer is no, since the probability of mitigation counteracting the natural effects of volcanoes, earthquakes, and orbital causes, range from unrealistic to impossible. However, climate models suggest that mitigation should inhibit ice melts, reduce the number and severity of weather events, restrict, or eliminate, sea-level rises, and limit increases in land and ocean surface temperatures. But how long will it take for mitigation to fulfil these promises? In the meantime, should adaptation measures be encouraged to constrain the harmful effects of both natural and anthropogenic climate drivers?

The appropriation of the term *Climate Change* by the UNFCCC has likely caused confusion among the general population and prompted some of the disagreement in the scientific community debates. Those who comment that changes in the climate have always occurred are often vilified and disparagingly labelled *deniers*. This situation is regrettable, but the confusion and the scientific challenges has roots in the assertion that climate change is due to human activities alone, as pronounced in the first reports of the UN's main scientific source, the Intergovernmental Panel on Climate Change (IPCC), and in the stated 'green' policies of the political governments of the associated UN countries. Providing, an example of what could be described as a *humpty-dumpty* definition [7], i.e.,

> "When I use a word," Humpty Dumpty said in rather a scornful tone, "it means just what I choose it to mean — neither more nor less". "The question is," said Alice, "whether you can make words mean so many different things."

Can it then be assumed that, prior to the arrival of humans, the Earth experienced no changes in climate? Palaeoclimatological studies, i.e., the what, when, and why of the Earth's climate since its formation about 4.6 billion years ago, have shown many changes in climate [8, 9]. The studies identified several factors as climate *influencers,* and these continue to contribute to these changes. Some scientists have found that the *greenhouse-effect* has always been the main climate *controller*, mainly through the variations in the levels of atmospheric Carbon Dioxide (CO_2).

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[2] Defined in Article 1 UN https://unfccc.int/resource/docs/convkp/conveng.pdf, 1992.

Other influencers, such as deviations in solar irradiance and cosmic rays are said to have only a small effect on climate, except in a few extreme cases, which are rare and temporary [8]. Not all scientists agree [10, 11]. Perhaps such disagreements are an inherent characteristic of the ubiquitous *scientific method*, compounded by the need for more hypothesis testing data. Despite the age of the Earth, methodical measurements of atmospheric CO_2 concentrations, using scientific instruments, did not start until the middle of the last century. Comparable quality surface temperature measurements have a slightly longer history, being available from the 1850s. How then can there be definitive statements about past climates and their changing nature? The answer is, by using *proxies* such as ice cores, tree-rings, and geological analyses. Subsequently, by using climate models, efforts can be made to replicate the proxy and measured data by finding possible causes for changing climates and assessing their impact on the quality of the model replication. This parametric-type approach has led to CO_2 atmospheric concentrations being considered the main cause of historical, and current, changes in climate; albeit that by volume CO_2 only accounts for 0.0407% of the current atmosphere [12]. Nevertheless, this miniscule proportion, and changes in its level, are believed to be the main influence on anthropogenic climate change and the key disrupter of climate stabilization.

A certain amount of atmospheric CO_2 is a necessary contributor to the *greenhouse-effect* which keeps the Earth at habitable and ecologically beneficial temperatures. But what are these temperatures, i.e., is there an ideal average surface temperature? There appears to be no definitive answer in the available encyclopedic scale literature on *global warming,* especially since the pre-industrial period[3] prior to 1750 CE[4] [13]. At that time, according to the *proxy* data, the global surface temperature was 13.42 °C [14], but in the twentieth century the measured global average land and ocean surface temperate was only 12.7 °C, which, by 2020, had risen to 13.86 °C [15]. However, others suggest that the average temperature over the last century was 13.9 °C, which, by 2019, had increased to 14.85 °C [16]. Such differences could be construed as unhelpful, but illustrate the difficulties met when trying to be definitive about average absolute[5] temperatures and probably explains why climate scientists prefer to use temperature anomalies i.e., differences between average temperatures over a given period, compared to a baseline average computed over another specific time span. Defining a baseline is therefore important when defining temperature anomalies, so when the members of the UNFCC formulated the 2015 Paris Agreement on climate change the chosen baseline was the *pre-industrial* period and the goal was to limit global warming in this century by achieving a temperature anomaly "*to well below 2, preferably to 1.5 °C*" compared to this period [17].

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[3] There appears to be some disagreement about the exact date.

[4] After a quoted year, CE stands for the *common era*, while BCE stands for *before the common era*.

[5] Not in the thermodynamic sense using the Kelvin scale.

So, why not add this targeted anomaly to the actual average temperature of the chosen baseline to provide the public with a definitive and understandable mean global temperature limit? Is this because the strength of messaging on climate change would be diluted by saying the temperature must be limited by 2100 to less than 1% higher than 1750, perhaps using the Kelvin temperature scale? The most likely answer is yes, but, in general, the Kelvin scale is only regularly used by engineers and scientists. A stronger message could be communicated if the Celsius (centigrade) scale were used as 15.42/13.42 would yield a 14% higher temperature limit, albeit the difference between a Celsius and Kelvin increase being a quirk of definition. Perhaps then the temperature anomaly approach is more efficacious if the baseline is clearly defined? But here again there can be problems, since there are contradictions in exactly *what is the pre-industrial period*. The IPCC have defined this period as being "*prior to the onset of large-scale industry activity around 1750*" [18] although both the IPCC and UNFCC have chosen the 51-year period, 1850–1900, "to approximate the pre-industrial *global mean surface temperature (GMST)".* The preferred 1.5 °C increase limit is based on this latter baseline. However, the NASA global temperature website base their anomaly charts from 1880 onwards on a baseline of 1951–1980 [19].

For the IPCC's *Special Report on Global Warming of 1.5 °C* a more detailed working definition of the target anomaly was adopted, i.e., a limiting increase of 1.5 °C warmer than 1851–1900 period or 0.87 °C more than 1986–2005 or 0.67 °C above the 2006–2015 average, likely to give more perspective to the mitigation targets [20]. Therefore, in assessing how much mitigation is needed, there is no target average global temperature, but only temperature anomaly targets based on differing baselines, which are probably not known or taken cognisance of by the public. Given that it can be somewhat tricky to measure mitigation success using surface and ocean temperatures, actual or anomalous, is there a more convincing yardstick? There is global acceptance of the CO_2 concentration data from the Mauna Loa observatory in Hawaii [21], and as there are often published correlations between average surface temperatures and atmospheric CO_2 levels, then reductions in GHG levels should be followed by temperature declines. Would CO_2 measurements then supply a better benchmark for mitigation success? Maybe, but it is also true that there are regional and historic instances where temperature rises happen before CO_2 concentration growth, but, even in these circumstances, the higher CO_2 levels can eventually amplify the temperature increases [22]. So, what does all this mean? If mitigation is the strategy to combat UNFCCC climate change, then authoritative measures of strategic success will be tenuous until universally accepted data becomes available. But can we wait until the end of the century? Perhaps the best that can be done is to use the continually improving hundred or so climate change models to predict the impacts of mitigation under various *what-if* scenarios? However, the accuracy of climate models' projections to-date has not been wholly encouraging, although, with the inclusion of some climate variabilities, they do appear to be improving [6].

Irrespective of the scale of success that mitigation strategies may achieve, at present there is measurable proof that changes in climate are taking place in many global regions, especially as measured by sea-level rises, albeit that *sea-level* is a surprisingly difficult concept to define. If the trends in such rises are well documented and substantiated, then it would be remiss not to construct suitable and proper sea-wall defences around the impacted population centres. Such an approach would be an obvious example of adaptation. But, if eventually mitigation were to prove successful, would immediate or short-term adaptation be necessary solely as a *band-aid* solution until ample mitigation successes are achieved? Conceivably, a parallel modern context could be whether face masks, social distancing, and lock-downs will suffice until efficacious vaccines for all become available in combating a global pandemic. However, not all vaccines provide lifelong immunity and further booster shots may be needed to eradicate the cause of a particular disease. In many cases, while pandemics can be avoided by global vaccination strategies, total elimination of harmful diseases has proved to be exceptionally challenging[6] and seasonal epidemics regularly occur.

In likening *mitigation* to immunization, and *adaptation* to mask-wearing, physical distancing etc., the contention is that mitigation *alone* will not eradicate the impacts of climate change and that more focus on adaptation will be necessary, not only as part of the continual human attempts to avoid the harmful effects of climate variability, but also to complement mitigation. This contention is explored in this chapter, while appreciating that with both approaches the interminable nuances are likely to be *costs*, human, societal, political, and economic. Subsequently, after discussing, in Sect. 1.2, exactly what is meant by mitigation and adaptation as defined by the IPCC [5, 16], in Sect. 1.3, the historical context and current approaches to mitigation, including the prospects and risks of using *geoengineering* are described. The approaches to adaptation of climate variabilities and the possible advantages and disadvantages of conjointly using mitigation and adaption are examined in the proceeding sections. Final remarks are given in Sect. 1.6.

1.2 Mitigation and Adaptation

As the climate debates began in earnest with the UNFCCC declarations of the 1990s, and the later IPCC Assessment Reports (ARs) which underpin the Paris Agreement, in any discussion of mitigation and adaptation it is arguably valuable to consider how these strategies are defined in these documents. It also needs to be emphasised, especially for post-secondary students, that IPCC reports incorporate a wealth of information and encyclopedic literature reviews and that individual chapters are multi-authored. It would be neglectful for any scholar or researcher to take no account of these publications in their climate studies. Unfortunately, the sections known as *Summaries for Policymakers* (SPM) do not always fully reflect the content of the individual chapters and this can lead to cavalier and misleading

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[6] To date, only small-pox has been eradicated in the past two centuries.

Table 1.1 IPCC AR5 [16], working group main report statistics

AR5 working group number	Description	Number of pages of main report	Lead and contributing authors	Number of references/ citations	Reviewers
1	Physical science basis	1552	809 (209 Lead/ 600 + contributing)	>9200	1089
2	Impacts, adaption, vulnerability	1846 (1150-Part A; 696 Part B)	678 (242 Lead/ 436 contributing)	>12,000	1729
3	Mitigation of climate change	1454	411 (235 Lead/ 176 contributing)	~10,000	1046
	Synthesis[a]	169			
All		5021	1898	~31,000	3864

[a] Distils and Integrates the findings of AR5 Working Groups 1–3 and incorporates the findings of IPCC Special Reports (a) *Renewable Energy Sources and Climate Change Mitigation* and (b) *Managing the Risks of Extreme Events and Disasters to Advanced Climate Change Adaptation*

quotations in the media. In the author's opinion, SPMs tend to be as much political and agenda-driven as scientific, but the peer reviewed main chapters present high-calibre, scientific, studies, even if, at times, the stated confidence and certainty levels may be revealed, ultimately, as somewhat inflated. The scale of the recent AR studies on adaptation and mitigation can be gauged by the details of AR5 as summarized in Table 1.1. It would be sensible for post-secondary students, their teachers, and researchers not to ignore such a comprehensive collection of peer-reviewed material.

The precise wording of the definitions of Mitigation and Adaptation has changed since the first UNFCCC and IPCC statements, almost 3 decades ago. In AR5 the reason for the amendments to adaptation is *progress in science* while for Mitigation, substances other than GHGs are included in the definition [23]. These added substances have long been named as criteria air pollutants by many countries. Shortened forms of these definitions are,

> Adaptation: *The process of adjustment to actual or expected climate and its effects.*
>
> Mitigation: *A human intervention to reduce the sources or enhance the sinks of greenhouse gases.* [The AR5 report] *also assess human interventions to reduce the sources of other substances which may contribute directly or indirectly to limiting climate change.*

Throughout the IPCC AR5 report the virtues of both Adaptation and Mitigation are emphasized, but global financial investments and strategies have, almost without exception, firmly focused on mitigation activities. These activities attracted $537 Billion US (93%) of total finance in both 2017 and 2018, which represents over 50% more, in US$ terms, than in 2010/11, but with a slightly smaller proportion, 93% versus 96% [24, 25]. This level of financial investment is a clear demonstration, perhaps, of the '*prevention is better than cure*'[7] approach, which underpins the medical and health sciences approach to disease control, as embedded in many national government policies [e.g., 26]. One dictionary explanation of the phrase is, "*It is better to stop something bad from happening than it is to deal with it after it has happened*" [27]. Could this philosophy be used to clarify the differences between mitigation and adaption? The answer is both yes and no. Mitigation is aimed at preventing something bad from happening i.e., anthropogenic climate change, but many climate scientists assert that something bad has already happened and the situation is likely to get worse. If this is the case, then, arguably, any mitigation measures could be viewed as a form of adaptation, at least until the anthropogenic climate change situation stabilizes. But how will it be known when this condition is achieved? As already noted, there are uncertainties surrounding global mean surface temperature estimates and precise CO_2 correlations. Indeed, a targeted CO_2 concentration level does not necessarily create a specific mean global temperature, or temperature anomaly, which can be used by politicians as a measure of mitigation success [28]. For now, there is only general political agreement that the average global temperature rise *should be* limited to no more than 2 °C, and preferably lower, by 2100. Any increase above 2 °C is depicted as being climatically dangerous. Yet, by some estimates the global temperature had already increased 1.1 °C by 2020 [29].

Whether or not the *should-be* limit can be achieved is a matter of intense discussion and analysis. If the use of fossil fuels were banned, it is hypothesised that global warming would continue and take at least four decades for the global temperature to stabilize, but at a higher level than experienced at the time of the prohibition [30]. As cutting fossil fuels is a cornerstone of mitigation strategies, then the consequent time-lags palpably reinforces the need to adapt to continually rising temperatures. Whatever the issues associated with defining targets and benchmarks it is obvious that both mitigation and adaptation strategies will be necessary to address the 2015 Paris Agreement goals. It can also be argued that adaptation improvements will need to be continual, even after mitigation is believed to be a success, so that adverse, albeit relatively temporary, natural changes in climate, floods, droughts, and so on, can be tackled as the need arises. The challenge will be how to fund these improvements to account for all eventualities. But what if the *eventuality* is an annual, or a *10-year,* or a *100-year,* or even a *500-year occurrence?* The likelihood of these occurrences, and their impact, should be a key element of adaptation. Normally adaptation infrastructure designs are based on a 100-year occurrence but that is not to say that two such events could not be experienced in consecutive years. There are a several *eventualities* or *occurrences* indices which are used for analysing and assessing changing climate and weather patterns. These are regularly updated as discussed in Sect. 1.4.1.

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[7] A tenet attributed to the Dutch philosopher Desiderius Erasmus at the start of the sixteenth century.

As will be seen, the approaches to mitigation and adaptation are not necessarily mutually exclusive, although their individual aims, as defined in Sect. 1.2, could be interpreted as requiring separate mind-sets. But if there is legislated mitigation to the use of non-carbon fuels, will that not require societal adjustment to the adaptation of the *new* energy sources? Moreover, some advocated mitigation methodologies require that people adapt their diet to reduce their meat and dairy product consumption by up to a half by 2050 [31], raising millennia old philosophical questions, which legal and political science scholars still grapple with, such as *obey or persuade,* and whether *political obligation* is the same as a duty *to obey the law* [32]? Difficult questions which, while they cannot be wholly ignored when considering the differing approaches to defeating the impact of adversely changing climates, even cursory attempts to answer are somewhat beyond the scope of this chapter.

1.3 Approaches to Mitigation

1.3.1 Historical Context

Mitigation was not a commonly used term, or even a major discussion topic, among scientists until the last two decades of the twentieth century. Therefore, it could be valuable, to appreciate how mitigation became a such a global scientific and law-maker focus. The dictionary definition of Mitigation simply means *the act of mitigating* which in turn means to make something less harmful or cause the consequences of a bad or unpleasant situation to be less severe. The IPCC have used these basic meanings to define what mitigation entails in terms of combating anthropogenic climate change. The AR5 report definition of Mitigation was quoted in Sect. 1.2, the preceding IPCC AR4 report gave a more economical definition, "*mitigation means implementing policies to reduce GHG emissions and enhance sinks*", substituting the phrase *anthropogenic intervention* of the Second Assessment Report (SAR) with implementing policies [33, 34]. In the updated and expanded AR5 definition the effects of the internationally acknowledged *criteria air pollutants and contaminants* have been added to the GHG concerns. Mitigation, then, has an ever-evolving meaning. Prior to the increasing popularity of the term Mitigation from the IPCC's second report, terms such as weather modification and climate modification were often used [35]. The notion of weather modification, principally rain-making, was known to, and practised by, ancient indigenous peoples using shamans, priests, and rain-dances thousands of year ago and in some regions continue [36]. By the mid-twentieth century, at the end of the 2nd World War, some scientists claimed that human activity was changing local weather and, with a post-war weapons race on the horizon, a small group of leading scientists agreed, at a meeting at Princeton University, that it might be possible to deliberately change weather patterns [35]. In the United States, this led to the funding of research projects investigating *climatological warfare* but, by 1977, the United Nations had created a *convention* banning the use of weather-warfare, although less than 20% of members have so far ratified the convention [37].

However, the original initiatives led to climate scientists investigating the causes of climate change and the modelling of the changes. Apart from the potential weaponization of weather and climate, there were also concerns that the average terrestrial surface temperatures in the northern hemisphere had fallen by 1.5 °C (2.7 °F) between the mid-1940s and early 1970s, so was the Earth entering a new ice age? If that were the case, and some scientists believed it was, could the climate be stabilized and changed to prevent further *global cooling* [38]? *Engineering schemes* were suggested to counteract the cooling and control climate change, including (a) removing Arctic sea-ice using *clean* nuclear bombs, (b) covering the ice with soot to reduce the reflectivity, (c) cutting down tropical forests in South American and Africa and (d) damming the Bering Straits, as shown on Fig. 1.1 [38]. All these proposals were aimed at *warming* the Earth and it is now known that reducing the extent of Arctic sea-ice does indeed lead to increased surface temperatures, albeit in the absence of nuclear weapons!

Clearly, the concept of defeating climate change is not new, but the proposition that the Earth was experiencing global cooling and that the climate was entering a new ice age, although it garnered a few media headlines, was revisited by scientists almost as soon as it had been announced. Using different model assumptions, although the same basic models and data, and amended forcing factors for the

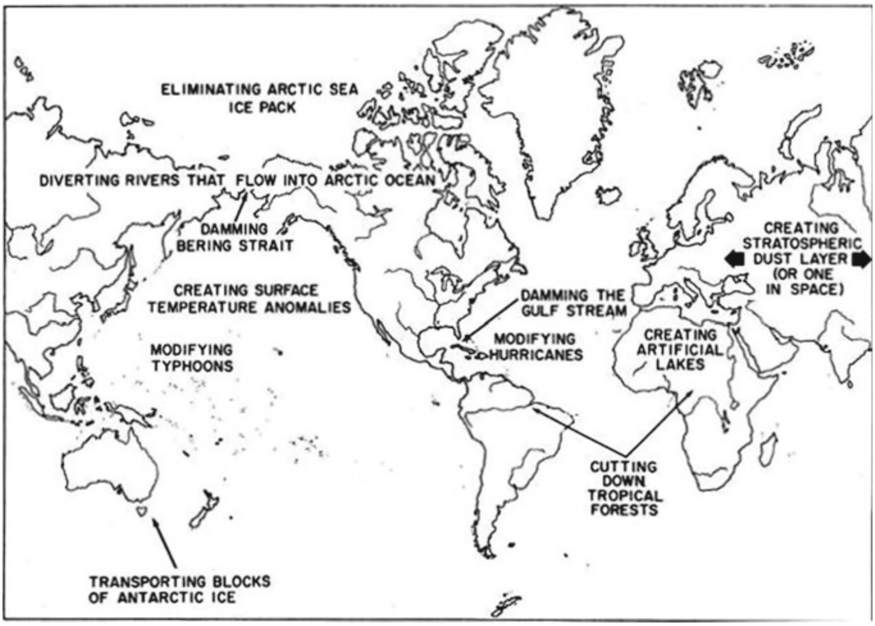

Fig. 1.1 Proposals to combat global cooling [38]

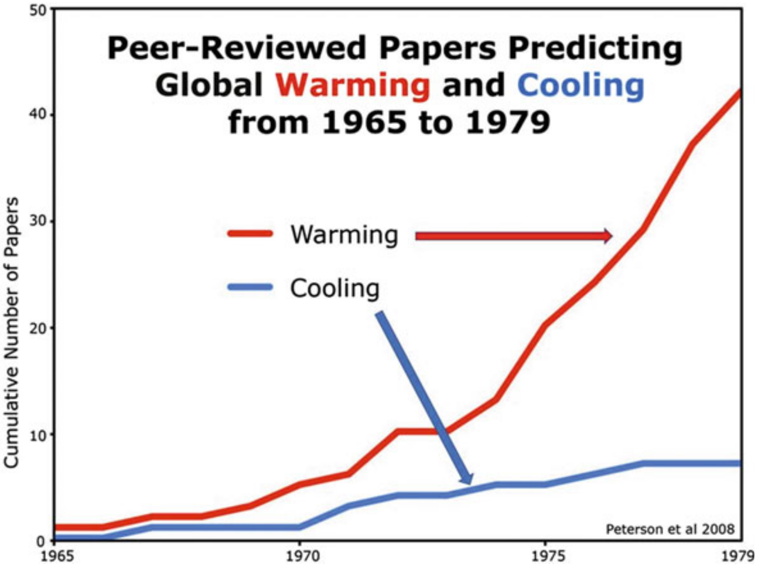

Fig. 1.2 Global cooling and warming publications 1965–1979 [39]

effects of GHG, the global cooling conclusions were changed to global warming conclusions in an increasing number of publications, Fig. 1.2 [39]. In the same decade, following the *Oil Crises* in many countries outside the Middle East and the fear that oil production had reached its peak and would soon run-out, the then United States President, Jimmy Carter, gave an address to the nation in 1977 on the 10 principles of his national energy plan. He said, "*we could use up all the proven reserves of oil in the entire world by the end of the next decade*" and thus advocated starting the development of new, unconventional energy sources to be used in the twenty-first century [40]. Although, one of President Carter's targets was to increase coal production by 66% by 1985. The combination of increased alertness to global climate change and the need for future energy transitions, in all probability, were the likely drivers for two UN agencies, the World Meteorological Organization (WMO) and the UN Environment Program (UNEP) to propose the formation of the IPCC, which the full UN General Assembly endorsed in 1988 [41]. The IPCC were tasked with producing a climate report including (a) a comprehensive review of the state of knowledge of climate change science, (b) the possible socio-economic impact of climate change, and (c) potential response strategies to climate change.

The IPCC report—the First Assessment Report (FAR)—laid the foundation for the UNFCCC, the seminal international convention/treaty aimed at reducing global warming and coping with its consequences. In the SAR, as previously mentioned, the terms *adaptation* and *mitigation* entered IPCC lexicon, while increasing carbon dioxide levels and deforestation were named as the chief causes of climate change.

Following the SAR, the *Kyoto Protocol* was set up [42]. The Third Assessment Report's (TAR) focus was the impact of climate change and the need for adaptation, while the Fourth Assessment Report (AR4) considered both Mitigation and Adaptation, and the last assessment report (AR5), as summarized in Table 1.1, provided an encyclopedic scientific assessment of the associated strategies. Throughout these reports, extensive and transparent, use is made of the results of climate change computer models, although this is not always acknowledged in the media or in policymakers' commentaries, which means that large swaths of the public likely assumed they were being presented with proven facts and observations. The IPCC reports, especially from the scientific working groups, invariably tried to present a more balanced interpretation, although some of their resulting opinions are prone to scientific and technological debate. For example, in the FAR, one of the key conclusions was that "*The size of this* {global} *warming is broadly consistent with predictions of climate models, but it is also of the same magnitude as natural climate variability*" [43]. However, the models at that time concentrated more on anthropogenic effects, such as rises in CO_2 emissions from human activities, rather than natural impacts such as volcanic emissions.

The next steps in the IPCC's assessments were to quantify exactly what proportions of global warming were anthropogenic and which were natural, and which human activities were the root causes of anthropogenic climate change. This work continues, and in the next assessment report (AR6) the computer models will include factors derived from both anthropogenic climate change and climate variability analyses. What the modelling results will show, and how well they will compare with the growing database of actual observations, is obviously uncertain. However, while it may be expected that the findings could result in a revision of mitigation targets, either more or less severe, it needs to be remembered that, over the last thirty years, the two main advocated mitigation approaches have been energy transitions, to address the desired reduction of sources of GHG, and reforestation, to deal with the enhancement of the sinks.

1.3.2 Current Mitigation Approaches

Of the 900 or so Mitigation strategies, along with the 300 baseline energy-use scenarios, reviewed in AR5, the core themes are still the same as the original SAR recommendations, i.e., reduce GHG emissions by energy transitions and increase GHG sinks by reforestation and *afforestation*.[8] These are evidenced based approaches since carbonaceous energy use accounted for around 65% of all global GHG emissions in 2016, with hydrocarbon fuel production and storage adding about another 6% [44]. Land-use and forestry change, and agriculture, impart a

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[8] Afforestation is the establishment of forests, through planting and/or deliberate seeding, on land that, until then, was not classified as forest.

further 18% of GHG emissions [44]. Thus, as almost 90% of GHG emissions involve the types of energy sources currently used and how humans use, or misuse, land, it can be wholly appreciated why mitigation strategies focus on these two issues, especially energy use transitions. However, the temporal target for the hoped for replacement of fossil fuels is within a decade from now, or at least by 2050, although it should be noted that the strategic pathways outlined in AR5 for mitigating atmospheric CO_2 do not extend beyond the end of the century [45]. Moreover, as there continues to be uncertainty regarding the physical relationship between surface temperature and GHG concentrations it may not be possible for these temperatures to return to the IPCC defined pre-industrial levels, but a *never to be exceeded* temperature level could be defined as an indicator associated within target bounds of CO_2 concentration levels [46, 47]. Therefore, it appears inevitable that mitigation pathways will continue into the twenty-second century, although the future actual strategies may be amended from those of this century.

1.3.2.1 *Mitigation by Energy Transition—Substitution of Fossil Fuels*

There is a long history of human energy transitions but, until the *Age of Coal,* changes in energy sources were slow to arrive and gain dominance, as shown in Fig. 1.3 [48, 49]. The combustion of fossil and other carbonaceous fuels, such as wood, emits the largest quantities of CO_2 and produces a sizable proportion of Particulate Matter (PM), the former being considered the major contributor to global warming, the latter a significant cause of both hazardous indoor and outdoor air pollution. The basic strategy is to substitute fossil fuels with renewable energies, e.g., solar, wind, and water-power. Water-power meaning hydroelectric systems including oceanic tidal and wave powerplants. However, hydroelectric power plants using dams and reservoirs now have nationally specified output limitations if they are to be classified as renewable sources, although the specified sizes are somewhat arbitrary. Why these restrictions? There is indisputable evidence that the dams and reservoirs and other large bodies of freshwater emit two GHGs, namely CO_2 and Methane, although, in the United States, less than 4% of the over 91,000 dams are used for hydroelectric installations [50]. Wholly attributing GHG emissions from freshwater sources, natural or purpose built, to hydropower is therefore problematic. Moreover, if the site of the hydroelectric plant was cleared of plant life prior to the flooding of the land and the creation of the dam there should be no GHG emissions from decaying vegetation.

However, GHG production is not the only environmental concern associated with hydropower installations since, depending on how much land area is appropriated, its topology, and location, there will be wildlife habitat destruction and unavoidable human displacement. To address these issues, and to diminish the GHG emission problems, thereby causing less harm to the existing ecological systems and the environment at a selected site, many regions and countries have imposed size restrictions on new hydropower projects. But why is there no universally accepted size requirement? Partial answers are likely, (a) *geography,* in that

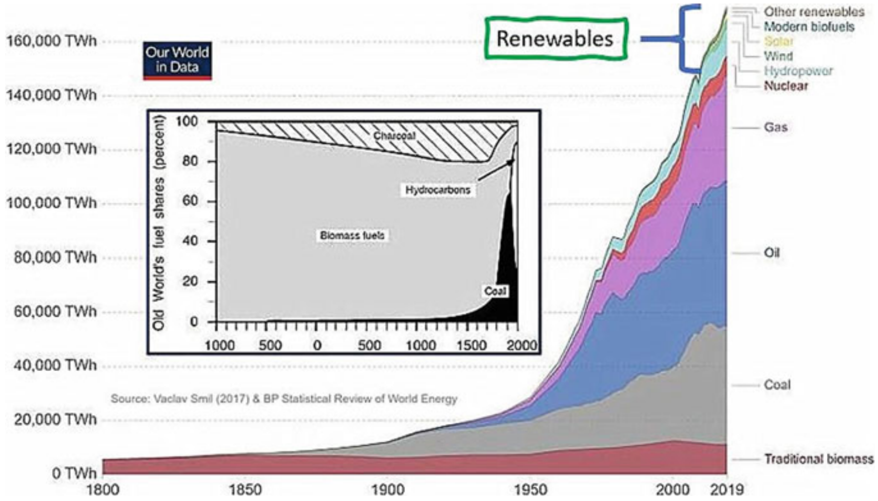


Fig. 1.3 Energy transitions 1000 CE to 2019 CE [48, 49]

installation locations having more mountainous terrains involving valleys and canyons will have a smaller surface footprint than in *flatter* areas for the same volume of water, and (b) *land-use management* of the surrounding areas as water run-offs from agricultural activity will adversely impact pollutant formation [45]. Nevertheless, if all hydropower electricity production were considered renewable, as in China, then many jurisdictions would have already met their Paris Agreement targets. Perhaps of more concern, is not the renewable energy accounting schemes, but how adaptation to droughts, floods, and water scarcity can be supported without dams and reservoirs?

As the main criteria of mitigation is to eliminate, or substantially reduce, anthropogenic CO_2 emissions, nuclear energy may seem an obvious replacement for fossil energy. However, there is a wide-spread public and media aversion to the use of nuclear sources because of safety concerns, which are largely gratuitous, and the fear of the proliferation of thermonuclear weapons leading to their uncontrolled use. Nevertheless, advances in nuclear fusion, as opposed to the conventional nuclear fission technique, and the plans to develop small community size nuclear reactors may eventually repair the negative perceptions of nuclear energy, but this is unlikely to happen in sufficient time to meet the 2050 climate change GHG goals [51, 52]. So, as hydropower and nuclear power are not going to be major enablers of the transition to renewable energy and the desired scale of mitigation, what will? A great deal of faith, and funding, is being placed in solar and wind power. Unfortunately, in addition to the proverbial epithet of what happens *when the sun don't shine and the wind don't blow*, there are also local and regional challenges in places lacking sufficient natural solar and wind energy densities and, moreover, where there are abundances, the ability to store overproduction is very limited [53, 54]. Maybe global, national, or regional transmission grids and networks could be constructed to carry solar and wind energy produced in abundant areas to those partially or wholly lacking such advantages? Thus, geography will play an increasing role if the spread of solar and wind energy is to increase, let alone replace all carbonaceous fuels, but intranational and international cooperation, including cost sharing on an unprecedented scale, will likely be needed.

Another alternative *fuel,* especially for use in the land and marine transportation sectors, is hydrogen [44, 55]. There have been occasional periods of interest in its application for the powering of prime movers since at least 1820 and, once again, hydrogen in the late 1990s and currently is being promoted as a fuel of the future [56, 57]. There have been varying reasons for this interest by the last quarter of the twentieth century. The oil supply crises, fears of diminishing fossil fuel reserves, and efforts to improve air quality provided the impetus for the consideration of hydrogen use, together with technological breakthroughs in membrane materials and manufacture, which made Fuel Cells more competitive. Today, the focus has become the contributions hydrogen use could make to reducing the impacts of anthropogenic climate change. If used in a fuel cell to generate electrical energy the process is emission-free except for the production of the GHG water vapour, which, because of its short lifetime, is not considered to be a factor in global warming. If used in an air-breathing combustion engine, no CO_2 is emitted, but there could be some NO_x production in the same way as a Hydrogen-Air fuel cell. However, methods for removing nitrogen oxides from exhaust streams are technically mature and very effective. Moreover, hydrogen is the world's most abundant element. So, why is hydrogen not yet a dominant primary energy source?

The answer is, because there is almost no naturally occurring sources of gaseous hydrogen, and it is produced largely by synthesizing conventional fossil fuels and biomass, although it can also be generated by water electrolysis and there is continuing research and development on microbiological and photobiological hydrogen generation [57]. If the electrolysis process is powered by a renewable energy source, then the resulting hydrogen is called *Green-Hydrogen*, while if made from carbonaceous raw materials it is named *Grey Hydrogen*. However, the form of manufactured hydrogen attracting increasing attention is *Blue Hydrogen*, which involves the combination of grey hydrogen production processes together with carbon capture, utilization, and storage (CCUS). Blue hydrogen can be produced in large, off-site facilities, and transported to its destination by pipeline or a suitable vehicle, or smaller, filling station sized, on-site installations. Germany, Japan, South Korea, and the United States already have some on-site hydrogen filling stations [58]. Many of the safety and material degradation issues, particularly steel embrittlement, have been addressed using highly sensitive detectors and non-metallic materials [58].

Could the use of hydrogen become significant over the next three decades to 2050? Yes, according to the multinational company, BP p.l.c., but only if particular energy-use scenarios are adopted. The company publishes a series of reports each year dealing with energy topics and possible global outlooks for the future. In their forecasts they use defined transition and energy use scenarios, like those found in IPCC Assessment Reports and the United States Energy Information

Table 1.2 BP energy outlook scenarios [44]

Scenario term applied to energy use	Paraphrased from full descriptions
Business-as-usual	Government policies, technologies and social preferences continue to evolve in a manner and speed seen over the recent past, but in 2050 carbon emissions are only 10% less than 2018 levels
Rapid	Conceives a series of policy measures, led by a significant increase in carbon prices and supported by more-targeted sector specific measures, such that carbon emissions are reduced by about 70%, limiting the rise in global temperatures by 2100 to well below 2 °C above pre-industrial levels
Net zero	The policy measures embodied in Rapid are both added to and reinforced by significant shifts in societal behaviour and preferences, which further accelerate the reduction in carbon emissions, in line with limiting temperature rises to 1.5 °C

Administration's (USEIA) International Energy Outlook publications. In BP's case, for their 2020 outlook publications, they used 3 scenarios: *Business-As-Usual; Rapid;* and *Net Zero* [44]. Analogous, if not always identical, terms and descriptions are used in various forms in the IPCC, USEIA reports, and others from *bone fide* international agencies. A précis of the BP descriptions is given in Table 1.2.

If future energy use is in harmony with, or closely approximates, the BP Rapid and Net Zero scenarios, then especially in the land and marine transportation sectors, but also as a contributor to total global energy consumption in a low carbon transition, hydrogen will become a common, if not a dominant, fuel by 2050, as shown in Fig. 1.4a, b [44]. But what type of hydrogen? It is forecast that by 2035 all three forms, grey, green, and blue could share the hydrogen market but by 2050 it would be equally shared between green and blue. Nevertheless, there are many challenges and uncertainties to overcome such as (a) if green hydrogen is to be produced then even more renewable energy may be needed within the various energy-use scenarios although such an issue could be tempered by utilizing any solar and wind power overproduction to produce green hydrogen and in effect become a renewable energy storage system and (b) the production of blue hydrogen is wholly reliant on the efficacy and economic viability of CCUS.

CCUS will also play a pivotal role in the use of biomass and biofuels [59]. These energy sources are considered carbon–neutral in many global jurisdictions, such as the EU, but the fact of the matter is that if their use involves combustion then CO_2 will be emitted. Those lawmakers and scientists, in favour of applying the carbon–neutral label, argue that the stored carbon in biomass, which is released quickly after the harvested product is burned and its CO_2 emitted, will be gradually removed—sequestrated—from the atmosphere by new plant and tree growth. However, depending upon the genus and species choice of the new replacements, the emission generated-sequestration process could take from decades to centuries, which is hardly the desired timeframe for addressing twenty-first century mitigation [60–62].

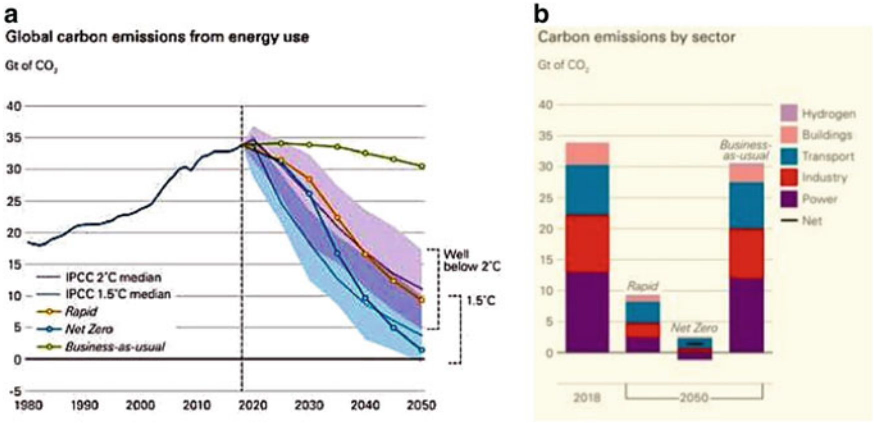


Fig. 1.4 **a** Total carbon emissions [44]. **b** Carbon emissions by energy sector [44]

Biomass could be thought of as a renewable energy, as harvested plants and trees can be directly replaced but the carbon–neutral moniker is less palatable to scientists, and both the IPCC and the EU have revisited the 2006 assessment of biomass emissions not counted as contributing to GHG, at least not being included in national GHG inventories [63]. In 2019, a major 5 volume refinement to the 2006 guidelines was published [64]. Both sets of guidelines have many proposals on how to calculate CO_2 emissions from Harvested Wood Products (HWP) and their removal using so-called *carbon-stocks*, i.e., a count of trees and plants existing in any one year. The emissions and removals are not reported in the energy or waste GHG inventories but in the Agriculture, Forestry, and Other Land-Use (AFOLU) category. The methodologies used are open to interpretation, as the IPCC acknowledges, and that “[i]*n practice, physically measuring either actual carbon stocks in the HWP pool, or actual fluxes between HWP and the atmosphere, can be technically challenging*” [65]. The overall situation on the carbon-neutrality of biomass is somewhat muddled, but for lawmakers there is literally a *get-out-of-jail-free* card as the guidelines state that “*The HWP Contribution can be reported as zero if the inventory compiler judges that the annual change in carbon in HWP stocks is insignificant*” [64].

So, can biomass be considered as part of an energy transition mitigation strategy? Analysts and scientists continue to debate the issue of whether biomass burning can be counted as a net zero contributor to anthropogenic climate change and suggest that its use may worsen rather than reduce global warming [66–68]. Despite the GHG inventory revisions and ongoing discussions about the use of biomass as an energy source, it will continue as part of the energy mixes for now and in the foreseeable future and CCUS could strength its acceptability. But if carbon capture can be used with one type of carbonaceous fuel, why not others? Other than economics, political ideologies, and maybe some technical challenges associated with size of the capturing devices, there appears no show stopping obstacles to the wider use of carbon capture [69, 70]. To complete the CCUS systems approach, it will be necessary not only to capture the CO_2 but also to store it. In North America this should not prove to be a problem because the United States National Energy Technology Laboratory (NETL) has reported that there is sufficient capacity to store 900 years or more of CO_2 at the current rates of production [62].

Whatever the scientific-political tensions about the use of biomass, there are still over 2.5 Billion people using it for basic domestic needs and, in doing so, producing the criteria pollutant PM in sufficient quantities to cause the premature deaths of millions, particularly in the regions where it is widely used for such purposes, but PM dispersal, especially the health-damaging PM 2.5 is not confined by national or international borders [71]. However, to attribute PM emissions solely to biomass burning and on-road diesel fuelled international combustion engines can be misleading, as illustrated in Fig. 1.5, which shows the sources of PM in the contiguous United States [72]. The planned elimination, by some governments, e.g., the UK [70], of fossil fuelled engines between 2030 and 2040 will reduce the amount of anthropogenically generated PM in the atmosphere but just modestly in comparison with the current contributions of coal-fired and biomass fuelled power stations, industry, and building HVAC systems. Yet, if the use of hydrogen and electricity are to be the dominant energy sources for the transportation, building, and power generation sectors, then far more renewable energy generation will be needed. As this is unlikely in the sought-after UK timeframe, nuclear and carbonaceous fuelled energy production, using CCUS, will also have to be part of the

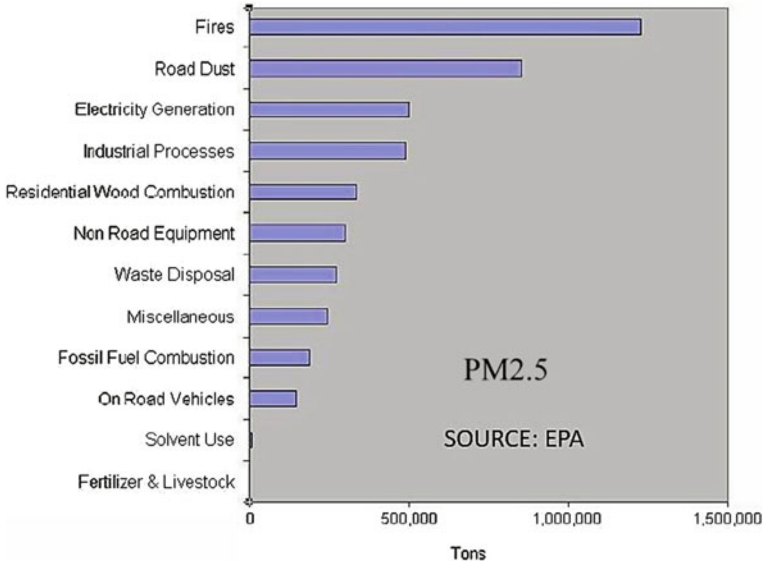


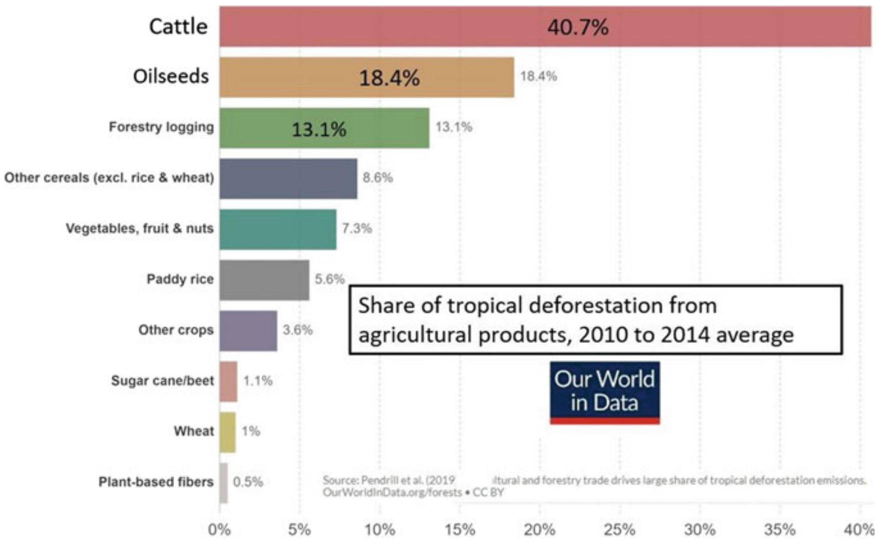
Fig. 1.5 United States sources of $PM_{2.5}$ [72]

energy mix. This scenario will doubtless be repeated in other countries but, for some, hydropower will also play a part, especially if used in *pumped storage* mode with solar and wind power installations [73].

Arguably, the mitigation measures discussed so far are reasonably pragmatic approaches which societies, even if reluctantly in some cases, will accept. However, when elected governments try to change societal behaviours based on their known ideologies, even with good intent, will they be as readily accepted, or lead to dissension [32, 74, 75]? For example, the imposition of carbon taxes is an increasingly common strategy for manipulating socio-economic behaviour towards the use of non-polluting energy sources. Is this approach indicative of a country's *Nationally Determined Contribution* (NDC) to the 2015 Paris Agreement targets, global leadership bragging rights, or sincere attempts to persuade their own society of the seriousness of anthropogenic climate change [76]? If persuasion is only partially successful does legislation and litigation have to be invoked? Perhaps, an exemplar of such a situation is Canada's carbon tax. The Federal Government of Canada's 2018 *Greenhouse Gas Pollution Pricing Act*, passed by a then majority government, was not greeted with overwhelming societal enthusiasm and, indeed, three of the ten Provincial governments, representing over 53% of the country's population, challenged the legality of the Act. In March 2021, the Supreme Court of Canada (CSS-CSA) in a 6–3 decision decided that the Act was legal and constitutional and noted that "*global warming causes harm beyond provincial boundaries*" [77]. On that basis, most of the justices decided that global warming was "*a matter of national concern under the "peace, order and good government" clause of the Canadian Constitution*" [77].

At the time of the passing of the Act, 72% of the country's most populous province believed it was more of a tax grab than a sincere attempt to mitigate global warming [78]. Will legal enforcement now change attitudes? Whatever, the underlying rationale for imposing a carbon tax, which is the path taken by over 40 countries, there is evidence to show that carbon taxes do lead to GHG emissions reductions, but these taxes are also *regressive,* in that they impose a disproportion burden on those with lower incomes as a higher percentage of their income will need to be used to obtain the basic necessities of life and, for such individuals, the transition to an electric vehicle could prove unattainable [79, 80]. However, in Canada, the government has sought to ease the carbon tax burdens by using a gradual increase annually, from $16US per tonne of CO_2 equivalent to $136 US by 2030 [81], which is still less than the lowest rate that the *New York Times*™ estimates the UN appears to believe is necessary to keep surface temperature increases to only 1.5 °C above the defined pre-industrial levels by the end of the century, and far less than the over $5000 US per tonne recommended by the UN, according to the same source [80].

Presumably, once the carbon-tax mitigation approach succeeds, it will no longer be needed as there will be no anthropogenic carbon to tax and hence no further revenues to generate, but when and if this happens are unequivocal suppositions. There are also exemplars for more profound behaviour-shaping strategies, the latest being recommendations to reduce meat and dairy consumption by 35%, and



Source: Pendrill et al. (2019 ltural and forestry trade drives large share of tropical deforestation emissions.
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Fig. 1.6 Deforestation from agricultural products (tropical) [85]

agricultural land use by 21%, for the UK to achieve zero-carbon by 2050 [31]. Will these recommendations be endorsed as a concession to lobbyists or as a bone fide approach to mitigation [82, 83]? Is the diet changing approach an example of adaptation as much as mitigation? Can agricultural land be reduced, but simultaneously the plant food supplies increased, to replace meat and dairy products for a growing population? It would be thoughtless for governments not to address these questions in clear, precise, and unambiguous ways before embarking on a legislated approach to enforcing human diet changes, but that is not to say it could not happen or that reducing meat consumption, particularly *red* meat, would have negative health effects [84]. Maybe the claims of ideological maneuvering are somewhat over-blown? There are elements of climate change pragmatism in advocating for a reduction in red meat consumption as cattle grazing is the single largest contributor to land being deforested for agricultural purposes, as shown in Fig. 1.6, for the period 2010–2014 [85]. However, it needs to be stressed that the chart is for tropical regions and that in terms of net forest change, i.e., forest expansion minus deforestation, the UK has experienced no change over the period 1990–2015 [84].

Other large contributors to agricultural deforestation, see Fig. 1.6, are oilseeds, especially palm-oil, and food crops. With the use of *healthy* non-meat protein products gaining momentum, global soya-bean production has tripled over the last three decades with the United States and Brazil leading the way, although not all soya-beans are used exclusively for food [85, 86]. The same level of increase has also been experienced with palm oil, but more than 80% of global production comes from just two countries, Indonesia and Malaysia, while India and China are the biggest importers of palm oil [85], Fig. 1.7. Palm oil is mainly used in food

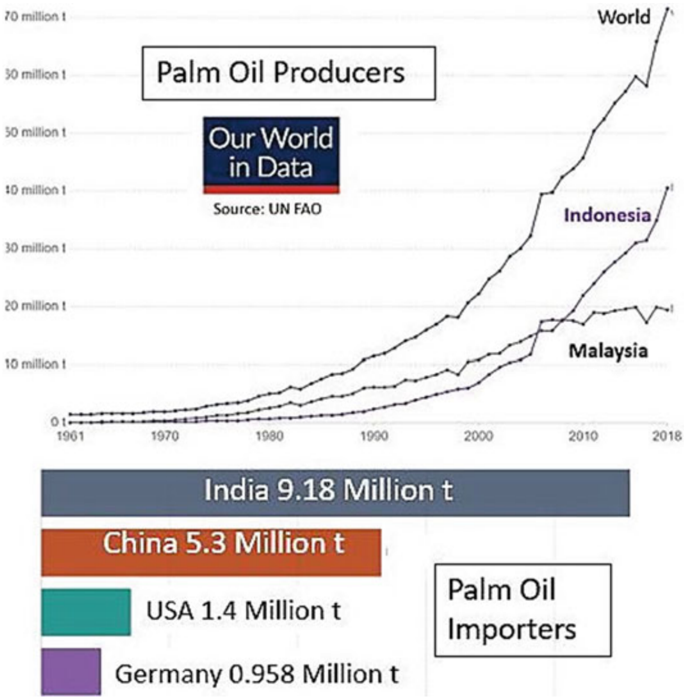


Fig. 1.7 Palm oil producers and importers (exemplars) [85]

products and industrial applications, but 5% is used for biofuels with some importing countries, e.g., Germany using more for biofuel production than food [87]. As these products have positive health effects, to reduce their dietary use in the same way as red meat would be problematic, as would be the rejection of their contributions to biofuel production.

1.3.2.2 Reforestation and Afforestation—AFOLU (Agriculture, Forestry, and Other Land-Use)

Despite the contentious issue of diet change, the accompanying zero-carbon advice to the Government of the UK is to reduce agricultural land to enable increased forestation and wetlands, and make peat beds tree-free, i.e., changing land-use, and this is in harmony, to a large extent, with the IPCC's Mitigation strategy of enhancing the sinks of GHGs [23]. But does this mean simply planting more trees? Yes, and no. Globally, since approximately the beginning of the present inter-glacial period between 10 and 11 millennia ago, about a third of forest cover has vanished, almost all of which has occurred since the eighteenth century industrial revolution and, especially, in the twentieth century, see Fig. 1.8 [85, 88].

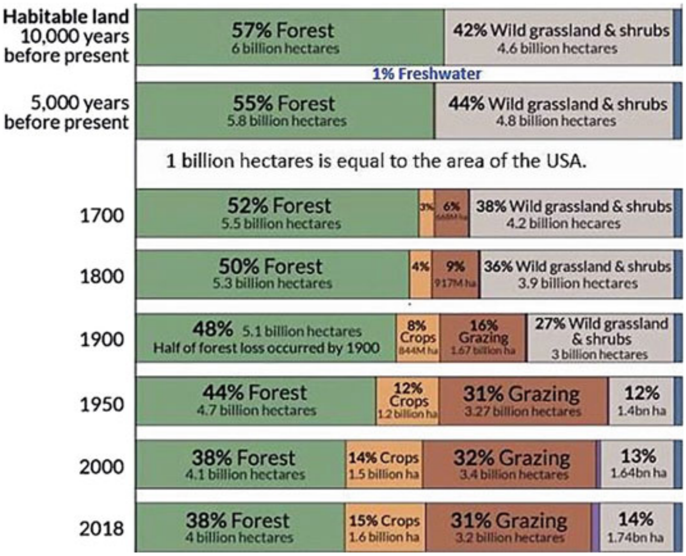


Fig. 1.8 Increasing deforestation from 10,000 BCE to 2000 CE [85, 88]

Planting more trees, some advocate 1 trillion could address this issue, but the IPCC, in their 2019 report on Climate Change and Land, highlight that afforestation and using biomass for bioenergy can also have adverse side-effects and risks including food insecurity and land degradation [89, 90]. Nevertheless, as frequently quoted in several UN publications and communications: "*Forests are a major, requisite front of action in the global fight against catastrophic climate change*"... "*Stopping deforestation and restoring damaged forests could provide up to 30% of the climate solution*" [91].

Consequently, is the scale of deforestation declining and reforestation and afforestation increasing? *Yes*, according to the UN's Food and Agriculture Organization (UNFAO) *Global Forest Resources Assessment* (FRA), but the World Resource Institute's *Global Forest Watch* (GFW) say *No* [92]. GFW reports that tree cover has declined by 50% since 2015, the FRA by about 11%, the differences being that annual forest regrowth is hard to quantify from GFW's satellite data and, if tree cover is lost, it is not clear whether the loss is permanent or temporary. FRA, on the other hand, is mainly reliant on nations reporting how *registered* land is used [92]. In the twentieth century it appears that the FRA and GFW were in reasonable harmony, but this is no longer the case, and the differences are marked, so while one system may report that certain countries have increased their forests, the other system reports the same countries have massive deforestation. This unhelpful situation is leading to a cacophony of articles about this important topic and the sooner a scientifically acceptable remedy is found the better. However, in this sub-section, as in other sections, since the data used in the discussions so far was largely extracted from UN published sources, the UNFAO data is used mainly in the form presented by the trusted and reputable organization, *Our World in Data* [93].

The many national efforts, such as those by India and China which together account for over 36% of the global population, to encourage more tree planting are having positive effects in expanding forests. But global deforestation continues, so the expansion results are not as reassuring as may be anticipated, as shown in Fig. 1.9a, b, where exemplars of deforestation and increasing forest cover are presented in juxtaposition [85]. Notwithstanding the current situation, there is little doubt that having more trees and vegetation can provide an increasing scale of carbon sinks which, if sustainable and well-managed, could help defeat the adverse impacts of anthropogenic climate change and simultaneously contribute to cleaner air and increased food supplies. In other words, reforestation, afforestation, and reduced deforestation are inherently attractive climate change mitigation strategies provided that anthropogenic CO_2 is unequivocally confirmed as the main change agent.

1.3.3 Is Mitigation Working?

There are some problems, as already highlighted, with assessing the AFOLU affects on climate change, not because of CO_2 data, but because of the unresolved issues surrounding the contradictions of AFOLU source data. However, can the efficacy of the other mitigation strategies be measured, which started with the Kyoto Protocol in 1997, but took almost 8 years to come into effect, or, its successor, the 2015 Paris Agreement [94]? If CO_2 is used as the indicator, then, using the general atmospheric measurements, like those taken at the renowned Hawaiian Mauna Loa observatory, or the emissions due to fossil fuel burning and cement production alone, as illustrated on Fig. 1.10, the mitigation strategies do not appear to have had the desired effect and, indeed, CO_2 levels have continued to rise during the COVID pandemic [95, 96]. This situation is not wholly surprizing as it is only 16 years since Kyoto came into force, but without the agreement of China and the United States, and latterly Canada, and the United States formally withdrew from the Paris Agreement in 2020—although it is set to rejoin [94, 97]. Perhaps a reasonable temporal benchmark for the possible success of mitigation is the first International environmental treaty, the universally agreed, *Montreal Protocol* [98]. This protocol is aimed at repairing the damage to the ozone-layer and it has been estimated that the repairs will be *almost complete* by the middle of this century, over 60 years since the protocol came into force [94, 99].

If the Montreal benchmark is applied to the progress of mitigation, and given that the Paris Agreement came into force in 2016, then even optimistically, it could be the last quarter of this century before the average surface temperature anomalies stabilize and, by then, the target *never to be exceeded* average surface temperature

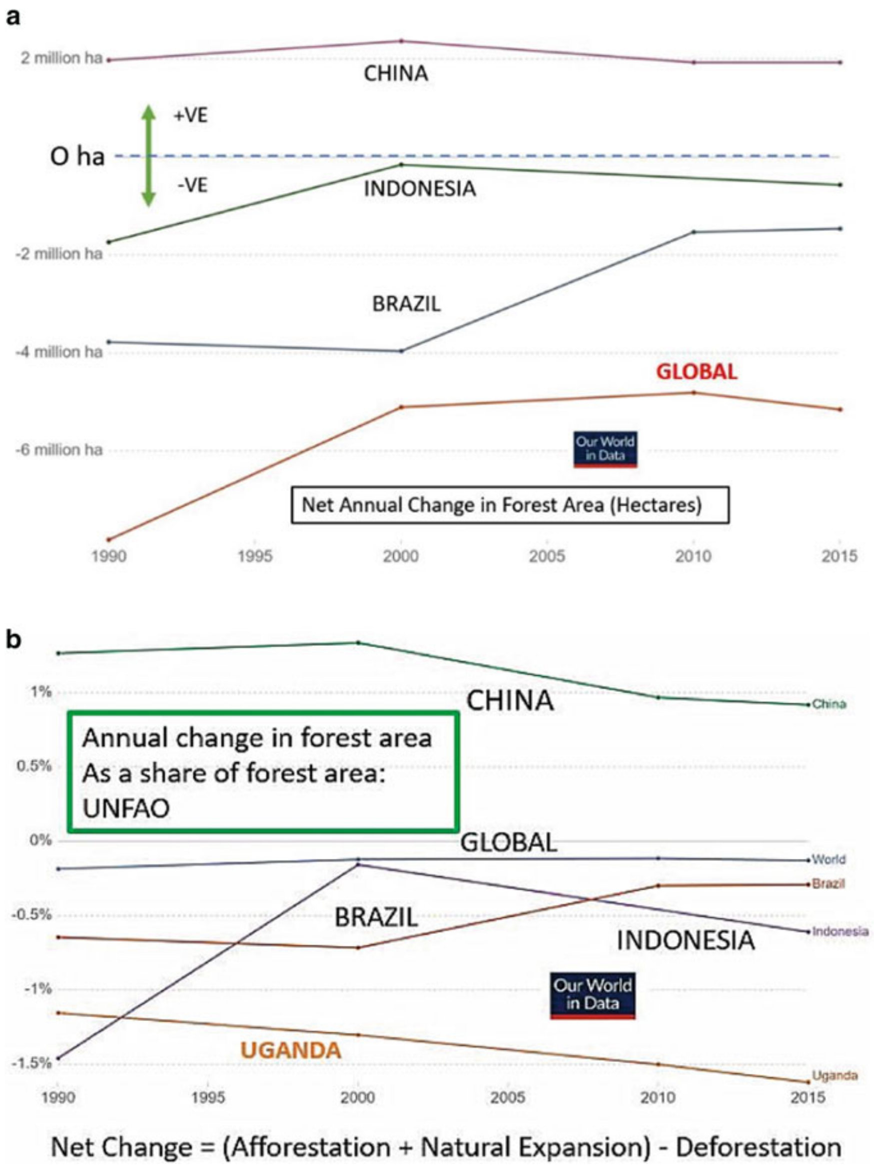
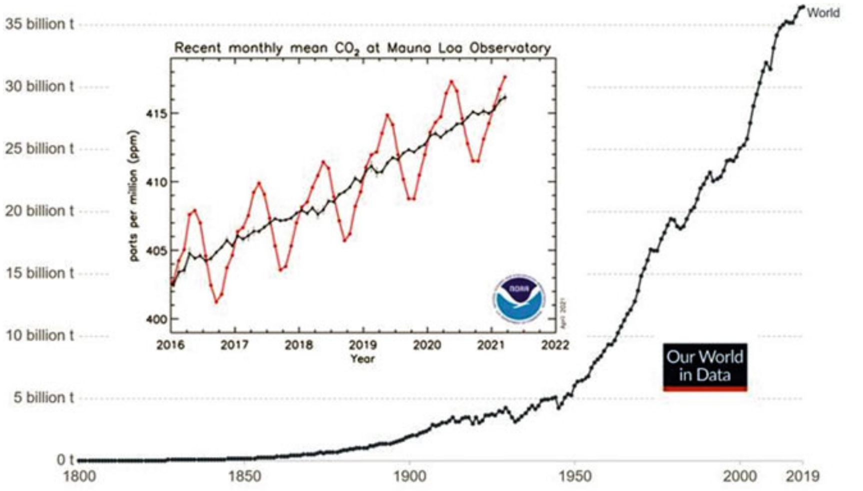


Fig. 1.9 **a** Change in forest areas (exemplars) [85]. **b** Percentage net change in forest area (exemplars) [85]

anomaly level of 2.0 °C could well have been surpassed, which for climatologists, is the tipping point. Moreover, as previously discussed in this section, it is likely that mitigation will have to continue well into the twenty-second century before atmospheric CO_2 concentrations and average global surface temperatures return to



Source: Global Carbon Project; Carbon Dioxide Information Analysis Centre (CDIAC) OurWorldInData.org/co2-and-other-greenhouse-gas-emissions/ • CC BY
Note: CO_2 emissions are measured on a production basis, meaning they do not correct for emissions embedded in traded goods.

Fig. 1.10 CO_2 emissions: recent concentrations [95] and amounts since 1800 CE [96]

pre-industrial levels. Arguably, while the mitigation strategies, advocated since the 1997 Kyoto protocol, should address the vagaries of CO_2-driven anthropogenic climate change, the long delays in their implementation, coupled with the perceived lethargic transitions away from fossil fuels, mean that more radical approaches to changing the climate are needed, even if only to allow *breathing room* for Mitigation to take effect. Traditional adaptation can hardly be considered revolutionary, but so-called *Geoengineering* techniques can, and may offer an interim solution [100].

Using the AR5 definitions given in Sect. 1.2, a case for classifying geoengineering as both mitigation and adaptation could be made, as it is an intervention in Earth's natural systems aimed at impeding the impacts of anthropogenic climate change, but also a method of adjusting to current or future climate change. However, because the geoengineering approach is probably a better fit to mitigation discussions, it is addressed in this section.

1.3.4 Geoengineering

The term *geoengineering* can be used as shorthand for Geological Engineering, or to describe some aspects of Civil Engineering, when referring to tunnel and bridge construction, for example. However, over the last decade it has been used in climate change discussions, almost wholly replacing the term Climate Engineering. In this context, what is its precise meaning? Different national and international agencies, as well as authoritative dictionaries, have different definitions but are very similar in intent if not words. In this section the definition, '*Geoengineering is the deliberate large-scale intervention in the Earth's natural systems to counteract climate change, particularly the World's temperature*', will be used, which was extracted and merged from two respected sources [101, 102].

However, it was concluded in the 2007 IPCC AR4 report that geoengineering proposals were "*largely speculative and unproven, and with the risk of unknown side-effects*" [33]. A somewhat bleak and partly impulsive conclusion, but at the time there was a great deal of hope that fossil fuels would be replaced promptly by renewable sources. So, perhaps suggestions, such as geoengineering, were considered a distraction from the main thrust of ensuring speedy energy transitions, which would make any geoengineering effort redundant? Given that the main aim of geoengineering is to lower surface and ocean temperatures to pre-industrial levels, numerous proposals have since been studied on how this could be achieved. These include imitating *natural* phenomena, such as volcanic eruptions, which, if their ash-plumes are of sufficient scale, are known to reduce global temperatures and result in harmful side-effects, or by capturing more CO_2 using better land-use management, i.e., increasing forestry cover [103]. Moreover, another possible class of geoengineering is weather or *climate modification*, e.g., firing or spraying specific chemicals into the clouds to make them give up their moisture, a technique used by the People's Republic of China prior to the 2008 Olympics to ensure that the upcoming games would be rain-free [104]. In Germany, such techniques using planes, so-called *Hail Fliers,* to deliver the chemicals, have long been used to cause thunderclouds to release their water vapor as rain before damaging hail is formed [105]. However, usually such approaches can be considered as more of a local adaptation rather than large-scale intervention but, by 2025, China, following declared technical research and development breakthroughs, has plans to deploy *weather modification systems* to generate rain and snow over an area of 5.5 Million square kilometers, about 60% of its total land area; a similar land area as the United States, over 1.5 times larger than India, and 20 times larger than the UK! [104].

There are two primary approaches to geoengineering; (a) Carbon Dioxide Removal (CDR), and (b) Solar Radiation Management (SRM) [100, 102, 106]. These approaches involve various methodologies which are summarized in Table 1.3. The burning of biomass combined with CCUS and burying cut-down trees or turning them into charcoal (bio-char) are considered by some to be forms of geoengineering, but these approaches are usually categorized as part of mitigation by energy transition.

The cirrus cloud approach is only at the theoretical stage, but most of the other methodologies are scientifically and technically possible, if not yet ready for universal deployment, except *avoided* deforestation and afforestation. This situation is mainly the result of, laboratory-scale only, experimental data being available due to a general lack of significant funding because of governments' hesitancy [102].

Table 1.3 Geoengineering methodologies [100, 102, 106]

Carbon dioxide removal	Solar radiation management
Capturing CO_2 from ambient air, not emission sources	**Stratospheric aerosol injection**
Fertilization of the Ocean using iron Compounds to increase capture of more atmospheric CO_2	**Reducing solar radiation** reaching the earth by shields, deflectors, mirrors is space
Ocean alkalinity enhancement to increase ocean CO_2 storage ability	**Albedo enhancement**—increasing surface, unused desert, and marine cloud reflectivity, e.g., painting the roofs of urban structures and pavements of urban environments white; use low altitude seawater/acid sprays to encourage greater cloud formation over the oceans
Geochemical weathering, the acceleration of natural geological weathering processes by injecting CO_2 into certain types of rock	
Avoided deforestation and afforestation	**Dissipation and prevention of cirrus clouds**, i.e., high altitude heat-trapping clouds

However, super-rich philanthropists, such as Bill Gates the co-founder of *Microsoft*™, have started to invest significant amounts in both CDR and SRM [e.g., 107]. Moreover, the Government of the United States is now investing in *Climate Intervention* research [108]. Yet, whatever the viability of geoengineering, there is a mountain of concerns associated not only with the AR4's "*the risk of unknown side-effects*", but also the global ethics and politics of instituting the methodologies [33]. For example, one of the major unknown effects of reducing Earth's surface temperatures and decreasing its heat energy absorption is how will agricultural food crops productivity be influenced at a time when global populations are increasing? Until far more research data becomes available, for the moment geoengineering should only be viewed as an approach of last resort, an *emergency* brake, to be used if mitigation does not flatten the rising temperature curve. However, many countries and jurisdictions have already proclaimed *climate emergencies* and, following China's announcement of their large-scale weather modification plans, others may take unilateral geoengineering actions in the absence of a global treaty.

The concept of using mitigation to circumvent the potentially damaging impacts of human-driven climate change is a relatively new phenomenon which has gained credence since the start of this century. Nonetheless, in the absence of harmful human influences for almost all the Holocene era, global climates have continued to change. Humans have learned, often painfully, to combat these changes using strategies which are now labelled *adaptation*. In the next section the approaches to adaptation, old and new, are discussed along with insights into the causes of climate variabilities.

1.4 Approaches to Adaptation and Causes of Climate Variability

Adapting to changing climates is a challenge that has existed since living things first inhabited the Earth. Scientists believe that these challenges have led to 99.9% of all species that ever existed becoming extinct and even trees disappeared for at least 10 millennia because of one of the 5 major mass extinctions that happened over the past 500 million years [109]. A less than outstanding record of adaptation success. However, with the arrival of *homo sapiens*, about 300,000 years ago, and, especially, since the onset of the present interglacial period, adaptation strategies have proved far more successful. The arrival of a globally warmer climate, coupled with learned human abilities for intentionally making fire, building protective shelters, and growing, rather than hunting, food, have been instrumental in this success. Particularly, over the past 2 millennia, humans have taken steps to harvest and store rainwater, build sea rise defences and weather-resistant buildings, and move to more habitable areas. Those who have not made such provisions have usually perished, but global populations have constantly increased, except for relatively short periods following wide-spread pandemics or wars.

On occasions, the traditional approaches to adaptation had to be modified to account for changing climate circumstances, i.e., natural climate variability, but now these changing circumstances are accelerating for reasons mainly attributed to anthropogenic climate change. Will these added climate influences result in more droughts and floods, more extreme weather events such as damaging hurricanes, changes in atmospheric and oceanic circulations, increases in sea-levels, and reductions in ocean alkalinity[9]? Research on all these effects is ongoing and there is uncertainty in some of the findings so far, so terms such as, *generally*, *more likely*, *expected to become, can worsen, more prone,* and so on are regularly seen in the climate change literature [e.g., 110–112]. The general theme is largely that *more of the same* adaptation techniques are going to be needed in the future, but that migration will not only impact populations but also agriculture, i.e., where plant-based food is grown. Moreover, urbanization will continue, and, in many instances, there will be a reluctance to move away from coastal areas. The latter means more, and better, sea-defences will be needed. In essence, risk analysis and risk management will play major roles in adaptation strategies and such assessments will rely on diverse forms of evidence, as illustrated in Fig. 1.11 [47].

Anthropogenic climate models are predicting increased global warming, which will cause changing precipitation and weather patterns, which in turn will affect adaptation approaches to local and regional terrestrial and coastal flooding, droughts, and water scarcity. Is there any way that real observations can help in deciding when and where enhanced adaptation will be necessary? Yes, using defined weather and climate indices, which are based more on observations rather

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[9] The term ocean acidification if often used to describe decreasing ocean alkalinity although the oceans still are alkaline.

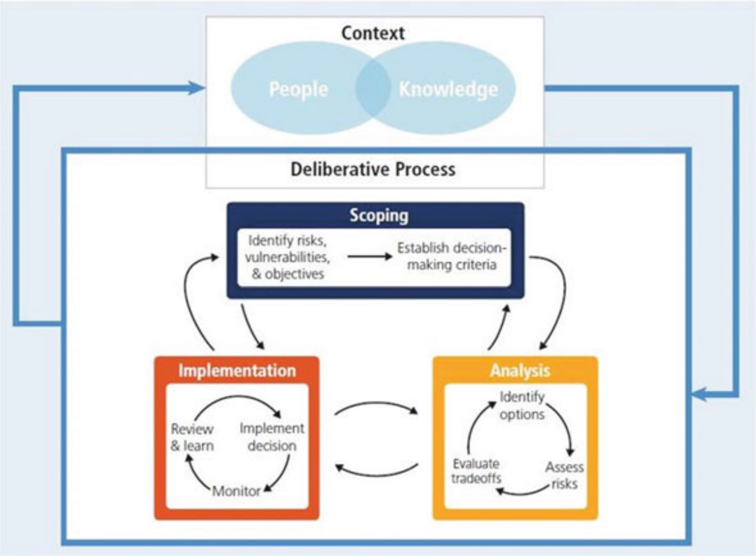

Fig. 1.11 Risks, analysis, implementation framework for adaptation [47]

than modelling results, and which include not only climate change effects but also the influences of climate variabilities. Although the precise contributions of each can be difficult to quantify. As discussed in Sect. 1.2, in the design of flood-prevention adaptation infrastructure, a *100*-year occurrence or eventuality usually supplies the benchmark.

However, the USGS (United States Geological Survey) suggest that the term *recurrence interval* is a better description than the sometimes-misleading use of comments about a 100-year flood. Moreover, they underscore that it must be appreciated that two comparable events, e.g., heavy floods, could occur at the same location only a few years apart rather than say a gap of 100 years. To address such issues, *the USGS and other agencies* use a factor called the *Annual Exceedance Probability* (AEP) in conjunction with a recurrence interval. So, if a 100-year occurrence has an AEP of 0.1 (10%) it means there is a 10% chance of that occurrence in any given year [113]. On a moving average, the AEP value could change because of climate change effects and not only the occurrence probability, but also what height of water is a major flood. The AEP and other weather and climate indices are key parameters which should be included in the design of future adaptation strategies whether, local, regional, or global. Exemplars of such probability indices are given in the next sub-section.

1.4.1 The Use Weather and Climate Indices

The numerical values of these indices are based on historic datasets, but the probability of occurrences is usually calculated using standard modelling techniques assuming normal distributions. The estimated values of the indices, recurrence intervals, and the specific eventually risks, rely to some extent on the chosen benchmarks or the quantity and quality of available data in much same way as with temperature anomaly data [114]. So, for example, as shown in the chart, given at Fig. 1.12, the SPIs for a region in the State of Idaho in the United States are based on a database of 111 years of observations, the *red curve*, based on 60-month timescales and are stated as tracking long-term drought, whereas the *blue curve* is based on 5-month timescales and when SPI = 0 ± 1, the precipitation situation is considered neutral, i.e., no dryer or wetter than usual over the years of observations [115].

If SPI values are above 1 then the climate will be wetter than normal and if below-1 it will be dryer, and the generic SPI distribution curve will be as shown as in Fig. 1.13 [116]. As a mathematical expression SPI, can be written,

$$SPI = (Xij - Xim)/\sigma) \tag{1.1}$$

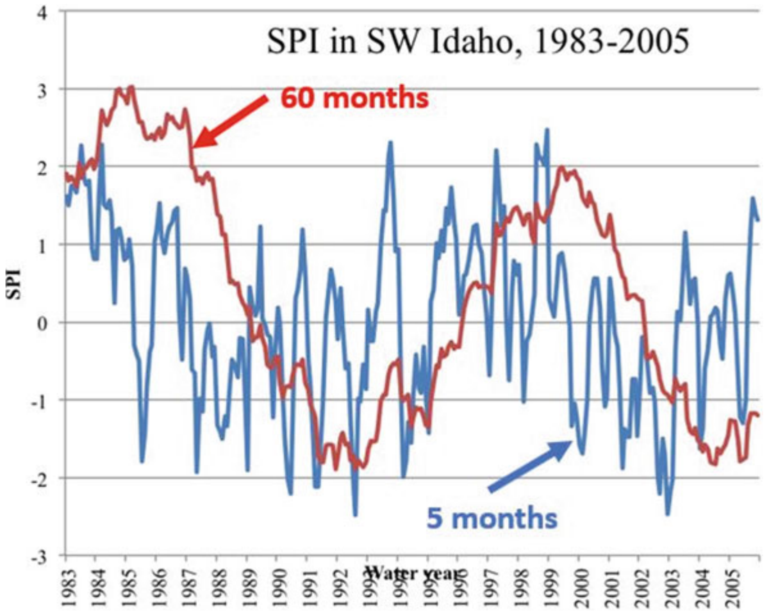

Fig. 1.12 Example of SPI curves in a USA region [115]

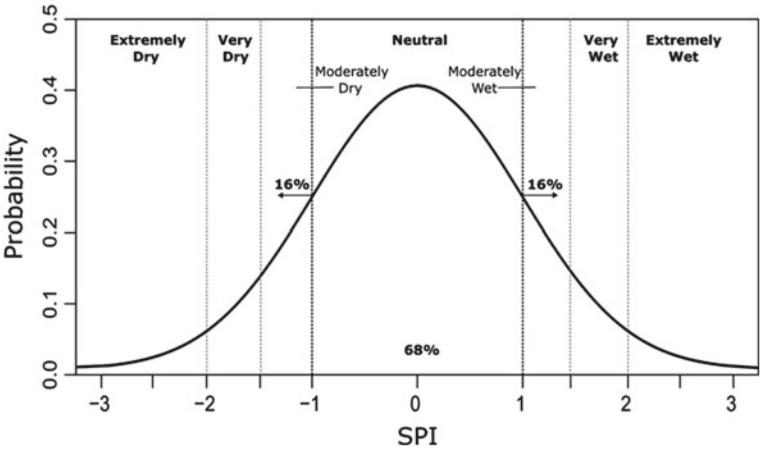

Fig. 1.13 Generic SPI normal distribution curve [116]

where,

Xij Seasonal precipitation in ith rain-gauge station and jth observation
Xim long term seasonal mean, and σ is the standard deviation.

Similar expressions, or computer algorithms, can be used to calculate the numerical values of the various indices. These can show what adaptation measures may need to be contemplated, if not already taken, and what adaptation measures are needed to be taken to avoid local, regional, and global disasters, what the United Nations Office of Disaster Risk Reduction (UNDRR) term *disaster risk reduction* [114, 116, 117].

1.4.2 Adaptation, Climate Variability and Climate Change

Since they first appeared as a specie, adaptation has allowed humans to address climate variabilities. But what are the sources of these variabilities? Over the last two centuries scientists, particularly geologists and anthropologists, became aware of current and historic *natural* climate changes and they tried to answer the question, why do they happen? However, awareness is different from understanding and there are still no wholly conclusive explanations for the causes and effects of such variabilities, but they have found several factors that are associated with natural climate changes. These include *Plate Tectonics*,[10] the idiosyncrasies of the *Carbon Cycle*, and the *Milankovitch cycles*, which are connected to the intricate

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[10] Formerly referred to as *continental drift.*

relationships between the amount of solar radiation reaching the Earth at specific locations at any given time and global periods of subsequent climate warming and cooling.

Plate Tectonics. Plate tectonics is the notion that the Earth's outer shell, or *lithosphere*, which is about 100 km thick, consists of slabs of rock, *plates*, which drift around the Earth, their movement being lubricated by an underlying viscous layer, the *asthenosphere* [118]. Plate collisions, and the geological movements along the boundaries of contiguous various plates, can lead to volcanic eruptions, earthquakes, and tsunamis which cause short-lived changes in local, and sometimes global, weather and climates and can have devastating effects on the impacted populations.

Adaptation strategies now include the continued development of scientific *early warning systems* of these events, although there is still a high degree of uncertainty in forecasting the timing and duration of such happenings. However, based on these developments, and using a growing body of accumulated observations and measurements, it is possible to categorize global regions where the likelihood of plate tectonic incidence is much higher. In these regions adaptation measures, such as requiring that buildings are *earthquake-proof* and constructing *sea-defences* (for example, walls, breakwaters, and wave disruptors), are used to reduce the risks from natural disasters [119, 120]. Although, it should be noted, that regions outside the active tectonic zones also use sea-defences to protect communities from the effects of tidal variations.

The Carbon Cycle. Carbon is a key part of all living things, being described in school textbooks as the *backbone* or *foundation* of life on Earth. Carbon compounds are present in various forms in the oceans, sedimentary rocks, soil and organic matter, vegetation, and in the atmosphere as GHGs, i.e., carbon dioxide and methane. Atmospheric carbon dioxide is captured by terrestrial vegetation and oceanic phytoplankton from which it enters both animal and human food chains. Eventually, the sequestrated carbon will be returned to the atmosphere by a variety of natural processes, as illustrated in Fig. 1.14 [121]. The Earth's amount of carbon is invariable and its transfer from one source to another is known as the *Carbon Cycle*. Any changes in the stored amounts in one source will alter the amounts in the other *sinks* and possibly the rate of transfer between them. While the atmospheric carbon dioxide and methane store only a trace of the Earth's total carbon, sedimentary rocks such as limestone account for almost all of the total carbon [122]. Volcanic and rock weathering processes are the main pathways for the return of carbon dioxide into the atmosphere. Plate movements can instigate these processes, and while weathering is usually an extremely slow activity, even measured in *geological* time, when volcanoes erupt the effects are immediate. In both cases the Carbon Cycle transfers are altered by plate tectonics [123]. This is not only important for climate variability adaptation but could also have a similar significance for climate change. This is because it appears that excessive tectonic outgassing of GHGs could affect global warming, but, conversely, such warming could

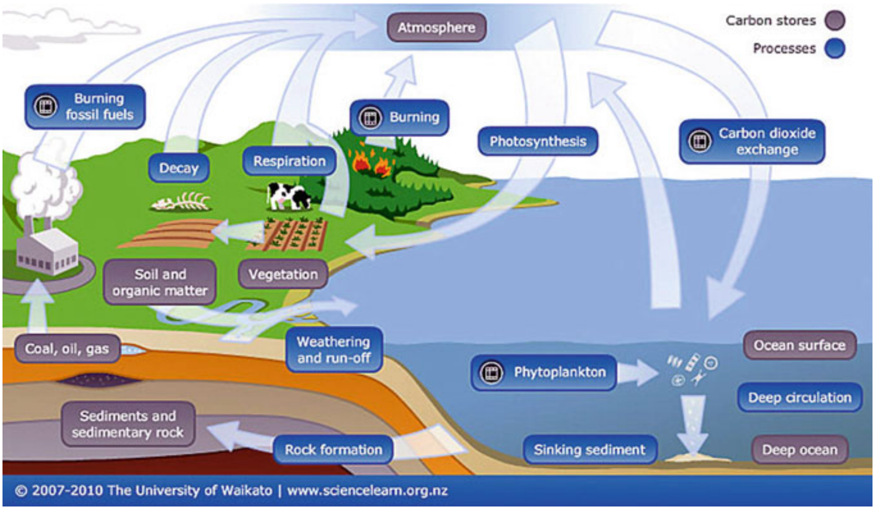

Fig. 1.14 A depiction of the carbon cycle [121]

reduce tectonic activity. The exact correlation between plate tectonics and anthropogenic climate change, and vice versa, are still matters of scientific debate [124, 125].

The Milankovitch Cycles. The final variability factor, and the most important, are the Milankovitch cycles, named after Dr. Milutin Milanković a Serbian civil engineer and mathematician.[11] By the early nineteenth century, several leading geologists suggested that abnormal surface rock *boulders*,[12] seen throughout some global regions, were the result of historic glaciation, *Ice Ages*, and hypothesised that the cause was likely to be *astronomical,* involving the amount of *isolation* (incoming solar radiation) from the sun reaching the Earth [126]. Their work intrigued Milankovitch and, after practising as an engineer, he entered academia and published his first paper on climate theory. During the 1914–1918 world war he was a prisoner of war and afterwards an *internee* [127, 128]. He returned to full-time academia after the war and continued his work for another three decades on developing a mathematical theory of how ice ages are caused by isolation. With a growing body of scientific evidence, eventually Milankovitch was able to model the effects for isolation on the Earth's climate for the 600,000 years before the nineteenth century [129]. He discovered, through modelling using a complex set of equations, that there were 3 orbital cycles involving the Sun and the Earth which triggered climate changes and, by considering the Earth as a *black body*, was able to

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[11] Milankovitch graduated in Civil Engineer both as an undergraduate and postgraduate student. He is often referred to as a geophysicist, astronomer, scientist and, more recently, a climatologist!

[12] Also known as *erractics.*

calculate the Earth's annual surface temperature variations [130]. He found that there were long periods, *glacial epochs*, when the surface temperatures would cool and glaciation, i.e., the ice cover, would increase. These were interspersed with shorter periods of surface warming, *interglacial periods*, when the glaciers would retreat. His theoretical model predicted when these periods had occurred, but it would be 5 decades before evidence was available to confirm the theory [129].

The three cycles were due to changes in (a) the Earth's orbital path around the sun, from almost circular to slightly elliptical i.e., the orbit's *eccentricity*, (b) the angle of the Earth's rotational axis relative to its plane of orbit around the sun, known as *obliquity* or *axial tilt*, from 22.1° to 24.5° and (c) the wobble, or *precession,* of Earth's spin caused by various combinations of the gravitational forces exerted by both the sun and the moon. An often used analogue is that of the motion of a child's spinning top as the Earth is not a perfect sphere [126–130]. These changes occur in a cyclic manner of varying frequencies, i.e., minimum to maximum eccentricity takes place over an average of about every 100,000 years; axial tilt cycles, from minimum to maximum and back again, take place over about 40,000 years, and significant changes in the precession trend occur about every 26,000 years. There is a lack of synchronicity between the highs and lows of the 3 cycles, but it needs to be stressed that while cyclic changes, albeit over long periods of time, are continuous, they do not suddenly change the climate during a normal human's lifetime. So why should we be interested in Milankovitch cycles?

First, they show that the amount of solar radiation reaching the Earth's geographical regions, especially the Northern Hemisphere, at certain times in the cycles will sooner or later lead to global cooling and the next glacial epoch. Secondly, it is now known that axial tilt is the prime driver of Earth's seasons, e.g., winter and summer. As the tilt changes, the seasons will vary in length, location, timing, and characteristics. So, for example, when the North Pole tilts toward the Sun, it will be summer in the Northern Hemisphere, and when the South Pole tilts toward the Sun, it will be winter in the Northern Hemisphere. Depending upon global location and elevation the seasons have different rates of precipitation, evaporation, and temperature change and while the tilt contributes to the timing and nature of the seasons, it is not the only factor which affects occurrences of floods and droughts, as natural hazards associated with plate tectonics, e.g., earthquakes and volcanic activity, occasional disruptions in atmospheric and oceanic circulations, together with wildfire and destructive hurricane incidences can also influence normal seasonal climates [131].

The type of indices given in Table 1.4 afford some insight into what regional adaptation techniques are needed to address the seasonal changes caused by tilt and then further altered by natural occurrences, i.e., *climate variabilities*. These indices enable infrastructure standards to be formulated, but as the climate has been changing since the 1970s, more up to date benchmarks than a hundred years ago could help to show the possible regional consequences of anthropogenic climate change on future adaptation strategies. In the absence of *climate change*, adaptation will still be necessary because of the climate variabilities involving Plate Tectonics, Milankovitch cycles, and others factors yet to be revealed [132]. However, weather

Table 1.4 Exemplar weather and climate indices [113, 115, 133–140]

Climate index or analysis	Use and definition	References
Annual exceedance probability (AEP)	Probability of a flood event occurring in any year	[113]
Standardized precipitation index (SPI)	Characterizes meteorological drought or abnormal wetness	[115]
Standardized precipitation evapotranspiration index (SPEI)	Combines precipitation and potential evapotranspiration (PET) data	[133, 134]
Standardized streamflow index (SSFI/SSI)	Characterizes hydrological drought from surface run-off water	[135]
Flood frequency analysis/return period	Determination of the statistical potential for floods	[136]
water exploitation index (wei+)	Indicator of water scarcity	[137]
Air quality index (AQI)	Numerical index of five major air pollutants	[138]
The U.S. climate extremes index (CEI)	Overview of climate extremes across continental United States	[139]
Risk of natural catastrophes (cat modelling)	Financial impact on infrastructure	[140]

and climate indices are based on measured data of actual events, not on predictions or projections of future incidences. There could be little, if any, economic and societal benefit from imposing unnecessary adaptation measures. Conversely, if enhanced adaptation approaches, e.g., higher sea-walls prove to be vital because of climate change, and steps have not been taken, there may be insufficient time to construct them and avoid disasters [114, 116, 117].

Mitigation cannot negate the need for adaptation, but it could influence the future scale of adaptation strategies. Moreover, modest enhancements to the current approaches may enable more time for mitigation processes to achieve their desired goals. The shortcoming of such tactics could be reduced public and political anxieties about anthropogenic climate change and reduced global investments in mitigation approaches. Hence, are there ways of constructively addressing both mitigation and adaptation simultaneously to defeat the impacts of changing climates, at least until the inevitable arrival of the next Ice Age? In the next section these matters are discussed.

1.5 Mitigation and Adaptation: Trade-Offs, Conflicts, and Synergies

Mitigation and Adaptation are both aimed at reducing the harm caused by changing climates, mitigation as a permanent global approach with the goal of eventually ending anthropogenic climate change, while adaptation is aimed at reducing the harm at more *local* levels which can be caused by natural climate variability and, more recently, the possible increasing influences of human-driven climate change. As urbanization continues to increase, albeit somewhat slower because of the COVID-19 pandemic, the discussions about local adaptation in cities and the relationships with national and global mitigation approaches have not abated [141]. Calls for better urban planning and management, with respect to creating friendlier environments through mitigation and adaption, are not new [e.g., 142, 143]. However, an adaption technique for, say, addressing water scarcity, e.g., the building of dams and reservoirs, can lead to conflicts with the mitigation techniques trying to reduce emissions, because of the potential GHG emissions from large bodies of water.

Furthermore, generating more *green infrastructure,* in and around population centers, could lead to the concentration of more people into smaller land areas by building residential and workplace structures vertically as opposed to horizontally, which in turn could enhance, rather than reduce, the climate impacts of urban heat islands. The taller buildings also need more steel and concrete, whose manufacture produces more GHG emissions. There could also be adverse socio-economic consequences for those seeking affordable housing away from urban areas, as demand exceeds supply and city housing costs rise. These individuals will need to travel greater distances to their places of work, and transportation, public or private, will produce more GHG emissions until mitigation strategies become effective. The suburban or rural areas that people must move to, may also be in less well protected flood locations and may have inadequate clean water supplies, at least initially. If this proves to be the case, then eventually, better and more flood prevention measures, and water supply infrastructure, may be necessary which would involve new dams and reservoirs especially as the local population rises. Subsequently, further mitigation versus adaptation conflicts may be created. Conversely, changing land-use from agricultural to reforestation could result in insufficient food production and loss of income.

While these are simple *what-if* examples many such issues have been raised in the climate literature and in place of labelling them as *conflicts*, terms such as *maladaptation* have been coined to describe adaptation strategies that increase GHG levels and *malmitigation* for a mitigation strategy that, while reducing global GHG levels, increases the local or regional vulnerability [144, 145]. There is a growing body of scientific literature dealing with maladaptation and malmitigation in climate change contexts, with the focus being largely, but not exclusively, on the issues that could be experienced in urban communities [e.g., 146–148]. Moreover, concerns about *uncertainty* are often expressed in this literature. However, according to a recent publication survey, there are significantly more articles dealing with trade-offs between mitigation and adaptation, particularly when cities do not have infinite resources [149, 150]. But could there not be a way where mitigation and adaptation could be used together without serious conflicts and enforced trade-offs, i.e., *synergies*? Yes, and such approaches are gaining more scientific attention [143, 151–153]. Possible *sweet-spots* for synergies between mitigation and adaptation have been identified, as shown in Fig. 1.14 [151, 154].

1.6 Concluding Remarks

In this chapter, the main approaches to limiting the average global surface temperature to the 2100 level specified in the ground-breaking Paris Agreement, i.e., the reduction of atmospheric GHG levels, *Mitigation*, were discussed. Aspects of the potentially damaging impacts of anthropogenic global warming on the Earth and its growing number of inhabitants were highlighted. It was emphasized that the Earth has been subject to intrinsically changing climates since its formation and that, since the arrival of homo sapiens, methods of addressing the harmful impact of these changes have evolved, albeit with varying degrees of success. Collectively, these methods are termed *Adaptation*. It is unrealistic to expect that mitigation can prevent natural climate changes, now defined as climate variabilities, so adaptation techniques will always be needed. However, without mitigation, adaptation could become progressively challenging and, in some instances, impractical, which could also be the case when mitigation adversely effects locally applied adaptation infrastructure and thus becomes malmitigation.

Although agencies such as the IPCC have advocated for both mitigation and adaptation, the bulk of government funding on climate research and innovation has been focused on mitigation strategies such as energy transitions [5]. Now, with the apparently growing realization that mitigation alone will not correct anthropogenic climate in the hoped-for timeframe, will governments of all levels, especially national and international, embrace adaptation as a necessary adjunct? After all, local and regional governments have a long record of adaptation actions. However, to avoid maladaptation and malmitigation and promote synergies, constructive frameworks will need to be established, at least, for those *sweet-spot* scenarios identified in Fig. 1.15 [155, 156]. This will require thorough and proper planning

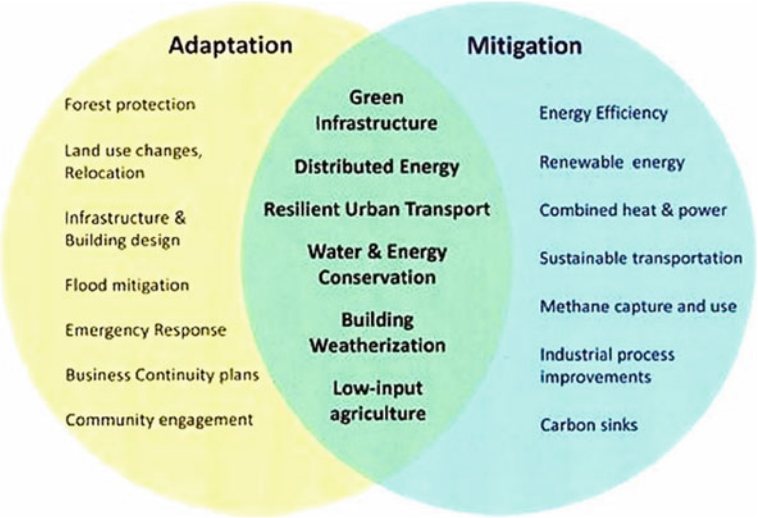

Fig. 1.15 Adaptation and mitigation *sweet-spots* [151, 154]

involving all those directly, or indirectly, taking part in, or impacted by, the proposed solutions. Unquestionably, such processes should include well coordinated rural and urban land management strategies to avoid technical, financial, and social conflicts where possible and practical.

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Chapter 2
Comparison on Critical Performance Characteristics of Perovskite-Based Flexible Solar Cells

Lutfu S. Sua and Figen Balo

Abstract The perovskite-based flexible solar cells are a novel group of photovoltaic devices that have drawn interest because of their considerable opto-electrical features with the inclusion of high carrier motions, tunable bandgaps, good absorption coefficients, long-range porter diffusion lengths, easy manufacturing, and low expense. The perovskite-based flexible solar cells have achieved performances of 18.36% and 22.70% on rigid with poly substrates and fluorine tin-oxide, respectively. These can be compared to those of copper-indium-gallium-selenium and single-crystal silicon solar cells. During a duration of more than 8 years, the perovskite-based flexible solar cells' photo transformation performance has been developed through adjustments in the device-architecture, and optimization of the absorber and electron/hole transport sheet. In the market, there is a wide range of photovoltaic cells. In the last years, new generation photovoltaic cells from diverse materials have taken their place in the market. In a photovoltaic cell, the primary operating characteristics are efficacy, area, and density characteristics. For perovskite-based flexible solar cells, this study aims to determine the photovoltaic effectiveness and compare the photovoltaic cells manufactured in various kinds with respect to primary operating characteristics. The main contributions of the study are the assessment of the collection of parameters needed in the assessment of solar concentrator cells, definition of their comparative priorities based on expert opinions, and the provision of a straightforward quantitative investigation.

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2.1 Introduction

Power should be the leading sector of the world's endeavor for renewable improvement, but the investment information reveals a harder reality. Energy investment as a share of global GDP (gross domestic product) has decreased by 20% from 2019 to 2020 in addition to a nearly 10% decrease in GDP [1].

For human society, the use of safe, sustainable power resources has become very important. With environmental pollution and growing global power use, human society's sustainable development cannot be met by conventional fossil power resources. Solar energy is certainly one of the most encouraging industries amongst a range of novel power industries. Sun energy is contemplated the most significant sustainable power source because it is inexhaustible, clean, affordable, and import independent. The sophisticated utilization of the solar power does not lead to damage to ecology or further pollution such as conventional fossil-based energy sources [2]. In truth, the solar industry has currently become a net producer of energy [3] and is seen as a significant potential source of renewable energy [4, 5]. Therefore, these developments illustrate the likelihood that solar industries could provide a substantial fraction of the next power supply blend, offering a solely appealing contribution to the challenges of energy security and ecological sustainability in the world [6, 7]. Thus, it is not surprising that clean energy technologies are an integral part of the global and national power policies.

Given the good-installed connection between fossil energy source expenditure and emissions of carbon dioxide, it is recently predicted that by 2050, around 25,000 GW of low C energy will be required to meet the ambition of international society to mitigate pernicious effects of climate change and reduce carbon dioxide emissions [8]. For this reason, it is assumed that to meet this challenge, a combination of solar industries could be named.

Over the last decades, different industries have been improved to utilize solar power, like artificial photosynthesis [9], solar architecture [10], solar heating [11], photocatalytic water splitting [12, 13], and photovoltaics [14]. Among them, solar cells that transform sunlight into electric has interested extensive attention because it is capable of supplying adequate amount of power to compensate all of our energy demand without creating any environmental pollution to the ecology for predictable future of humanity. A photovoltaic film is a device that transforms light power immediately into electricity energy by photochemical reactions or photovoltaic effects. So far, different kinds of photovoltaic cells have been developed, for instance, thin-film silicon films [15, 16], sole crystalline silicon-based solar cells [17–19], polycrystalline silicon solar cells [20], CIGS films [21, 22], CdTe based films [23, 24], CZTS [25–27], GaAs-based films [28], dye-sensitized films [29], perovskite-based flexible films [30], organic photovoltaics [31], and quantum dot-sensitized films [32].

For photovoltaic films, the most significant figures of worth for commercialization are energy on cost and type performance. The photovoltaic market has been perpetually growing during the last years, bringing opportunities for novel photovoltaic industries of which perovskite-based flexible solar cells are encouraging nominees. For the perovskite-based flexible solar cell industry, toxicity and long-term stability are also significant topics at the existing step. The perovskite-based flexible photovoltaic cells have intensely impacted the photovoltaic society by ensuring high energy transformation performances. Perovskite-based flexible solar cells have attracted important interest because they are appropriate for mass-manufacturing by the roll to roll production technics, favorable tremendous potency for feasible implementations in light, portable, and wearable electrical appliances. Both the precursor materials' accessibility and low cost for the thin films and the perovskites' easy formation by low-temperature methodologies give primarily assistance for the flexible perovskites' utilization in solar films [1, 33]. The solar cells' diverse generations are displayed in Fig. 2.1 [34].

There has been a great deal of technical and scientific interest in wearable and portable sensors that can adapt to people's skin and easily capture functional signs [35–37]. The full realization of their functionality for these wearable electronics depends heavily on their matched power supply's credible operation, which is required to be lightweight and versatile while retaining high energy and providing long longevity at the same time [38–40]. Nonetheless**,** traditionally rigid energy supplies like lithium-ion battery pads are still dominated by the existing demand for wearable electronics, so the pursuit of multi-functional power tools that can supply power production whenever required to introduce self-powering properties occur very immediately [41–43]. The fast improvement of arising power storage and harvesting industries might benefit from the logical structure of such a wearable energy system [44–46].

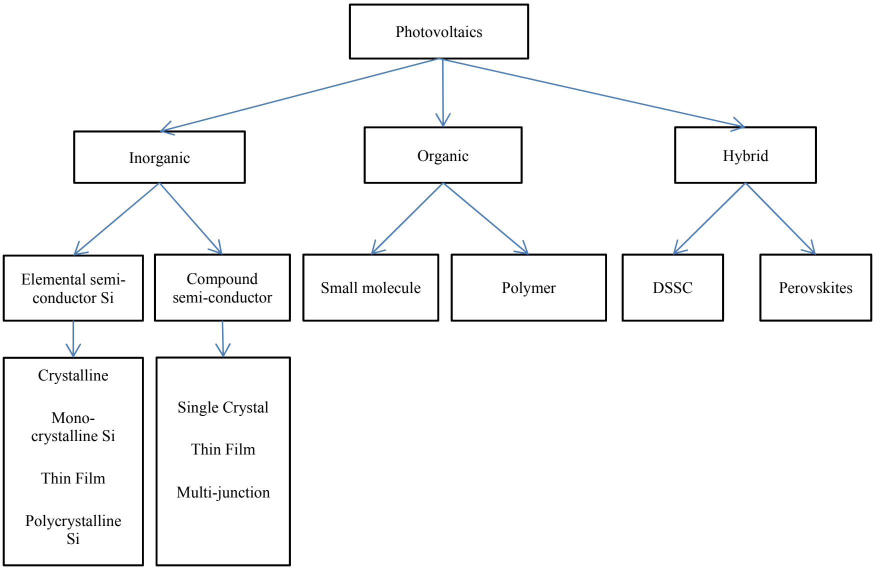


Fig. 2.1 The solar cells' diverse generations

The combination of mature photovoltaics, like dye-sensitized films and organic photovoltaic films, with representative power storage tools like lithium-ion batteries and supercapacitors, is one of the actual research issues, thus achieving simultaneous storage and harvesting of energy [47–49]. Sparse sun power could be adequately stored by implementing thus-integrated photo-rechargeable systems; however, in comparison to that of bare films, output energy could be supplied in a more reliable form. However, from the practical application viewpoint, due to the restricted photoelectric transformation performance of the photovoltaic cell, the overall efficiency of the organic photovoltaic cell and dye-sensitized cell charging systems has stayed usually poor (normally <4%). In this regard, the creative and low-cost production of high efficiency (photoelectric conversion performance: 15–20%) perovskite solar cells enables their direct integration into different power systems. [50–52]. For example, an integrated perovskite-based flexible solar cell and supercapacitor power pack has shown a 1.45 V output voltage with an overall device efficiency of up to 10% [52].

Four series-connected perovskite-based flexible solar cells were used for charging a Li4Ti5O12/LiFePO4 lithium-ion battery along similar lines, demonstrating an overall efficiency of 7.8% [53]. A perovskite-based flexible solar cell was recently utilized to photo-charge a lithium-ion battery provided with a voltage transformer and achieved an overall complex performance of 9.36% [54]. Despite this noticeable progress reported by far, almost all systems have adopted button-type or planar interface configurations, which have many disadvantages, including heavyweight, lack of versatility, and bulky shape, which may be incompatible with self-powering wearable electronics functionality.

Perovskite-based flexible materials were primarily utilized in dye-sensitized films as a sensitizer. The Miyasaka team used a sensitizer of $CH_3NH_3PbBr_3$ and achieved a performance of 3.8% [55]. However, in iodides containing liquid electrolytes, $CH_3NH_3PbBr_3$ was very unstable, leading to rapid degradation of the unit. Park's team developed quantum dot-sensitized films in 2011 utilizing presynthesized perovskite-based materials with a diameter of 2–3 nm. The $CH_3NH_3PbI_3$ quantum dots' good absorptivity and the thin TiO_2 film's low current loss resulted in a photoconversion efficiency of 6.54% [56]. Park and his co-workers manufactured heterojunction, sensitized, solid-state, perovskite films in 2012 (device build: fluorine-doped tin oxide, TiO_2 blocking sheet, mesoporous TiO_2 perovskite, spiro-OMeTAD, N-di-pmethoxyphenylamine, Au; through the optimization of layer thicknesses, the highest efficiency, 9.7%, was achieved). For over 500 h without encapsulation, a remarkable improvement in system stability was the most important development: it was air-stable [57]. This is a landmark for the perovskite solar cells' development, allowing more performance improvements. As it accomplishes high photoelectric conversion efficiency, other researchers have widely adopted this system.

2.2 Perovskite-Based Flexible Solar Cells

The perovskite-based flexible films have illustrated competitive potentials with higher-efficiency potential, but the perovskite-based flexible film's stability is restricted compared to that of leading photovoltaic industries: They do not hold up good against light's prolonged periods, high heat, or dampness. For the production of commercial perovskite solar products, improved cell durability is paramount. Investigators are researching the deterioration of both the contact layers and the perovskite materials to improve stability. The possible ecological effects concerned with the perovskite-based absorbent, which is lead-sourced, are further obstacles to commercialization. As such, to assess, minimize, and mitigate ecological issues and ultimately remove toxicity, future and existing materials are being examined. In order to decrease or remove these possible problems, existing materials discovery activities are assessing lead-free perovskite-based buildings. In high-efficiency tandem system architectures, buildings in which they are coupled with another absorbent material to produce more energy, another beneficial implementation for perovskite-based films may exist. The perovskite-based films transform visible light and ultraviolet into electricity effectively; they might be perfect duo partners with absorbent materials like crystalline silicon that effectively transform less-power light.

In addition, the perovskite-based materials being researched have adjustable band gaps, so they can be custom-planned to supplement their partner material's absorption. Doing so could lead to PV tandem implementations that are even more powerful and more cost-effective. A critical and final difficulty lies in the fabrication processes' optimization and scale-up for perovskite-based films [58].

In the module/solar cell realm, perovskite provides a wide range of benefits [59]:

- With present solar cell goods, the return on power investment is calculated in years and months.
- Perovskite material is extremely flaw-tolerant, providing high yields and ease of production when operating in cells bigger than 300 W (present lamellas need risk, cost, and exceptional engineering to raise the fabricating deposition field).
- Present laboratory effectiveness reflects those in crystalline silicon and other lamella materials, and tandem perovskite-based flexible solar cells have a feasible roadmap to achieve more than 33%.
- It has a large bandgap, which results in more sunlight and greater tunability being transformed to electricity.
- No supply-limited or rare earth material is needed.
- With 20 times fewer materials, it is fabricated as a lamella product.
- Perovskite material manufacturing is highly simplified through the processing of solutions and does not need the high-cost machinery and equipment necessary for semiconductor procedure.
- Depending on the production methodology used, perovskite-based solar cell output has a limited ecological footprint.

- Perovskite-based solar cells can be formed as conventional rectangular photovoltaic cells or be elastic, opening up novel implementations and markets.

Big endeavors have been made since the emergence of perovskite-based photovoltaic technology to obtain high-quality flexible perovskite solar cells with high crystallinity, full coverage, and lack of pin-holes, especially utilizing low-cost and simple manufacturing methodologies. Investigations include the diverse technics utilized to manufacture perovskite-based flexible films in this stage. The perovskite-based flexible solar cell structure schematic diagrams are provided by the Handbook of Nanomaterials for Industrial Applications [33].

2.2.1 *One-Stage Deposition Methodology*

In the one-stage deposition methodology, a blended precursor resolution including a non-stoichiometric (3/1) or stoichiometric (1/1) molar rate of metal halides and MA:FA halides are immediately deposited by a one-stage spin-coating procedure onto the required substrates. To create perovskite-based solar cells, the specimens are then recycled at a low temperature (100 °C) [60]. The YangQs team blended 3/1 CH_3NH_3I and $PbCl_2$ with a molar rate and manufactured the perovskite layer at room temperature using the one-stage spin-coating process [61]. The annealing temperature's effect on the formation of $CH_3NH_3PbI_3$ perovskite-based films was researched by Grtzel and his colleagues using the one-stage spin-coating process [62]. On flexible plastic substrates, the optimized low tempering temperature made it possible to produce high-quality, uniform perovskite-based solar cells. The resolvents utilized to dissolve the pioneer materials influence crystalline and morphology features during perovskite formation in solution-processed methodologies [63–65]. *N*-dimethylformamide, N, toluene, dimethyl sulfoxide, r-butyrolactone (GBL), methyl-2-pyrrolidinone, or a combination of these chemicals are the most widely utilizations [65–68]. In a GBL/DMSO blended solution, Seok and colleagues added toluene and safely manufactured remarkably dense and uniform perovskite-based thin solar cells through an MAI-PbI_2-DMSO intermediate process, and a 16.2% certified power conversion efficiency without hysteresis was produced for the tools based upon the perovskite-based films [69].

2.2.2 *Two-Stage Consecutive Deposition Methodology*

The one-stage deposition methodology utilizing a blend of MAX and PbX_2 in a widespread resolvent leads to the perovskite's uncontrolled precipitation. This causes broad morphological differences and contributes to the spread of photovoltaic output in the resulting tools, hampering the potential for practical implementations [70]. As a conclusion, a two-stage consecutive deposition methodology with a low-temperature was developed, here the lead pioneer is initially covered to the lower layers, then MAI is presented onto the found specimen's superficies, generally through revealing it to the MAI chemical [71]. By this methodology, the pioneer materials can be transformed into perovskite within a short period of time at room temperature conditions [70]. Through spin-covered stacked sheet interdiffusion of MAI and PbI_2, Huang and his co-workers highlighted the importance of a diverse two-stage consecutive deposition methodology to manufacture methyl-ammonium lead tri-iodide perovskite-based flexible films [72]. With flexible plastic bottom layers, the low temperature utilization is harmonious.

The two-stage consecutive solution-treated deposition methodology supplies an effective low-cost way to high-efficiently perovskite-based flexible solar cells, it also has some disadvantages: PbI_2 utilizing this methodology cannot generally be transformed entirely, and the perovskite crystals formation cannot be controlled [73]. Thus, other changed deposition methodologies were improved to develop the perovskite film morphology and PbI_2 conversion. For the solution-treated methodologies, additives propose an effective route to develop the perovskite-based flexible solar cell quality [74]. For the low-temperature perovskite, production process investigators have improved and utilized many diverse additives in the pioneer solution, such as fullerene [75], polymers [76], solvents [77–80], inorganic acid [81], and the like [82–84]. Inflexible tools, the polymer-pier perovskite sheet strengthens the structure and develops strain tolerance, hopeful implementation [81]. Inorganic acid adds substances, like hydrobromic acid, hydrochloric acid, and hydriodic acid, have been improved to develop the perovskite-based flexible solar cell efficiency for their benefits as follows. The inorganic add substances connect with PbI_2 to type a pre-crystallized middle level complicated, which then aid to develop the perovskite-based crystal outgrowth.

The inorganic acid-based intermediate mixture has been proven to greatly slow down the process of perovskite crystallization, leading to developed crystalline consistency due to the difficult dissociation of inorganic acid from PbI_2. Inorganic acid additives are also more efficient in improving the crystalline structure and the size of the perovskite grain, providing high-quality perovskite film for better efficiency of the solar cell. With the enabled HI's addition, PbI_2 complete conversion into perovskite, thus manufacturing big crystal grains and pinhole-free to high-quality perovskite. The perovskite-based flexible solar cells prepared as perovskite flexible film display mean effectiveness up to 17.2% due to the developed decreased trap density, separation/charge-injection effectiveness, diffusion coefficient, charge collection effectiveness, and carrier lifetime [85]. As an additive, water was utilized in the perovskite pioneer solution, though it has a higher vapor pressure and fewer boiling points compared to the other additives of solvents. When the additive of water was presented into the pioneer solution during the growth of crystal perovskite, well stability and crystallization were also shown. Lately, Yang and his co-workers utilized dimethyl sulfide to slow down the perovskite-based crystal procedure as an additive, and accomplished good quality perovskite-based films with bigger crystal grains, less trap density, and well ecological stability, leading to 18.40% record effectiveness for perovskite-based flexible solar cells and to 19.61% effectiveness for rigid perovskite-based flexible solar cells [77].

2.2.3 Other Methodologies with Low-Temperature

Other effective deposition methodologies were improved to develop the PbI_2 morphology and conversion. Kelly and his co-workers developed the perovskite-based solar cells, changed the two-stage deposition method with heat evaporation utilized to produce the PbI_2 pioneer solar cells, therefore avoided the troubles created through the PbI_2 pioneer solution's viscosity or solubility [86]. YangQs team improved a vapor-aided solution-treated methodology to build polycrystalline perovskite-based films with good standards. Afterward, spin-covering the PbI_2 sheet on the DMF solution substrates, MAI powder was spread out over the PbI_2 covered substrates, which were then coated through a petridish coating. Then tempering at 150 °C, perovskite-based solar cells with little superficies roughness, overall superficies coverage, and grain size upwards small-scale were found [87].

2.2.4 Potential of Perovskite-Based Flexible Solar Cells

As a novel sprouting clean industry, the commercialization feasibility of the perovskite-based flexible films is one of the most related issues since its introduction. It improved a changing vacuum deposition methodology to manufacture good quality perovskite-based solar cells, ensuring a qualified route to encourage the technological materialization [88, 89]. Comparing to the solution that simply fabricates deficiently superficies coverage, especially for bigger scale solar cells, creates humidity penetration and solvent inclusion, the vacuum deposition methodology supplies well quality perovskite-based solar cells with more smooth morphology, full superficies coverage, and smaller roughness, together with higher purity's crystalline phases. Because the vacuum deposition media proposes more preferable humidity conservation, the tools display high efficiency and excellent stability with minimal efficiency difference. Furthermore, contrary to the conventional vacuum deposition methodology that needs to observe and check the deposition ratios, the option sheet deposition industry relieves the complex processes.

For bigger-scale perovskite-based tool production, the primary point is to stay the perovskite-based solar cell quality like coverage and uniform. The low-temperature methods and the vacuum deposition method combination proposes an encouraging route to actualize the mass production of the perovskite-based flexible solar cells. Another cost-efficient route to actualize the mass production of perovskite-based flexible solar cells is continual roll to roll industry that feeds tools on the flexible substrates' roll [90]. As known for its concentrate on potential big-scale production procedures, roll to roll treating has been meaningfully applied in photovoltaic production, especially in the area of dye-sensitized films [91] and organic films [92]. Compared to existing films, the perovskite-based photovoltaics are more useful to improve big-scale flexible tools utilizing roll to roll industry, due to perovskite materials' excellent features, like super absorption coefficient, good mechanical toughness, and high solubility in the polar solvent [93, 94]. Moreover, the production of flexible perovskite-based solar cells by the roll to roll industry is anticipated to be meaningful due to the easy tool construction and advantageous production procedure [94]. Generally, the flexible substrates utilized in this method to manufacture big scale perovskite-based flexible solar cells are PEN or PET, due to the good conduction that guarantees the event light is converted into the perovskite absorbing sheet. Although the active field is far from adequate to be included in the actual implementation, this study strongly displayed that the perovskite-based flexible solar cells are consistent with roll to roll treating.

Additionally, further studies are required to optimize the continual roll to roll production operation characteristics to carry out the commercialization of perovskite-based flexible films with efficiency and high stability perovskite-based flexible solar cell commercialization, like the film thickness, deposition flow and speed, annealing and substrate temperature, and solvent selection.

2.2.5 Credibility for Perovskite-Based Flexible Solar Cells

International specifications such as 'Thin-film terrestrial photovoltaic cells, type approval and design qualification' (IEC 61646) and 'Crystalline silicon terrestrial photovoltaic cells, type approval and design qualification' (IEC 61215) have been developed and published by the IEC for commercial photovoltaic industries. Before the cells are placed into area implementations, basic endurance tests need to be passed. These tests assess the thermal and electrical properties of the cells and are important to demonstrate that, in the climates defined in the aim, the cells are withstanding prolonged exposure's capability. The real-life expectancy of such eligible cells still depends upon the installation, design, and conditions of the environment in which they work.

Currently, inorganic and silicon photovoltaic thin-film cells have shown remarkably maximum norms of credibility in area implementations and can offer a 25-year warranty, and after 25 years, photovoltaic cells can sustain a power performance of about 80% of their main performance. Particularly, not only are the lifetimes of such photovoltaic cells estimated through speeded up aging experiments, but statistical valuations found with cells under real outside operational terms were also confirmed [86, 95]. A low expense per watt is crucial, which means that both lifetime and performance requirements to be compared to present characteristics. The big decreases in crystalline silicon have been visible in the performance gap between industrial modules and laboratory cells; perovskite-based flexible solar cells would likewise enlarge cell fields to the panel norm and require reaching lifetimes comparable to those of inheritance photovoltaic industries. Technology scale electronic-grade cells, recycling methodologies to resolve lead toxicity issues, and the implementation of normed test protocols to estimate the lifetime of perovskite-based flexible solar cells would require further improvements. Potential-induced degradation, light-induced degradation, mechanical shock, and partial-shade stress would need to be experienced by cells.

2.3 Analytic Hierarchy Process Methodology

Analytic Hierarchy Process, since its development, has been a device in the hands of scientists and decision-makers; and it is one of the most broadly utilized decision-making devices of various parameters. Numerous studies have been published on Analytic Hierarchy Process: they conclude Analytic Hierarchy Process implementations in various fields, such as preparation, choosing the best option, allocating resources, disaccord resolution, optimization, etc.

The strength of the Analytic Hierarchy Process is its elasticity to be combined with various methods such as fuzzy logic, implementation of quality functions, linear programming, etc. This helps the user to take advantage of all the integrated strategies and thereby, in a better way, accomplish the desired target. The Analytic Hierarchy Method is a decision-making mechanism with several parameters. This is an approach to the eigenvalue of pair-wise comparisons. It also offers a technique for calibrating the numeric scale for quantitative as well as qualitative performance assessment.

The scale of comparison among the parameters ranges from 1/9 to 1 for ‘equal’ and to 9 for ‘completely more significant than’ spanning the whole spectrum of the comparison. The Analytic Hierarchy Method aids to integrate the consensus of a group. This normally consists of a questionnaire to compare each of the factors and to arrive at a final solution by geometric means. The Analytic Hierarchy Method intends to capture both objective and subjective ways of a decision through decreasing complex determinations to a sequence of pairwise comparisons and then synthesizing the outcomes. Furthermore, the process integrates an advantageous methodology to verify the accuracy of the assessments of the decision-maker, thus decreasing the bias in the decision-making operation [96].

2.3.1 AHP Analysis

This study’s goal is to obtain the solar performance and compare the perovskite-based flexible solar cells produced in diverse kinds with respect to primary operating characteristics. The set of characteristics for the alternatives are provided in Table 2.1 [91–97]:

Table 2.1 Characteristics

Perovskite	Film	PCE (%)	E_{loss} (eV)	FF (%)	J_{SC} (mA cm^{-2})	V_{oc} (V)	Reference
$CsPbI_3$	One-step film	10.74	0.64	65	14.88	1.11	[91–97]
$CsPbI_3$	One-step film	11.86	0.60	71	14.53	1.15	[91–97]
$CsPbI_3$	NC film	13.4	0.55	78	14.37	1.20	[91–97]
$CsPbBr_3$	two-step film	4.92	0.98	54	6.91	1.32	[91–97]
$CsPbBr_3$	two-step film	6.7	1.14	73	7.4	1.24	[91–97]
$CsPbBr_3$	NC film	5.4	0.88	62	5.6	1.5	[91–97]
$CsPbBrI_2$	Two-step film	9.22	0.84	66	12.96	1.08	[91–97]
$CsPbBrI_2$	two-step film	9.8	0.81	75	11.89	1.11	[91–97]
$CsPbBrI_2$	NC film	12.02	0.5	70	13.13	1.32	[91–97]

- PCE (photoconversion efficiency) (%)
- E_{loss} (energy loss) (eV)
- FF (fill factor) (%)
- Jsc (short-circuit current density) (mA cm^{-2})
- Vo (open circuit voltage) (V).

However, the listed characteristics are not expected to have the same impact on the overall goal. Thus, the relative priorities of these characteristics are determined based on expert evaluations. Experts are asked to rate the relative importance of the characteristics through a pair-wise comparison of them based on the scale of comparison in Table 2.2.

Based on the pair-wise comparison, the decision matrix presented in Table 2.3 is constructed. The table indicates the relative priorities of the characteristics used.

Based on the relative priorities shown in Fig. 2.2; PCE is the characteristic with the highest impact.

For the purpose of this study, 9 alternatives are determined. The scores of these alternatives are provided in Fig. 2.3.

Figure 2.4 further presents the overall scores as indicated in the last row of the table. The results indicate that $CsPbI_3$ has the highest score (0.1335) among all other alternatives. Figure 2.5 presents the schematic overview of the applied method.

Table 2.2 The scale of comparison [96]

Intensity	Definition	Explanation
1	Equal significance	2 events take part evenly to the target
2	Slight or weak	
3	Moderate significance	Judgement and experience insignificantly favour 1 event over another
4	Moderate positive	
5	Strong significance	Judgement and experience firmly favor one event over another
6	Strong positive	
7	Too firm or indicated significance	One event is favored too firmly over another; its superiority indicated practically
8	Very, very strong	
9	Extreme significance	The proof favoring 1 event over another is of the maximum feasible order of assertion
Reciprocals referred to above	If event *i* as compared to activity *j*, has one of the above non-zero numbers assigned to it, then *j* has the reciprocal value compared to *i*	An acceptable assertion
1.1–1.9	If the events are too close	

Table 2.3 Decision matrix

Matrix		PCE (%)	E_loss (eV)	FF (%)	J_sc (mA cm−2)	V_oc (V)
		1	2	3	4	5
PCE (%)	1	1	7	5	2	2
E_loss (eV)	2	1/7	1	1/2	1/5	1/3
FF (%)	3	1/5	2	1	3	3
J_sc (mA cm−2)	4	1/2	5	1/3	1	2
V_oc (V)	5	1/2	3	1/3	1/2	1

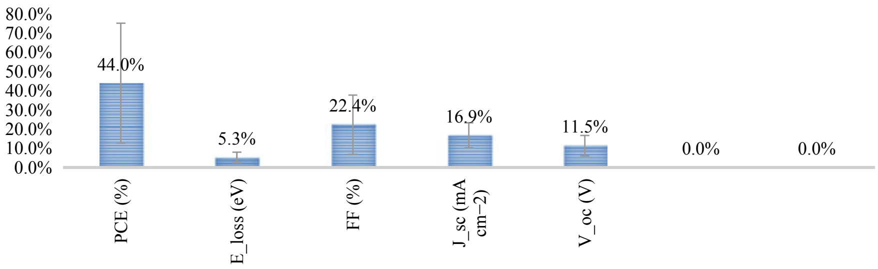
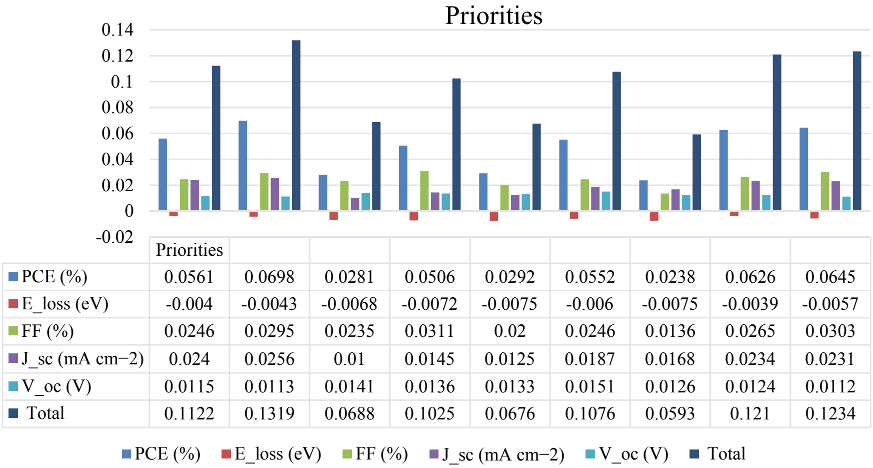
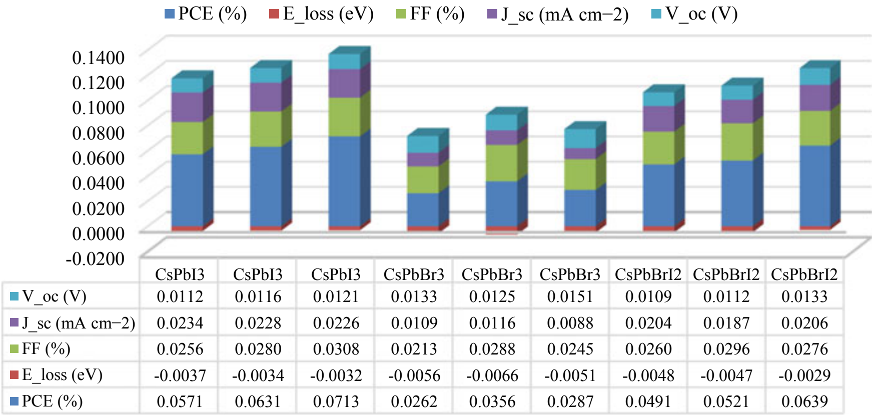


Fig. 2.2 Relative priorities of criteria



	Priorities								
🟦 PCE (%)	0.0561	0.0698	0.0281	0.0506	0.0292	0.0552	0.0238	0.0626	0.0645
🟥 E_loss (eV)	-0.004	-0.0043	-0.0068	-0.0072	-0.0075	-0.006	-0.0075	-0.0039	-0.0057
🟩 FF (%)	0.0246	0.0295	0.0235	0.0311	0.02	0.0246	0.0136	0.0265	0.0303
🟪 J_sc (mA cm−2)	0.024	0.0256	0.01	0.0145	0.0125	0.0187	0.0168	0.0234	0.0231
🟦 V_oc (V)	0.0115	0.0113	0.0141	0.0136	0.0133	0.0151	0.0126	0.0124	0.0112
🟦 Total	0.1122	0.1319	0.0688	0.1025	0.0676	0.1076	0.0593	0.121	0.1234

Fig. 2.3 Priorities



	CsPbI3	CsPbI3	CsPbI3	CsPbBr3	CsPbBr3	CsPbBr3	CsPbBrI2	CsPbBrI2	CsPbBrI2
🟦 V_oc (V)	0.0112	0.0116	0.0121	0.0133	0.0125	0.0151	0.0109	0.0112	0.0133
🟪 J_sc (mA cm−2)	0.0234	0.0228	0.0226	0.0109	0.0116	0.0088	0.0204	0.0187	0.0206
🟩 FF (%)	0.0256	0.0280	0.0308	0.0213	0.0288	0.0245	0.0260	0.0296	0.0276
🟥 E_loss (eV)	-0.0037	-0.0034	-0.0032	-0.0056	-0.0066	-0.0051	-0.0048	-0.0047	-0.0029
🟦 PCE (%)	0.0571	0.0631	0.0713	0.0262	0.0356	0.0287	0.0491	0.0521	0.0639

Fig. 2.4 Resulting scores

2.4 Conclusions

The photovoltaic films are thought to be one of the leading sustainable power sources proper for big-scale acceptance in a carbon-restricted world and can contribute to reducing dependency on power imports while improving energy protection. The inorganic–organic perovskite is a recent arrival in photovoltaic film technologies. The key driving force behind the endorsement of these novel films is their potency as an environmentally and economically practicable option to traditional silicon-based industry. Due to their various advantages, including low density and durability, as well as cost-effective development, perovskite-based flexible

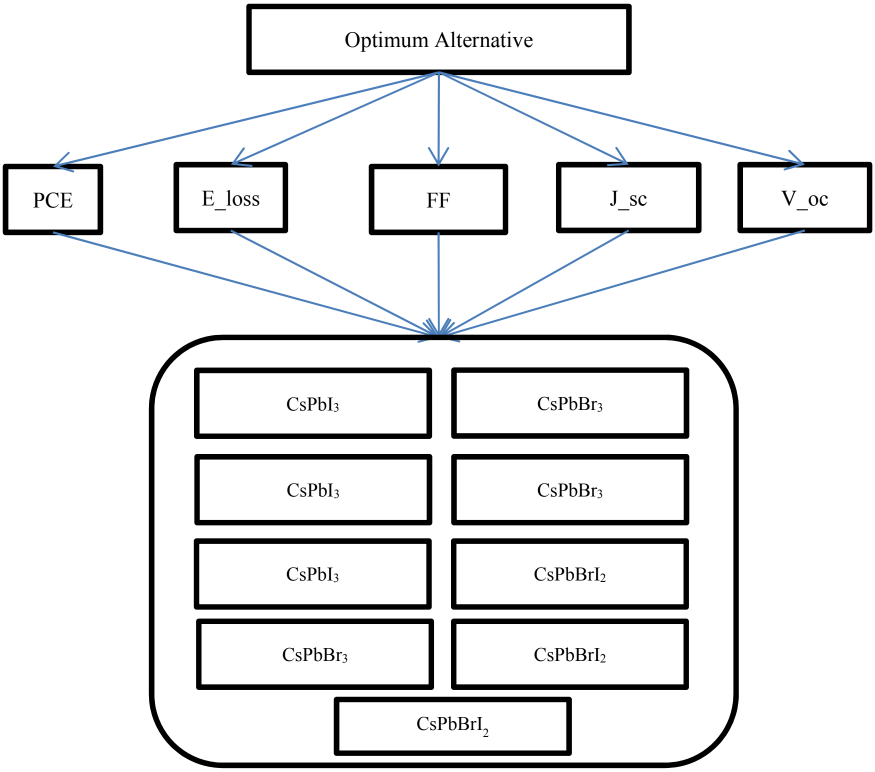


Fig. 2.5 Schematic overview

solar films, for utilization in excellent photovoltaic tools with low expense and high energy transformation performance in 3rd generation photovoltaic industries, have experienced fast progress in the past decades [3–5]. The perovskite-based films are significant as solar films that have been universally valuable by conventional solar cell industries as an ecologically and financially feasible renewable industry choice to address global challenges in the fields of environmental protection, effectiveness, and energy generation [98]. In addition to being a high-performance and low-expense single-junction solar film, perovskite-based solar films have big potency as a top solar cell (bigger bandgap material) for tandem solar cells with either CIGS or c-Si films. As an energetic layer, perovskite has many interesting electrical and photonic features, like little density of defects, a big absorption coefficient, long diffusion lengths, and low binding energy of the exciton. Perovskite has made these features a superior alternative for solar thin-film cells. It also displays some difficult characteristics, like environmental instability, hysteresis in light calculation, evolution of voltage, degradation caused by photons, and self-degradation in darkness given all the exciting features. In recent years, there has been a market for flexible solar cells made of separate metals based on perovskite. Density, area, and effectiveness characteristics are the key working parameters of the perovskite-based flexible solar cells. The goal of this research is to obtain the photovoltaic efficiency and to crosscheck the perovskite-based flexible solar cells generated in different types through the key working parameters.

The aim of this search is to shed light on the comparison, amongst other things, of photovoltaic cells generated in different types with regard to main operating characteristics and the determination of the optimum photovoltaic option available. Therefore, there is a valuable contribution from three aspects: the assessment of the collection of parameters needed in the assessment of solar concentrator cells, their comparative priorities' definition on the basis of expert opinions, and the provision of a straightforward quantitative investigation. It is possible to raise the variable number in a future research and to adjust their relative preferences based on new information. The analysis and review could be created a road map supply comparison framework in windows of opportunity and identifying pathways for next photovoltaic plans towards sustainable and cleaner power generation.

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Chapter 3
Electro-thermal and Mechanical Optimization of a Concentrated Solar Thermoelectric Generator

Chika Maduabuchi, Ravita Lamba, Chigbogu Ozoegwu, Howard O. Njoku, Mkpamdi Eke, and Emenike C. Ejiogu

Abstract Solar thermoelectric generator (STEG) is a relatively less efficient direct energy conversion device which converts input solar heat directly into electricity based on thermoelectric effects. A comprehensive model consisting the detailed electrical, thermodynamic and mechanical analysis of STEG is still missing in the literature. Thus, this paper presents a numerical model and analysis of a hybrid solar thermoelectric generator. The hybrid system is made up of a compound parabolic concentrator (CPC) attached to a thermoelectric module (TEM). A three-dimensional finite element model is developed and employed in analysing the hybrid system for varying concentrated solar irradiation and external load resistance. The optimum external load resistance, current, voltage and heat absorption rate required to maximise the electrical and thermodynamic performance

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of the device are obtained. The results in this study will provide useful information in the design of power generation systems.

Keywords Thermoelectric generator · Compound parabolic concentrator · Finite element analysis · Thermodynamics · Performance optimization

Nomenclature

A	Thermeoelement area (m^2)
C	Concentration ratio
E	Electric field intensity (V/m)
G	Global solar irradiance (W/m^2)
I_m	Matched load current (A)
J	Current density (A/m^2)
R_L	Load Resistance (Ω)
S	Seebeck coefficient (V/K)
u'''	Joule heat (W/m^3)
W_m	Matched load power (W)
V_m	Matched load voltage (V)
q''	Concentrated solar irradiance (W/m^2)
η_m	Matched load efficiency
τ	Thomson coefficient (V/K)

3.1 Introduction

3.1.1 Literature Review

The sun is considered a major source amongst all the renewable energy sources because of its cleanliness and availability. The two methods of harvesting energy from the sun is by solar thermal conversion and photovoltaic processes. Solar thermal conversion involves the indirect conversion of solar energy into electricity and solar photovoltaic process involves the conversion of the solar energy into electricity. Another alternative to convert heat energy into electricity is the thermoelectric generator. It has the advantages of simplicity, silent operation, relatively low cost and environmental friendliness. When the input heat source of a TEG is the solar energy, then it is called a solar thermoelectric generator (STEG). The major drawback of these devices is their low energy conversion efficiency. Therefore, researchers are exploring various methods for increasing the efficiency of thermoelectric devices. One possible way of improving the performance of a STEG is the use of concentrated solar radiation as the input heat energy. Solar concentrators employ optical devices which focus a large area of sunlight unto a small area in order to increase the incident solar energy. Mgbemene et al. [1]

studied the generation of electricity from the sun using a compound parabolic concentrator and thermoelectric module. The results showed that the setup could generate and sustain energy required to power a small device. Mgbemene et al. [2] in their work studied the effects of the parameter, ψ, due to thermoelectric irreversibilities on a hybrid 3D CPC/TEM system. Their results revealed that a plot of ψ against collector thermal efficiency produces a linearized plot, but when plotted against other system parameters, an exponential decay was obtained. Baranowski et al. [3] studied concentrated STEGs for terrestrial applications. When a three-stage TEG subsystem was modelled, the modules suggested that an experimental efficiency value of 18% with a temperature gradient of 1000–100 °C. Chen et al. [4] numerically investigated the performances of thermal-concentrated STEGs at various geometric types. The smallest element which had a substrate area of 90×90 mm^2 yielded the peak system efficiency 4.15%. The steady temperature variation of a spectrally selective absorber coating with solar irradiation flux using a Fresnel lens and a vacuum enclosure has been experimentally analysed by Cheruvu et al. [5]. It was also reported that the experimental results obtained exhibited a fair agreement with a COMSOL simulation of the model set-up. Lamba et al. [6] developed and optimized a thermodynamic model for a concentrating STEG considering the Thomson effect, Fourier heat conduction, Peltier and Joule heating in MATLAB environment. The results obtained revealed that the optimum concentration ratio and load resistance ratio for maximum energy and energy efficiencies of 5.85 and 6.29%, were 180 and 1.3, respectively with a power output of 4.213 W. Xiao et al. [7] implemented a thermal design and performance optimization of a STEG using a three-dimensional finite element model. They showed that performing a thermal optimization of a STEG significantly increased its overall performance. Liu et al. [8] modelled a flat plate STEG and investigated the effect of thermal concentration ratio, TE leg length and other geometrical factors on the device performance. Liu et al. [9] upgraded the performance of a STEG by altering the leg geometry of segmented TE pins. The alteration in the leg geometry increased the performance of the segmented STEG by 4.21%. Li et al. [10] combined solar concentration and carbon nanotube absorption in enhancing the performance of a STEG. It was reported that for a solar concentration of 78 and 106 × suns, the peak power output and efficiencies obtained were 11.2 W and 4.3%, respectively. He et al. [11] studied the performance of a STEG under non-uniform solar radiation distribution. Results indicated that the STEG which used large solar irradiation gradient generated a higher power output and rendered a better performance. Shittu et al. [12] further analysed a STEG using PCM subject to transient and non-uniform solar radiation. It was revealed that placing the PCM at the STEG hot junction shielded the STEG from very high concentrated solar radiation. In the same vein, Maduabuchi and Mgbemene [13] developed a numerical model of a STEG using PCM. They reported that the PCM lens increased the temperature gradient and overall device performance of the STEG. Sui et al. [14] also improved the TEG performance by using a Fresnel lens and a PCM. Pereira et al. [15] evaluated the performance of a silicon–germanium STEG subject to a concentration ratio above 100 and a high temperature exceeding 450 °C and found out that an electric power output, thermoelectric efficiency and system efficiency of 500 mW, 3% and 1.6%, respectively, were generated. The mechanical behaviour of a TEG is very crucial in estimating the life span of the device. This is because an increased amount of thermal stresses implies a high rate of plastic deformation within the TEG layers thus, resulting in device failure. Some researchers have studied this phenomenon in TEGs. For instance, Yilbas et al. [16] studied the effect of thermal stresses on a TEG with rectangular and trapezoidal leg configuration and concluded that the stresses developed in a tapered pin configuration were lower than that in a rectangular one. Bakhtiaryfard and Chen [17] investigated the effect of TE layout on the thermal stresses developed in a TEG and reported that a circular geometry TEG reduced the von-Mises and shear stresses by 13% and 42%, respectively. Turenne et al. [18] determined the thermal stresses in a TEG subjected to a fixed temperature gradient and reported that the solder alloys reduced the thermoelastic deformation of the TE legs. Wu et al. [19] found that a thicker ceramic plate is required to alleviate the TEG thermal stresses.

This published literature indicates the possibility of harvesting solar energy using STEGs. The modelling and optimization of STEGs have been carried out. Most of the published studies utilised a two-dimensional (2D) model in the optimization analysis which results in inaccurate outcomes. Therefore, a three-dimensional (3D) model is considered in this study which is more robust and will provide a more reliable result. The temperature dependent material properties are included and all thermoelectric effects are accounted for. This study considers a varying concentrated solar radiation instead of fixed temperatures. Further, a robust model, simultaneously investigating the electrical, thermodynamic and mechanical performance of a STEG has not been carried out yet. Therefore, it is necessary since such study will provide vital insight into the actual operation of the device while estimating its relative market advantages as compared to contemporary energy sources. This study will also predict the static failure in the components of a STEG under varying concentrated solar radiation.

3.2 Methodology

3.2.1 System Description

The schematic diagram of the proposed hybrid system setup is depicted in Fig. 3.1. It comprises of, from top to bottom, a compound parabolic concentrator and a thermoelectric module connected to an external load resistance. The TEM comprises of electrically series and thermally parallel bismuth telluride based thermoelements. In the C-STEG system, the concentrated solar irradiance from the CPC is focused on the hot junction of the TEM, while the cold junction is subject to a temperature dependent heat transfer coefficient, as specified in ANSYS Thermal-Electric, in order to create the required temperature difference necessary for continuous power generation. The hot junction made of ceramic plat receives the heat input, Q_h, while the cold junction rejects the heat output, Q_c. The properties of thermoelectric and elastic materials employed during the analysis are depicted in Tables 3.1, 3.2 and the mathematical expression of the temperature dependent thermoelectric material properties are given in Eqs. (3.1–3.4), respectively [6, 20].

The following assumption are made to reduce computational time and complexities with negligible deviations from the actual case [6, 21]

- Steady state analysis has been considered i.e. $\left(\frac{\partial T}{\partial t} = 0\right)$.

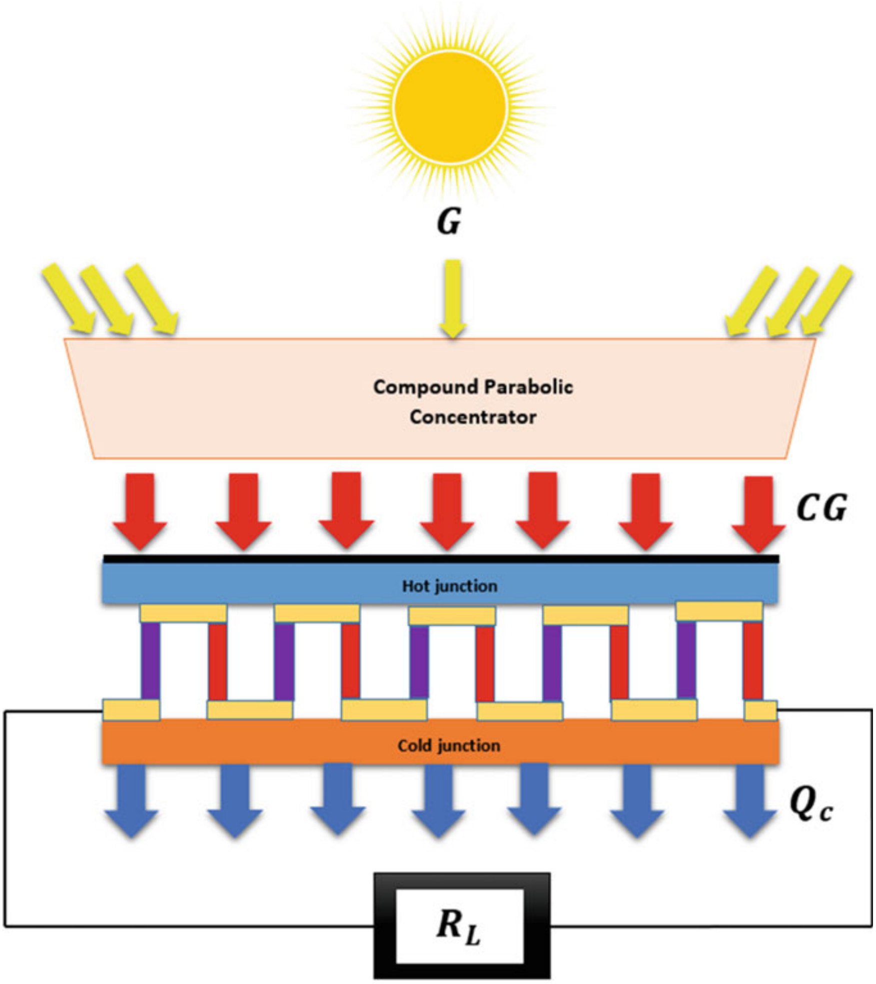


Fig. 3.1 Schematic diagram of the hybrid STEG system

Table 3.1 Thermal and electric material properties

Material	Thermal conductivity (W/m K)	Electrical resistivity (Ωm)	Seebeck coefficient (V/K)
96% Al_2O_3	25	–	–
Cu alloy	401	$\rho(T)$	–
Bi_2Te_3 (n–p type)	$k(T)$	$\rho(T)$	$S(T)$

Table 3.2 Linear elastic material properties

Material	Young's modulus (GPa)	Poisson's ratio	Bulk modulus (GPa)	Shear modulus (GPa)
96% Al_2O_3	350	0.33	343	132
Cu alloy	110	0.34	115	410
Bi_2Te_3 (n–p type)	$E(T)$	0.23	$\kappa(T)$	$G(T)$

- All other surfaces of the STEG are perfectly insulated except the hot junction and the cold junction.
- Negligible electrical and thermal contact resistances at the junctions of the STEG.
- Radiation and convection heat losses from the surfaces of the STEG are negligible.
- Symmetric distribution of the Thomson effect between the hot and cold junction.

$$S = \left[S_p - (-S_n)\right] = 2\left(22,224 + 930.6T_m - 0.9905T_m^2\right) \times 10^{-9} \tag{3.1}$$

$$\rho_p = \rho_n = \left(5112 + 163.4T_m + 0.6279T_m^2\right) \times 10^{-9} \tag{3.2}$$

$$k_p = k_n = \left(62,605 - 277.7T_m + 0.4131T_m^2\right) \times 10^{-4} \tag{3.3}$$

$$\tau = \left[\tau_p - (-\tau_n)\right] = 2 \times \left(930.6T_m - 1.9817T_m^2\right) \times 10^{-9} \tag{3.4}$$

where S, ρ, k, τ and T_m are the overall Seebeck coefficient, electrical resistivity, thermal conductivity, Thomson coefficient and mean temperature of the cold and hot junction of the STEG, respectively.

3.2.2 Electrical and Thermodynamic Analysis

The equations that govern heat and current density for a non-isotropic and non-homogenous medium is expressed as [21, 22]

$$\rho C_p \frac{\partial T}{\partial t} = \dot{q} - \overrightarrow{\nabla} \cdot \overrightarrow{q} \tag{3.5}$$

$$\nabla \cdot \left(\xi \frac{\partial \overrightarrow{E}}{\partial t} + \overrightarrow{J} \right) = 0 \tag{3.6}$$

where ξ is the electrical permittivity and $\vec{J}$ is the current density vector, which is a consequence of the Seebeck and Joule effect as specified by [1].

$$\overrightarrow{J} = \frac{1}{\rho}(\overrightarrow{E} - S\overrightarrow{\nabla}T) \tag{3.7}$$

where T is the absolute temperature. The current continuity equation for a non-uniformly heated isotropic thermoelectric material is given by [23].

$$\overrightarrow{\nabla} \cdot \overrightarrow{J} = 0 \tag{3.8}$$

The electrical field intensity vector, $\vec{E}$ is given by

$$\overrightarrow{E} = \overrightarrow{J}\rho + S\overrightarrow{\nabla}T \tag{3.9}$$

The heat flux vector is obtained from the Thomson-Onsager equation [23]

$$\overrightarrow{q} = ST\overrightarrow{J} - k\overrightarrow{\nabla}T \tag{3.10}$$

where $k = k(T)$.

For steady state analysis, Eq. (3.5) reduces to

$$\dot{q} - \overrightarrow{\nabla} \cdot \overrightarrow{q} = 0 \tag{3.11}$$

where the heat flow rate, $\dot{q}$, is given by [23, 24].

$$\dot{q} = \overrightarrow{E}.\overrightarrow{J} = J^2\rho + \overrightarrow{J}.S\overrightarrow{\nabla}T \tag{3.12}$$

Substituting Eqs. (3.12) and (3.10) into (3.11) gives

$$\vec{\nabla}.\left(k\vec{\nabla}T\right)+J^2\rho-T\frac{dS}{dT}\vec{J}.\vec{\nabla}T=0 \tag{3.13}$$

The Thomson coefficient is deduced from Eq. (3.13) as

$$\tau=T\frac{dS}{dT} \tag{3.14}$$

In Eq. (3.13), from left to right, the first term accounts for thermal conduction, the second term accounts for Joule heat and the third term accounts for Thomson heat.

The matched load heat absorbed at the hot junction is given by [21, 23]

$$Q_{hm}=n\left[ST_hI_m-0.5I_m^2R+K\Delta T\right] \tag{3.15}$$

where T_h, I_m, R, K and ΔT are the hot junction temperature, matched load current, module internal resistance, thermal conductance and temperature gradient, respectively.

Similarly, the heat dissipated at the cold junction is

$$Q_{cm}=n\left[ST_cI_m+0.5I_m^2R+K\Delta T\right] \tag{3.16}$$

An energy balance reduction enclosing the STEG yields

$$W_m=Q_{hm}-Q_{cm} \tag{3.17}$$

Substituting Eqs. (3.15) and (3.16) into Eq. (3.17) gives the power developed as

$$W_m=n\left[SI_m\Delta T-I_m^2R\right] \tag{3.18}$$

It is often more convenient to define the power developed by a STEG over an external load resistance, R_L

$$W_m=nI_m^2R_L \tag{3.19}$$

The matched load voltage is obtained by equating Eqs. (3.18) and (3.19)

$$V_m=nI_mR_L=n[S\Delta T-I_mR] \tag{3.20}$$

The module matched load current is obtained from Eq. (3.20) as

$$I_m = \frac{S\Delta T}{R + R_L} \tag{3.21}$$

Introducing the optimal resistance ratio, m, Eq. (3.21) takes the form

$$I_m = \frac{S\Delta T}{R(1 + m')} \tag{3.22}$$

The STEG conversion efficiency is evaluated using Eqs. (3.15) and (3.19) as

$$\eta_{th} = \frac{(1-\chi)m'}{(1-m') - \frac{1}{2}(1-\chi) + \frac{1}{2Z\overline{T}}(1-m')^2(1+\chi)} \tag{3.23}$$

where $\chi = \frac{T_c}{T_h}$, $m' = R_L/R$ and $Z\overline{T} = \frac{S^2(T_c + T_h)}{2\rho k}$, are the temperature ratio and the dimensionless figure of merit.

3.2.3 Mechanical Analysis

Internal electrical heating within and temperature gradient across the STEG setup thermal stresses in the thermoelectric legs and cause possible changes in device operation [25]. Nevertheless, since temperature dependent material properties were considered, stresses will arise from incompatibilities between constraints and irregularities in expansion processes. To account for these, a non-symmetrical Jacobian matrix specifying the stress relation coupled to the temperature spatial field is given in a dimensionless form as:

$$\begin{Bmatrix} \overline{\sigma}_{xx} \\ \overline{\sigma}_{yy} \\ \overline{\sigma}_{zz} \\ \overline{\sigma}_{yz} \\ \overline{\sigma}_{zx} \\ \overline{\sigma}_{xy} \end{Bmatrix} = \frac{\overline{E}}{(1+v)(1-2v)} \begin{bmatrix} 1-v & v & v & 0 & 0 & 0 \\ v & 1-v & v & 0 & 0 & 0 \\ v & v & 1-v & 0 & 0 & 0 \\ 0 & 0 & 0 & 1-2v & 0 & 0 \\ 0 & 0 & 0 & 0 & 1-2v & 0 \\ 0 & 0 & 0 & 0 & 0 & 1-2v \end{bmatrix} \begin{Bmatrix} \overline{\varepsilon}_{xx} \\ \overline{\varepsilon}_{yy} \\ \overline{\varepsilon}_{zz} \\ \overline{\varepsilon}_{yz} \\ \overline{\varepsilon}_{zx} \\ \overline{\varepsilon}_{xy} \end{Bmatrix} - \begin{Bmatrix} 1 \\ 1 \\ 1 \\ 0 \\ 0 \\ 0 \end{Bmatrix} \frac{\overline{\alpha}\,\overline{ET}}{1-2v} \tag{3.24}$$

where the dimensionless stress relations are given as

$$\bar{\varepsilon}_{xx} = \frac{\partial \bar{u}}{\partial \bar{x}},\ \bar{\varepsilon}_{yy} = \frac{\partial \bar{v}}{\partial \bar{y}},\ \bar{\varepsilon}_{zz} = \frac{\partial \bar{w}}{\partial \bar{z}} \tag{3.25}$$

$$\bar{\varepsilon}_{xy} = \frac{1}{2}\left(\frac{\partial \bar{u}}{\partial \bar{y}} + \frac{\partial \bar{v}}{\partial \bar{x}}\right),\ \bar{\varepsilon}_{yz} = \frac{1}{2}\left(\frac{\partial \bar{v}}{\partial \bar{z}} + \frac{\partial \bar{w}}{\partial \bar{y}}\right),\ \bar{\varepsilon}_{zx} = \frac{1}{2}\left(\frac{\partial \bar{u}}{\partial \bar{z}} + \frac{\partial \bar{w}}{\partial \bar{x}}\right) \tag{3.26}$$

3.3 Results and Discussion

The Electrical, Thermodynamic and Mechanical analysis of a STEG has been carried. The corresponding performance characterization has also been implemented. The effects of the concentrated incident solar irradiance, q'', and external load resistance, R_L, on the matched load power and conversion efficiency were studied and the optimum values were obtained under maximum operating conditions. The number of thermoelements used were 127, the area was 1.996 mm^2 and the area to length ratio was 0.78 mm. The ambient temperature used during the simulation was 298 K. The concentrated solar irradiation and external load resistance were varied from 1000 to 7860 W/m^2 and 0 to 1Ω, respectively.

3.3.1 Electrical Analysis

The three dimensional finite element distributions of total electric field intensity along the thermocouple length for a concentrated solar irradiation of 7860 W/m^2 is shown in Fig. 3.2. It is observed that a uniform maximum electric field intensity of 2.6 mV/mm was encountered at the p–n legs while the top and bottom copper plates were maintained at zero field intensities.

The chart depicting the Seebeck voltage, total electric field intensity and Joule heat for varying concentrated solar irradiation have been plotted in Fig. 3.3, respectively. Predictably, a concentrated solar irradiation of 7860 W/m^2 yielded the highest numerical values of Joule heat, total electric field intensity and Seebeck voltage, bearing numerical values of 5.4 W/m^3, 2.6 V/m and 13 mV, respectively. On the other hand, the global incident solar radiation of 1000 W/m^2 generated the minimum values of 0.1 W/m^3, 0.3 V/m and 1.6 mV. Also, it was observed that for increasing values of solar irradiation, the total electric field intensity values were higher than the Joule heat values up till an optimum value of 3744 W/m^2, where the reverse became the case, with the Joule heat taking the lead by a margin of 0.1, 0.6, 1.6 and 2.8 for irradiation values of 3744, 5116, 6488 and 7860 W/m^2, respectively.

The temperature gradient variation with incident irradiation has been portrayed in Fig. 3.4. It is noted that the temperature gradient values exhibited a gradual

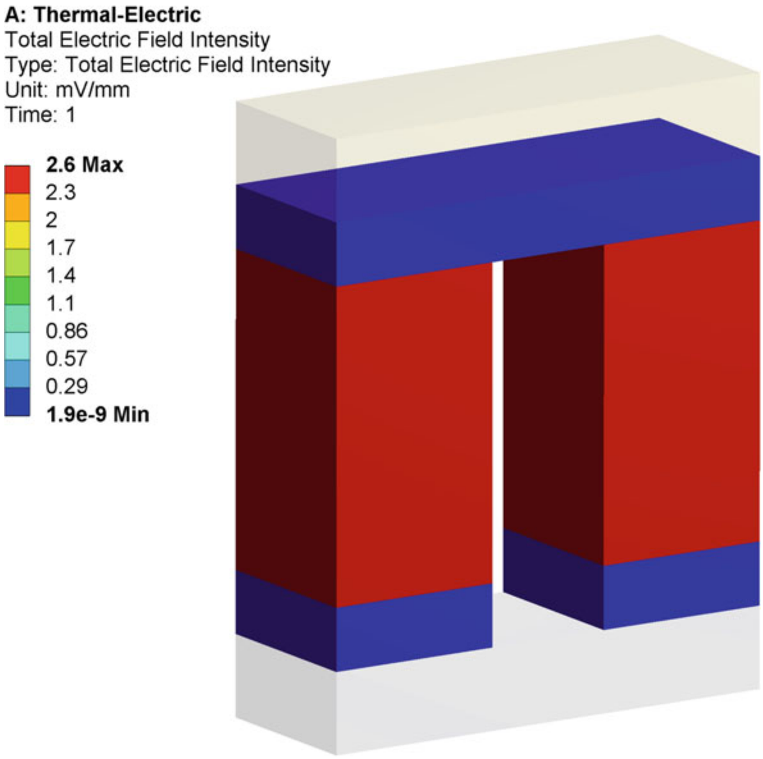


Fig. 3.2 Total electric field intensity distribution

increase with progressive values of irradiation. The rather marginal increase in the temperature gradient can be explained considering the gradual increment in the irradiation values employed during the simulation. The maximum and minimum values of 275 and 289 K are obtained for irradiations of 1000 and 7860 W/m^2.

3.3.2 Mechanical Analysis

Fig. 3.5a, b illustrate the three-dimensional finite element distributions of the equivalent (von-Mises) stress and strain for a constant concentrated solar irradiance of 7800 W/m^2. Fig. 3.5a reveals that the maximum stress is obtained at the interface between the top copper and ceramic plates, with a numerical value of 129 MPa, while gradually decreasing stress values of 58–115 MPa are noticed along the edges of the top ceramic-copper plate interface. This is followed by a spontaneous decrease along the length of the STEG from top to bottom, with minimum values of about 0.14–58 MPa, occurring on the p–n legs, bottom copper electrodes and top

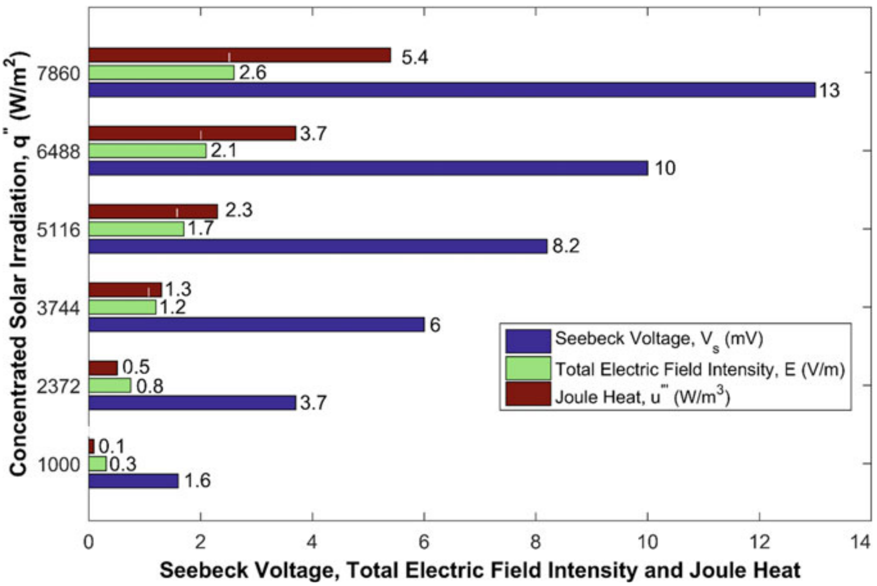


Fig. 3.3 Chart depicting the Seebeck voltage, Total electric field intensity and Joule heat for varying irradiation

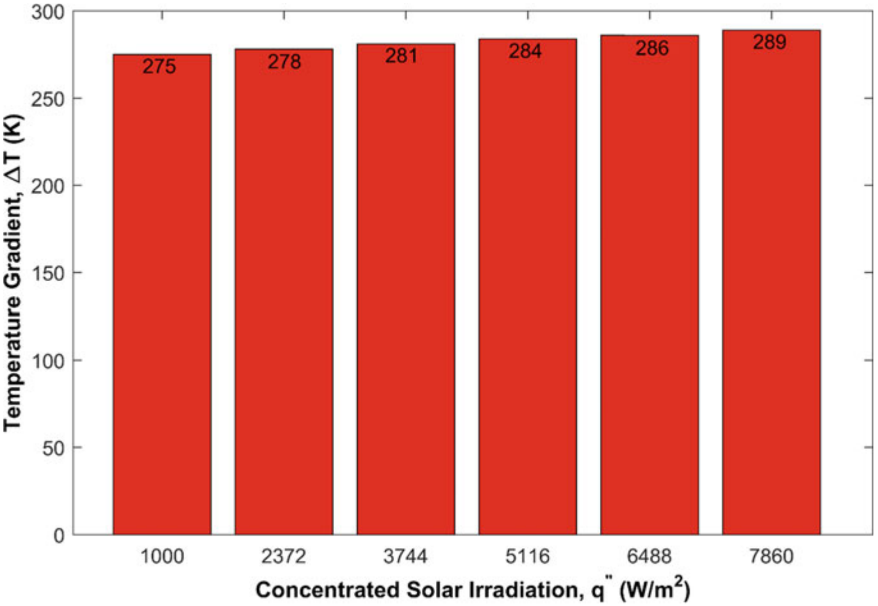
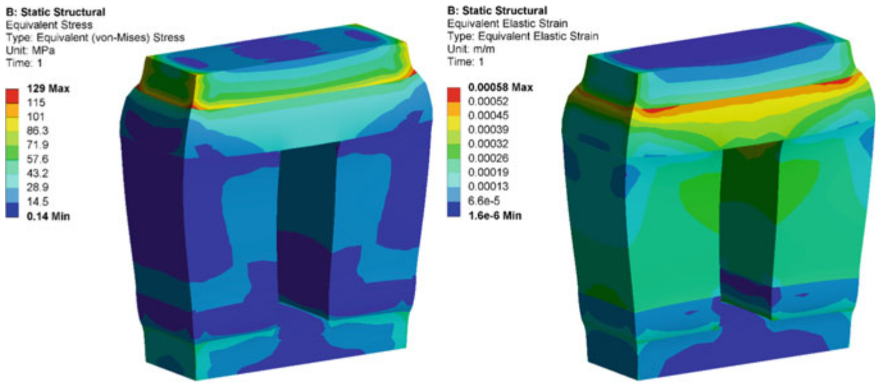


Fig. 3.4 Temperature gradient variation with incident irradiation



(a) (b)

Fig. 3.5 Static-structural distributions **a** equivalent (von-Mises) stress **b** equivalent elastic strain

and bottom ceramic plates. The maximum values obtained on the edges of the surfaces can be accounted for by considering the imposed heat load placed on the top ceramic plate. However, the stress values were minimum on the ceramic plates and p–n legs, due to the relatively low thermal conductivity of alumina and bismuth-telluride compared to copper alloy. A reduced thermal conductivity implies a reduction in efficient heat transfer in a material, hence the comparatively low stress values harvested on the ceramic and p–n leg materials compared to the copper materials. Similarly, Fig. 3.5b shows the equivalent elastic strain distributions of the model resulting from the von-Mises stress values obtained in Fig. 3.5a.

3.3.3 Thermodynamic Analysis

Fig. 3.6 depicts the three-dimensional analogue variation of matched load power against voltage and current for various incident irradiation. It is observed from this figure that the matched load power increases with increasing voltage and current up till an optimum value. This is accompanied by a sudden decrease of the power output with increasing current and voltage. It then follows that for a STEG under loaded conditions, there exists an optimum value of current and voltage during which maximum power is developed. It is also noted that the current generated decreases linearly with increasing voltage and external load resistance. This is in accordance with Ohm's law as expressed in Eq. (3.20). From the figure, the maximum power output for increasing solar irradiations of 1000, 2372, 3744, 5116, 6488 and 7860 W/m^2, respectively, were found to be 0.0036, 0.0206, 0.0513, 0.0957, 0.1537and 0.2252 W, respectively.

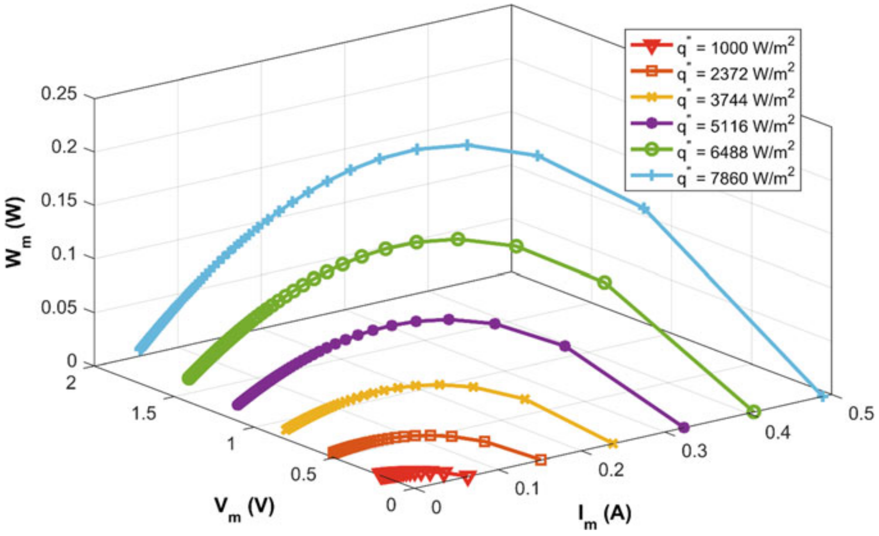


Fig. 3.6 Three-dimensional analogue variation of the matched load power against voltage and current for increasing solar irradiation

The schematic variation of the matched load conversion efficiency with the hot junction heat absorption rate has been shown in Fig. 3.7. It is observed that the matched load conversion efficiency increases with progressive increase in the hot junction heat absorption rate up to a certain maximum value. This is followed by a rapid decrease in the efficiency for corresponding increase in the rate of heat input. It then follows that for a hybrid CPC-STEG system, there exists an optimum heat input rate at which the maximum conversion efficiency for increasing irradiation values occur. It was noted that the optimum heat input values for increasing irradiations of 1000, 2372, 3744, 5116, 6488 and 7860 W/m^2, respectively were 1.88, 4.0212, 5.1168, 8.0545, 9.5623 and 11.6702 W, respectively. The plot also revealed that the optimum heat input approached higher values for increasing solar irradiation.

3.4 Conclusion

A three-dimensional finite element model for a bismuth telluride-based module has been developed and the corresponding performance evaluation was carried. The performance evaluation was carried out using a numerical iterative process. The Seebeck voltage, total electric field intensity, Joule heat, equivalent (von-Mises)

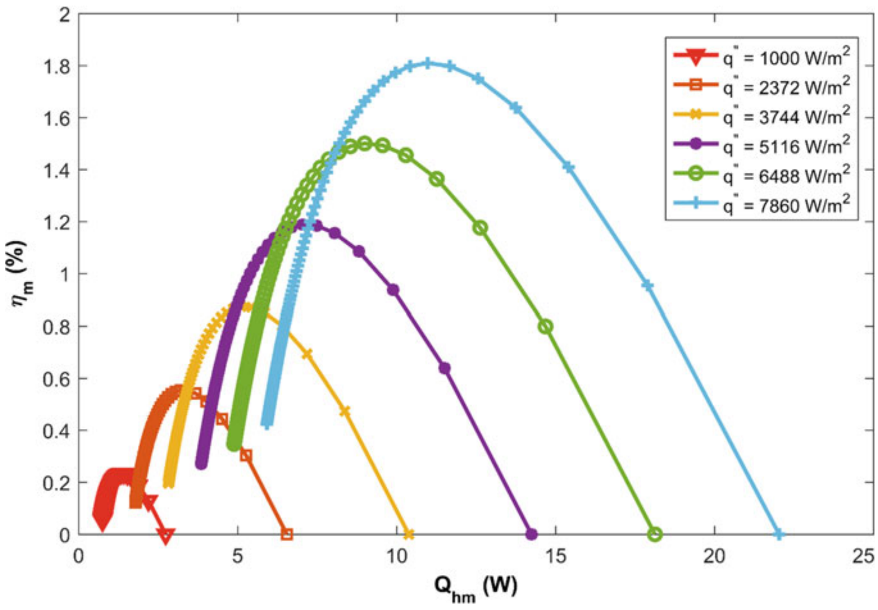


Fig. 3.7 Variation of matched load conversion efficiency with heat input for different incident solar irradiation

stress and corresponding equivalent strain were evaluated by solving thermodynamic, thermoelectric and static-structural coupled equations. The computation was carried out under varying incident solar irradiation of 1000, 2372, 3744, 5116, 6488 and 7860 W/m^2, rather than fixed temperatures. All temperature dependent material properties were considered and all thermoelectric effects were accounted for. The results obtained revealed that

- The irradiation value of 7860 W/m^2 yielded the highest temperature gradient, total current density, Seebeck voltage, total electric field intensity, Joule heat, equivalent (von-Mises) stress and corresponding equivalent strain numerical values. Thus suggesting, that higher irradiation values are suitable for STEGs.
- The maximum stress was obtained at the interface between the top copper and ceramic plates, with a numerical value of 129 MPa, while gradually decreasing stress values of 58–115 MPa were noticed along the edges of the top ceramic-copper plate interface. Thus, inferring that structural deformation will begin at these spots compared to the others.
- The least thermal stresses were recorded on the ceramic plates and p–n legs.

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Conflict of Interest Statement The authors state that they have no known conflict of interest.

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Chapter 4
Green Technology: Application of Solar Energy into the Transportation Sector for Global Energy and Environmental Vulnerability

Md. Faruque Hossain

Abstract The conventional development of the transportation sector all over the world has increased and, thus, the consumption of fossils does, resulting in deadly depletion of global energy and an environmental crisis. Ideally, the technology applied on transportation sector for energy sustainability in this research, will have no adverse effects on the environment. Simply, this research provides critical test through mathematical modeling, as to how solar energy can be trapped by acting photovoltaic panel (PV) using the exterior curtain wall of the transportation vehicle to supply the required energy for the transportation vehicle naturally. Consequently, the mathematical modeling showed that the solar energy conversion technology via the acting PV panel of the vehicle's exterior wall are doable which revealed that this finding would be an exciting venture for the engineering field in terms of offering a solution to environmental and global energy sustainability in transportation sector globally which is environmentally friendly.

Keywords Solar power · Solar panel implementing · Control mechanics · Energy modification · Power for transit vehicle

Highlights

- The modeling of solar-powered vehicle by using of its exterior curtain wall as an active PV panel.
- Employing engineering techniques in the transportation vehicles to readily convert solar energy into electrical energy.
- The utilization of converted solar energy to electricity in turn powers the transportation vehicle as the source of self-generated energy to run the vehicle.

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4.1 Introduction

Prime concern of produces of solar energy by using solar panel installed in the vast land include visibility and the misuse of the lands that effects the harmonium of the landscape [1, 2]. Besides, the technological application for the conversion of solar power into electricity supply through the national grid is cost concerns, engineering challenges along with transmission and operational mechanisms, are more likely to restrict the use of solar energy commercially globally [3–5]. Therefore, an appropriate solar energy technology implementation into the transportation vehicle can be an interesting idea to utilize these renewable powers to reduce the impact on energy in transportation sector globally. Thus, the installation of solar panels on the exterior wall of vehicles for solar energy tapping can result in increased fuel efficiency and decreases carbon dioxide emissions throughout the world.

A recent study by Hossain et al. have previously modeled that solar energy has the tremendous potential to meet the net energy demand of running a vehicle. Although their research on this renewable energy technology suggested hypothetically to analyze the possibility of utilizing it for many sectors but the application of solar energy into the transportation sector have not been attempted yet to mitigate global energy demands for the transportation sector [6–8]. Simply, the knowledge gap and the novelty of their research for the application of the solar power has been ignored despite it has the tremendous potentially to meet the near-term and long-term energy mitigation in transportation sector and meet the goal greenhouse gas (GHG) emissions mitigation [9–11].

Thus, to utilize this renewable energy, in this study, a mathematical modeling of acting solar panel is being used by using its exterior wall of the transportation vehicle to capture solar energy and create required energy to power the transportation vehicle naturally. Subsequently, the solar energy conversion mechanism, and the process of electricity energy generation from the solar energy through the main subsystems were mathematically calculated using the MATLAB Simulink which suggested that this innovative mechanism of solar energy utilization in the transportation sector indeed would be a cutting-edge technology to console the energy and environmental vulnerability worldwide.

4.2 Material, Methods, and Simulation

Since the photoreaction is correlated to the photon charge, therefore, the attributes of photon electromagnetic-wave dynamic of the solar energy are being induced into the exterior wall of the transportation vehicle which is the active PV panel [3, 12]. Then the photon energy density frequency into the exterior wall of the transportation vehicle is computed considering the quantum flow of photon radiation [13, 14]. Consequently, a computational model of photon radiation is being quantified to demonstrate the photon energy trapping from the sunlight considering

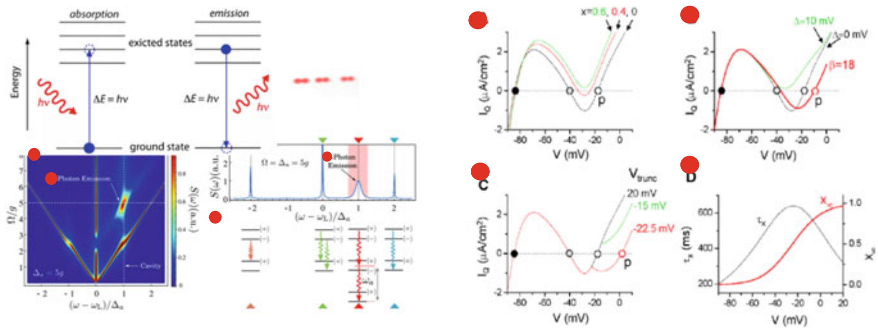


Fig. 4.1 Shows the mechanism in which photon emitted are trapped on the wall of the active PV panel on the wall of the vehicle, which is then transferred into the *I–V* circuit diode and transformed into the photovoltaic mode

radiation intake by the active PV panel of the exterior wall of transportation vehicle (Fig. 4.1). The induced solar irradiance is, thereafter, collected by the acting photovoltaic array of the exterior wall considering the parameters of solar energy proliferation, and transformation rate. The accurate calculation of the current–voltage (*I-V*) characteristic is being subsequently calculated by the mode of solar energy intakes into a single diode circuit connected to the exterior wall acting PV cell [15, 16].

Thereafter, the PV current formed through the I_{pv} assuming a single diode is carried by the calculation of *I-V-R*. Here, the correlation of the current within the active PV panel and the exterior wall of the vehicle is necessary for powering up the vehicle [5, 17]. Therefore, this equation is confirmatory of the energy transfer from the sunlight photon irradiance to the photovoltaic (PV) panel:

$$P_{pv} = \eta_{pvg} A_{pvg} G_t \tag{4.1}$$

In that case, η_{pvg} denotes the rate of performance of the PV, whereas, A_{pvg} denotes the array of PV generation, (m^2), and G_t is the rate of intake of photon irradiance on the plane (W/m^2) of the active PV cell. Thus, η_{pvg} becomes:

$$\eta_{pvg} = \eta_r \eta_{pc} \left[1 - \beta\left(T_c - T_{c\,ref}\right)\right] \tag{4.2}$$

η_{pc} indicates the efficiency of energy transformation, in the case where the maximum power point tracking is close to 1; in that case, β is indicative of the temperature co-factor (0.005–0.007/°C); η_r is the model of efficiency of energy; T_{cref} is the energy condition at °C. Whereby, the optimum cell temperature (Tc_{ref}) is computed in the form;

$$T_c = T_a + \left(\frac{NOCT - 20}{800}\right) G_t \tag{4.3}$$

Here, the acting solar panels work as superconductors, whose role is to transform energy passing through the active PV panels. The connection here is in a parallel circuit, where a one diode circuit aligns concerning the N_s series connecting, and N_p parallel-interlinked arrays are being connected in order to determine the following cell current and volt relationship

$$I = N_p \left[I_{ph} - I_{rs} \left[\exp\left(\frac{q(V + IR_s)}{AKTN_s} - 1 \right) \right] \right] \tag{4.4}$$

where

$$I_{rs} = I_{rr} \left(\frac{T}{T_r}\right)^3 exp \left[\frac{E_G}{AK} \left(\frac{1}{T_r} - \frac{1}{T} \right) \right] \tag{4.5}$$

In this case, Eqs. 4.4 and 4.5 depicts the electron-charge (1.6×10^{-19} C), *A* refers to the standardized cell efficiency, and *T* is the cell temperature (K), *K* is the Boltzmann's constant, Further, I_{rs} is the PV cell current motion which is in the reverse form at T, the T_r is the conditioned temperature of the cell, I_{rr} is the current in its reverse form at T_r, and the E_G is the photonic energy released through the PV cell superconductor. Therefore, the photonic current I_{ph} is not constant and is dependent on the temperature of the PV cell's and sunlight irradiance condition is expressed as:

$$I_{ph} = \left[I_{SCR} + k_i (T - T_r) \frac{S}{100} \right] \tag{4.6}$$

In this case, I_{SCR} is the short circuit cell's current flow, with the consideration that the optimum temperature of the cell and the dynamic sun irradiance on the active PV plane panel, k_i here, is the short-circuited current flow, whereas *S* is the solar radiation computation in a specified area (mW/mm^2). Subsequently, the *I-V* features of the active PV cell can be computed from the unique cell mode and can be expressed;

$$I = I_{ph} - I_D \tag{4.7}$$

$$I = I_{ph} - I_0 \left[\exp\left(\frac{q(V + R_s I)}{AKT} - 1 \right) \right] \tag{4.8}$$

I_{ph} is the photon current dynamic (A), where I_D is the diode coming from the current-dynamic (A), I_0 is the inverse of the current-dynamic (A). The *A* is the induced constant, The electron charge is designated as *q* (1.6×10^{-19} C), the

Boltzmann’s constant denoted as K, *T* represents the cell temperature in °C, R_s is the series-resistance in ohms, The resistance in Ohms ids denoted as R_{sh} denotes the shunt resistance (Ohm), *I* denotes the cell current-motion (A), and *V* denotes the cell voltage-motion (V). Therefore, the net current flow into the acting PV cell is then determined as:

$$I = I_{PV} - I_{D1} - \left(\frac{V + IR_S}{R_{SH}}\right) \tag{4.9}$$

where

$$I_{D1} = I_{01}\left[\exp\left(\frac{V + IR_s}{a_1 V_{T1}}\right) - 1\right] \tag{4.10}$$

Here, I and I_{01} are the reversed current flows inside the diode, where V_{T1} and V_{T2} are the optimum thermo-dynamical cell voltages. So, the standard factor of the diode is represented by a_1 and a_2, then balanced the mode of the photovoltaic panel as per the expression;

$$v_{oc} = \frac{V_{oc}}{cKT/q} \tag{4.11}$$

$$P_{max} = \frac{\frac{V_{oc}}{cKT/q} - \ln\left(\frac{V_{oc}}{cKT/q} + 0.72\right)}{\left(1 + \frac{V_{oc}}{KT/q}\right)}\left(1 - \frac{V_{oc}}{\frac{V_{oc}}{I_{SC}}}\right)\left(\frac{V_{oc0}}{1 + \beta\ln\frac{G_0}{G}}\right)\left(\frac{T_o}{T}\right)^{y} I_{sc0}\left(\frac{G}{G_o}\right)^{a} \tag{4.12}$$

where v_{oc} denotes the standard point of volt V_{oc} denotes the thermo-dynamical volt $V_t = nkT/q$, *c* is the continuous flow of current, the Boltzmann’s consonant is K, whereas T is the PV cell temperature in kelvin, The non-linearly function photocurrent motion is denoted as $\boldsymbol{\alpha}$.

$\boldsymbol{q}$ is the electron charge, the function for the non-linear current for voltage is γ, whereas β is the photovoltaic (PV) mode of activated function for increasing the rate of current flow; as a result, Eq. 4.12 depicts the generation of energy at its peak for a mono photovoltaic set-up arranged in both series and parallel. Therefore, the net energy formed in the arrangement of the N_s cells arranged in a series circuit and N_p parallel circuit interlinking, if the power P_M for each mode of connection is expressed as;

$$P_{array} = N_s N_p P_M \tag{4.13}$$

Then the configuration of the diode circuit is being applied for the computation of the characteristics of its current–voltage I-V relation considering their parameters at the single diode circuit, as shown below (Fig. 4.2).

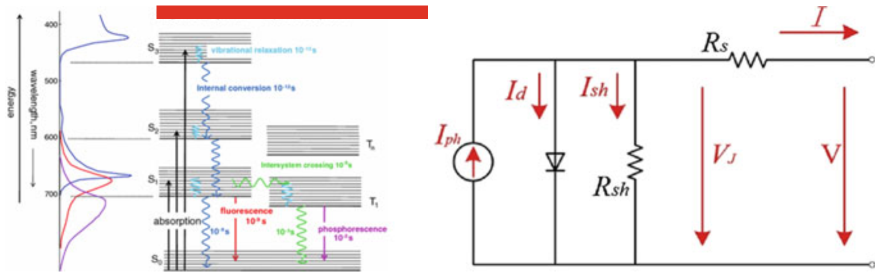


Fig. 4.2 The configuration of the electrical energy generation (I-V) from solar irradiance is implemented by the single diode circuit

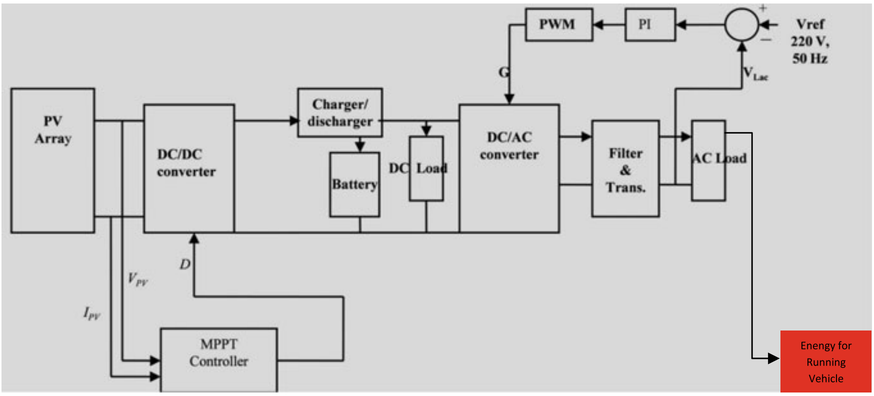


Fig. 4.3 The MATLAB is used for modeling the sing-diode for the photovoltaic cell (PV), resulting in the generation of current followed by the conversion of DC to AC by using the I-V-R relationships

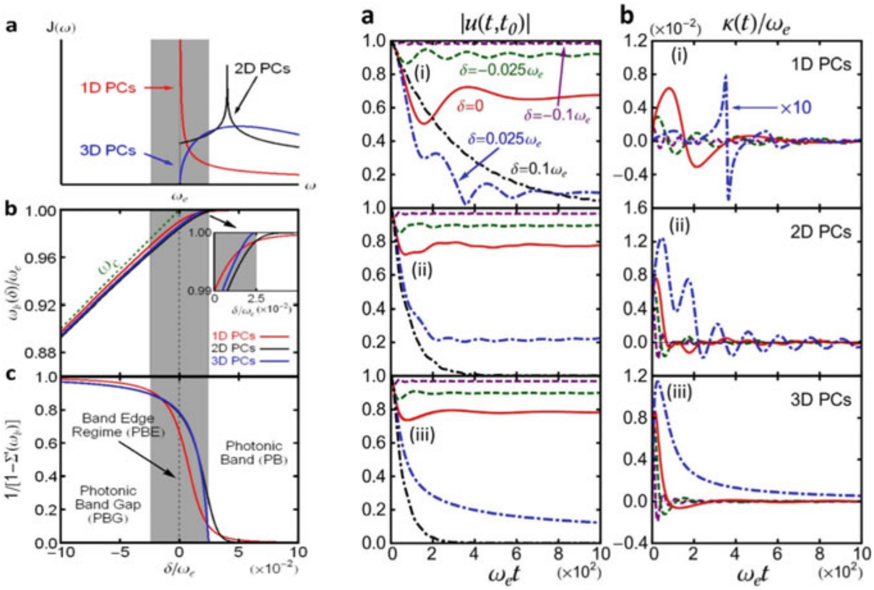
Then, the current production by calculating the Ipv from one diode model, which is derived from the I-V-R relationship, is being carried out by employing the photovoltaic array collected and conversion from DC to AC for use on the transport vehicle (Fig. 4.3).

4.3 Results and Discussion

To calculate the photon capture in the acting PV panel of the on the vehicle, the motion of photon generation flow has been determined by integrating Eqs. (4.12), (4.13). Necessarily, the functional unit area $J(\omega)$ of active PV panel, the excited quantum field and its unit area $J(\omega)$ is being calculated considering the constant agitated-energy point in order to determine the accurate photon generation capture by exterior wall of the vehicle [18, 19].

Consequently, a tipped peak frequency shut-off at Ω_d which controls both DOS (Density of States) of the photons of 1D and 2D of the PV cells are being calculated where $\mathrm{Li}_2(x)$ is an algorithm and $\mathrm{e}_{\mathrm{rfc}}(x)$ is an extra function [2, 20]. Therefore, the DOS of different PV cells represented as $\varrho_{PC}(\omega)$, are being actively achieved solar energy through the computation of photonic energy frequency into the PV panel wall [21–23]. For a 1D PV cell, the represented DOS is thus being expressed as $\varrho_{PC}(\omega) \propto \frac{1}{\sqrt{\omega-\omega_e}}\Theta(\omega-\omega_e)$, where $\Theta(\omega-\omega_e)$ denotes the classical function and ω_ee expressed the frequency in the photonic energy generation (Fig. 4.4).

Thus, in determining the DOS, there is a need to confirm the 3D isentropic role in the active PV cells for purposes of calculating the photonic energy generation into the PV cell on the vehicle [23–25]. Since the 3D cell of the PV panel is the functional DOS of the PBE, designated as: $\varrho_{PC}(\omega) \propto \frac{1}{\sqrt{\omega-\omega_e}}\Theta(\omega-\omega_e)$ is therefore being integrated into the vector field of PV cells to ascertain the energy generation inaccurate terms [26]. In the event the 2D and 1D of the PV cells, the photo-ionic



A B

Fig. 4.4 **a** The structural composition of photon and rate of energy deliberation in the acting PV panel. *a* A functional area at varied DOS magnitude of 3D, 2D, and 1D PV cells. *b* Photon frequency rate at the functional photonic band edge regime (PBE) and photonic bandgap (PBG). *c* Photon's magnitude to deliver high energy into the functional photonic band edge regime (PBE) and photonic bandgap (PBG). **b** The proliferation of photon dynamics into photovoltaic cells. *a* Considering the PBE area, $\langle a(t)\rangle = 5u(t, t_0)\langle a(t_0)\rangle$, and *b* photon dynamic rate $k(t)$, functional variable for (i) 1D, (ii) 2D and (iii) 3D quantum field into the PV cells. *Courtesy* Ping-Yuan Lo, Heng-Na Xiong & Wei-Min Zhang (2015); Scientific Reports, volume 5, Article number: 9423

DOS are being calculated by determining the algorithm divergence of PBE, $\varrho_{PC}(\omega) \propto -[\ln|(\omega-\omega_0)/\omega_0|-1]\Theta(\omega-\omega_e)$, where ω_e is the algorithms' midpoint [27, 28]. Therefore, the functional area $J(\omega)$ is its energy generation field that is within the acting PV cell, and the photon energy generation of velocity $V(\omega)$ relies on the photonic band (PB) of the acting PV cell [29, 30],

$$J(\omega) = \varrho(\omega)|V(\omega)|^2 \tag{4.14}$$

Then, the PB frequency ω_c and proliferative photonic dynamic is being calculated as the function $u(t,t_0)$ of the generation of photon energy in the relative to $\langle a(t)\rangle = u(t,t_0)\langle a(t_0)\rangle$. Hence, this is determined by the functional equation outlined as:

$$u(t,t_0) = \frac{1}{1-\Sigma'(\omega_b)}e^{-i\omega(t-t_0)} + \int_{\omega_e}^{\infty} d\omega \frac{J(\omega)e^{-i\omega(t-t_0)}}{[\omega-\omega_c-\Delta(\omega)]^2+\pi^2J^2(\omega)} \tag{4.15}$$

where $\Sigma'(\omega_b) = [\partial\Sigma(\omega)/\partial\omega]_{\omega=\omega_b}$ and $\Sigma(\omega)$ denoted the storage induced PB photonic energy proliferations,

$$\Sigma(\omega) = \int_{\omega_e}^{\infty} d\omega' \frac{J(\omega')}{\omega-\omega'} \tag{4.16}$$

in that case, the frequency ω_b in Eq. (4.16) reveals that the photon frequency module in the PBG $(0<\omega_b<\omega_e)$ and computed with the areal condition: $\omega_b - \omega_c - \Delta(\omega_b) = 0$, where $\lesssim\Delta(\omega) = \mathcal{P}\left[\int d\omega' \frac{J(\omega')}{\omega-\omega'}\right]$ is integral [4, 31].

Thus, the results pointed out that the calculation of the dynamic photons are the generation with a functional rate of ω_c the PV cell [30, 32]. Since the range in $u(t,t_0)$ is $1 \geq |u(t,t_0)| \geq 0$, thus, the crossover area is being depicted as $0.9 \gtrsim |u(t\rightarrow\infty,t_0)| \geq 0$ which is related $-0.025\omega_e \lesssim \delta \lesssim 0.025\omega_e$, considering the generation rate $\kappa(t)$ within the PV panel cell $(\delta < -0.025\omega_e)$ in the functional area of the cell $(-0.025\omega_e \lesssim \delta \lesssim 0.025\omega_e)$ of the PV cell [9]. Consequently, the motional photonic energy captures are being shown in Fig. 4.5 whereby the cross-sectional area are the photon energy frequency in the surrounding of the PC cells [2, 32].

Then, the proliferation of quantum is being clarified considering variations in the thermal energy concerning the function of the photon concentration $v(t,t)$ through the scattering of photons on the exterior wall of the vehicle [19],

$$v(t,t) = \int_{t_0}^{t} dt_1 \int_{t_0}^{t} dt_2 u^*(t_1,t_0)\tilde{g}(t_1,t_2)u(t_2,t_0) \tag{4.17}$$

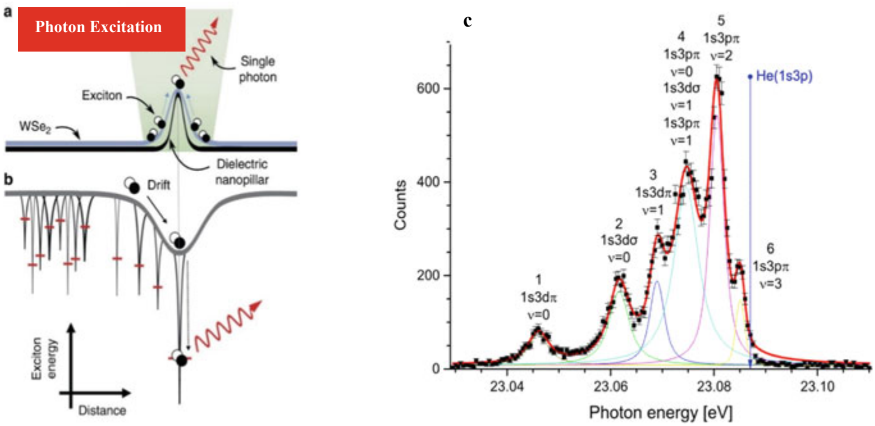


Fig. 4.5 Here, the photonic movement acts on the curtains' wall skin (*a*) Field of photon's excitation (*b*) Photon energy formed acts on the curtain of the PV cells (*c*) the production of photon energy (eV) takes into account a consideration the agitated photons

In this case, the duo-function correlates as $\tilde{g}(t_1, t_2) = \int d\omega J(\omega)\bar{n}(\omega, T)e^{-i\omega(t-t')}$ which reveals the photonic dynamic is very much doable. Thus, the photo dynamic calculation brought by this condition has suggested that the photonic energy generation, $\bar{n}(\omega, T) = 1/\left[e^{\hbar\omega/k_B T} - 1\right]$ is related to the photonic wave length proliferation into the PV cell which is:

$$v(t, t \to \infty) = \int_{\omega_e}^{\infty} d\omega \mathcal{V}(\omega) \tag{4.18}$$

with

$$\mathcal{V}(\omega) = \bar{n}(\omega, T)[\mathcal{D}_l(\omega) + \mathcal{D}_d(\omega)] \tag{4.19}$$

For more specificity, the net photon energy generates is considered via counting the number of photons that are activated, that is $n_0, i.e.\ \rho(t_0) = |n_0\rangle\langle n_0|$, that is mathematically computed via the photons quantum dynamics and through integration in Eq. (4.19) concerning time t on the PV cell $\rho(t)$:

$$\rho(t) = \sum_{n=0}^{\infty} \mathcal{P}_n^{(n_0)}(t)|n_0\rangle\langle n_0| \tag{4.20}$$

$$\mathcal{P}_n^{(n_0)}(t) = \frac{[v(t,t)]^n}{[1+v(t,t)]^{n+1}}[1-\Omega(\mathrm{t})]^{n_0} \times \sum_{k=0}^{min\{n_0,n\}} \binom{n_0}{k}\binom{n}{k}\left[\frac{1}{v(t,t)}\frac{\Omega(\mathrm{t})}{1-\Omega(\mathrm{t})}\right]^k \tag{4.21}$$

Therefore, the results indicate the electron in their photon states are evolved into the varied functional states as $|n_0\rangle$ *is* $\mathcal{P}_n^{(n_0)}(t)$ and the proliferation of photon dissipation $\mathcal{P}_n^{(n_0)}(t)$ evolved from the primary state $|n_0 = 5\rangle$ and steady-state limit, $\mathcal{P}_n^{(n_0)}(t \to \infty)$ of the photon energy which is expressed as

$$\mathcal{P}_n^{(n_0)}(t \to \infty) = \frac{[\overline{n}(\omega_c, T)]^n}{[1+\overline{n}(\omega_c, T)]^{n+1}} \tag{4.22}$$

In order to probe the photon energy capture, the calculation of photon distribution is being determined within the quantum field. Thus, a set of conditions here is the high-temperature coherent states are also being solved with equation by determining factor here is the photons' proliferation states, which is expressed as follows;

$$\rho(t) = \mathcal{D}[\alpha(t)]\rho_T[v(t,t)]\mathcal{D}^{-1}[\alpha(t)] \tag{4.23}$$

where $\mathcal{D}[\alpha(t)] = exp\left\{\alpha(t)\alpha^{\dagger} - \alpha^*(t)\alpha\right\}$ denotes the displacement functions with $\alpha(t) = u(t,t_0)\alpha_0$ and

$$\rho_T[v(t,t)] = \sum_{n=0}^{\infty} \frac{[v(t,t)^n]}{[1+v(t,t)]^{n+1}}|n\rangle\langle n| \tag{4.24}$$

The ρ_T is the thermal state whose average particle quantum is $v(t,t)$, In Eq. (4.11), the peak point photon energy generated has undergone an evolution from its activation state to photonic energy state as:

$$\begin{aligned}\langle m|\rho(t)|n\rangle = J(\omega) &= e^{-\Omega(t)|\alpha_0|^2}\frac{[\alpha(t)]^m[\alpha^*(t)]^n}{[1+v(t,t)]^{m+n+1}} \\ &= \sum_{k=0}^{\min\{m,n\}} \frac{\sqrt{m!n!}}{(m-k)!(n-k)!k!}\left[\frac{v(t,t)}{\Omega(t)|\alpha_0|^2}\right]^k\end{aligned} \tag{4.25}$$

In an attempt to transform this photon energy into electricity, the acting PV panel installed on the vehicle is arranged in parallel and series circuit of the single-diode cell. The I-V correlation and the I-V relation to the PV Panel clarification are as follows:

$$\mathrm{I} = \mathrm{I_L} - \mathrm{I_O}\left\{\exp^{\left[\frac{q(V+I_{RS})}{AkTc}\right]} - 1\right\} - \frac{(V+I_{RS})}{R_{Sh}} \tag{4.26}$$

In this case, the photon formation current is the $\mathrm{I_L}$, whereas $\mathrm{I_O}$ is ideal current flow into the cell, $\mathrm{R_s}$ is indicative of the resistance in the series. The diode function is denoted as A, The Boltzmann's constant k (= 1.38×10^{-23} W/m^2 K), q (=1.6×10^{-19} C) is its charge amplitude of the electron, the cell temperature is denoted as $\mathrm{T_C}$ when the condition is optimum [10, 23]. Therefore, the I-q linked in the PV cells along with variation in the diode cells expression is as follows [8, 28].

$$\mathrm{I}_O = \mathrm{I_{RS}}\left(\frac{T_C}{T_{ref}}\right)^3 \exp\left[\frac{qEG\left(\frac{1}{T_{ref}} - \frac{1}{T_C}\right)}{KA}\right] \tag{4.27}$$

In that case $\mathrm{I_{RS}}$ is the dynamic current represented by the functionality of transforming solar radiations into electrical energy. The *qEG* is the bandgap solar radiation acting on the PV cell resulting in unique modes of generation of electricity (Fig. 4.6).

Here, the acting PV cell, the I-V relationship's computed results link the I-V curve in the cells of the PV panel that is determined by the V-R relationship, which is expressed by:

$$\mathrm{V} = -\mathrm{IR_s} + \mathrm{K}\log\left[\frac{I_L - I + I_O}{I_O}\right] \tag{4.28}$$

where K denotes the constant $\left(=\frac{AkT}{q}\right)$ and $\mathrm{I_{mo}}$ and $\mathrm{V_{mo}}$ are being denoted as the charge and volt the acting PV panel, and thus, the relationship among $\mathrm{I_{mo}}$ and $\mathrm{V_{mo}}$ shall remain steady in the PV cell I-V and which can be written as:

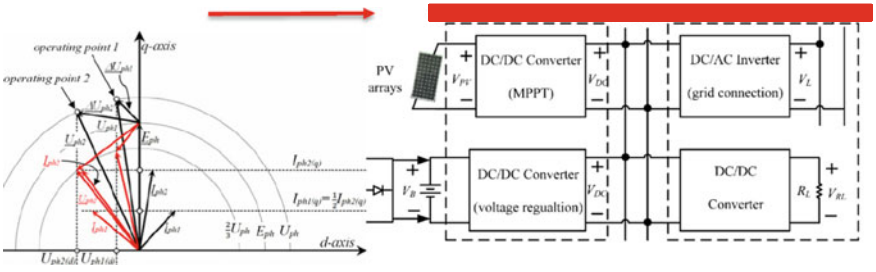


Fig. 4.6 Shows the model diagram of the active PV panel energy flow mechanism. The proposed PV power system module flow mechanism is done through the maximum power point track and the DC/DC converter then to the usable AC power via the PV panel

$$\mathrm{V_{mo}} = -\mathrm{I_{mo}R_{Smo}} + \mathrm{K_{mo}} \log\left(\frac{I_{Lmo} - I_{mo} + I_{Omo}}{I_{Omo}}\right) \tag{4.29}$$

where $\mathrm{I_{Lmo}}$ denotes the photon-induced current, $\mathrm{I_{Omo}}$ denotes the dynamic current into the cell, $\mathrm{R_{smo}}$ denotes the resistance in series, and $\mathrm{K_{mo}}$ denotes the factorial constant.

Here, all series resistance is being, thus, calculated considering the sum of each cell series resistance $\mathrm{R_{smo}} = \mathrm{N_S} \times \mathrm{R_S}$ current considering the functional-coefficient of the constant factor $\mathrm{K_{mo}} = \mathrm{N_S} \times \mathrm{K}$. Since the flow of current dynamics into the circuit are linked to the cells in a series connection, therefore, the current dynamics in Eq. 4.29 remain equals in each part of $\mathrm{I_{omo}} = \mathrm{I_o}$ and $\mathrm{I_{Lmo}} = \mathrm{I_L}$. Thus, the mode of $\mathrm{I_{mo}}$-$\mathrm{V_{mo}}$ relationship for the $\mathrm{N_S}$ series of connected cells can be expressed by:

$$\mathrm{I_L} = \mathrm{G}[\mathrm{I_{SC}} + \mathrm{K_I}(\mathrm{T_C} - \mathrm{T_{ref}})] \tag{4.30}$$

where $\mathrm{I_{sc}}$ denotes the PV current at 25 °C and $\mathrm{KW/m^2}$, $\mathrm{K_I}$ denotes the acting PV panel coefficient factor, $\mathrm{T_{ref}}$ denotes the PV panel's optimum temperature, and G denotes the solar energy in $\mathrm{mW/m^2}$ [14, 19].

Finally, this energy is being implemented by the electrical subsystem to corporate this energy into the vehicle (Fig. 4.7).

Thus, the functional mechanism of the electrical subsystem is thus implemented for transforming the produced electric energy by the synchronous voltage equation below:

$$V_q = -R_s i_q - L_q \frac{di_q}{dt} - \omega L_d i_q + \omega \lambda_m \tag{4.31}$$

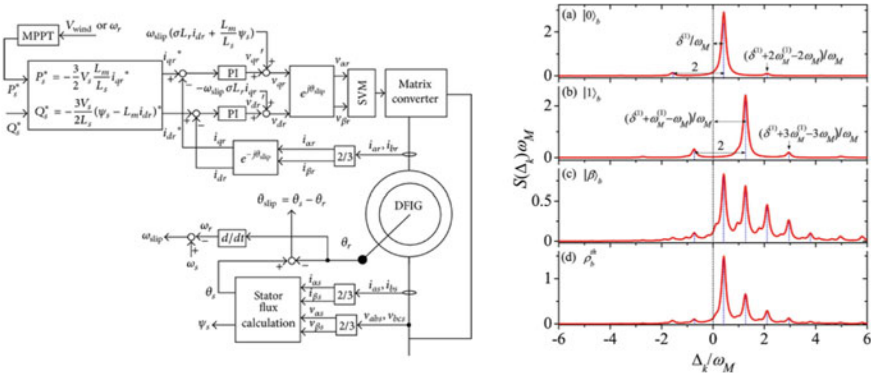


Fig. 4.7 Shows the block diagram of the MPPT ($\mathrm{V_{wind}}$) that consists of the control system with an attached to the velocity of DFIG in the aerodynamic subsystem. The system performs important functions that include the conversion of solar energy to electrical as well as powering off the vehicles using the stator flux rotor

This electrical energy furthered simplified as an equation that depicts the complexities in the modeling of energy in its active form as illustrated;

$$\begin{bmatrix} V_{qs} \\ V_{ds} \\ V_{qr} \\ V_{dr} \end{bmatrix} = \begin{bmatrix} R_s + pL_s & 0 & pL_m & 0 \\ 0 & R_s + pL_s & 0 & pL_m \\ pL_m & -\omega_r L_m & R_r + pL_r & -\omega_r L_r \\ \omega_r L_m & pL_m & \omega_r L_r & R_r + pL_r \end{bmatrix} \begin{bmatrix} iq_s \\ id_s \\ iq_r \\ id_r \end{bmatrix} \tag{4.32}$$

whereby R_r, R_s, L_{ls}, L_m, ω_r i_d, L_{lr}, V_q, i_q, V_d, λ_d, and λq are designations for stator resistance, current inductance current resistance, stator, and current leakage inductance, electrical conductance, current, voltage, and fluxes of the d-q model [10, 32].

Eventually, the analysis of the active energy has been implemented by using series circuit modeling to introduce the electricity produced into the vehicle to power the vehicle and which is calculated by the following equation [2, 12].

$$\begin{cases} v_{dr} = \sigma L_r \frac{di_{dr}}{dt} + R_r i_{dr} + fem_d \\ v_{qr} = \sigma L_r \frac{di_{qr}}{dt} + R_r i_{qr} + fem_q \end{cases}, \tag{4.33}$$

Here, fem_d is a designation of the coupling in the d-axis. Whereas, fem_q is the coupling in the q-axis. Also, the stator has an association with the current produced as shown.

$$\begin{cases} P_s = -V_s * \frac{M}{L_s} i_{qr} \\ Q_s = -V_s * \frac{M}{L_s} \left(i_{dr} - \frac{\phi_{ds}}{M} \right) \end{cases}, \tag{4.34}$$

whereby i_{qr} represents the stator active and i_{dr} shows the reactive powers, which is the ultimate power to activate the transport vehicle to ignite and run (Fig. 4.8).

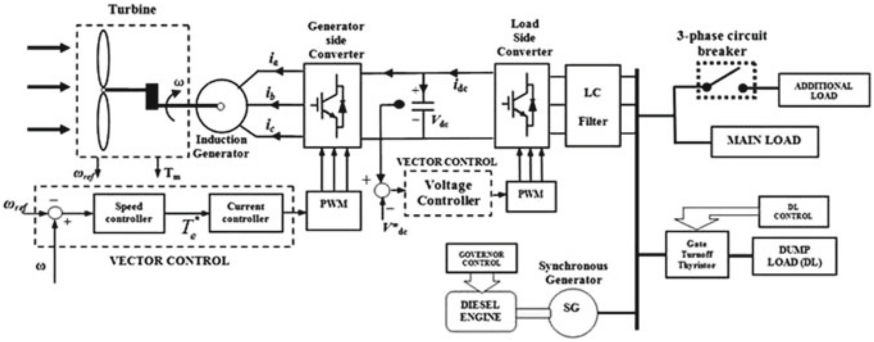


Fig. 4.8 Depicts the control levels, the side converter of the generator, the turbine, the load side converter for transforming solar energy into electrical energy through a 3-phase circuit breaker

In a calculation, the peak solar irradiance can emit 27. 77 mWh/m^2 eV per year, which is approximately 28,000 kWh per year, an equivalent of 76 kWh per day in terms of energy consumption, and it can be trapped by the exterior wall of the vehicle to supply its required energy [13]. Since an ideal sedan car can run an average of 10 miles by utilizing 1 kWh thus, it will need only one solar panel of 1 m^2 that can deliver energy in a day of 10 peak hours of sunlight to power the car to run (760/24) * 10 = 316 miles per day [10]. Subsequently, a 10 compartments train need 1 kWh/mile, and thus it used 40 solar panels of each 1 m^2; it will produce energy to run a train on 400 miles/day, and 300 seat capacity aeroplane need in average 0.10 kWh/mile, and it will need only 40 solar panels of each 1 m^2 to fly 2000 miles/day. Simply, this result suggested that induced solar energy by an exterior wall of the vehicle to power its required energy is quite applicable commercially to global energy and environmental crisis naturally.

4.4 Conclusion

Fossil fuels are the most used sources of energy that are used in most transportation vehicles; however, these sources of energy are much costly and cause environmental crisis. Just because to satisfy the net energy supply in the transportation sector worldwide, the traditional fossil fuel burning technologies are being utilized, which is accelerating enormous stress on conventional energy consumption, and thus, total fossil fuel reserved is getting finite level. As the transportation utilized nearly 30% of global fossil fuel energy, which is nearly 5.6×10^{20} J/Years (560 EJ/Year) and thus, it is creating alone environmental crisis nearly 30% by depleting CO_2 into the atmosphere. Simply, the application of solar power in the global transportation sectors shall indeed be an innovative energy and engineering technology, which will reduce the stress on fossil fuel consumption and as well mitigate the global environmental vulnerability dramatically since it is abundant everywhere and also benign to the environment.

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Chapter 5
Renewable Energy Sources: A Study Focused on Wind Energy

Adeel Bashir and Sikandar Khan

Abstract The excessive emission of the greenhouse gases like carbon dioxide has caused various global climatic changes. In order to mitigate the effects of global warming, caused by the excessive emission of the fossil fuels, the renewable energy sources should be installed globally. In the current study, the renewable energy sources are discussed with an increased emphasis on wind energy. Importance of electrical energy for human being is first discussed, followed by brief description of the conventional ways of producing electricity from different types of fuels. Effects of the greenhouse gases on the earth's environment is also discussed. Harvesting of wind energy is reviewed in detail. Different types of wind turbines, their advantages and disadvantages are also presented. Latest research related to the wind energy is presented with a focus on horizontal axis and vertical axis wind turbines. The renewable energy storage strategies are discussed and finally the role of renewable energy in mitigating the effects of global warming is also discussed.

Keywords Renewable energy sources · Wind energy · Greenhouse gases emission

5.1 Introduction

The level of carbon dioxide (CO_2) in the atmosphere is increasing exponentially due to the excessive burning of the fossil fuels. The excessive emission of carbon dioxide has caused various global climatic changes like global warming [1]. One of the possible strategies, for mitigating the level of carbon dioxide in the atmosphere is to reduce the dependency on the fossil fuels. Using the renewable energy sources is a possible way to reduce the dependency on the fossil fuels. Energy is the basic

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requirement of all living things. Energy is required to perform various voluntary and involuntary tasks in daily life. There are certain types of energies which are building block of food chain like plant use light energy for photosynthesis (process through which plants make food for themselves) then these plants are consumed by human beings and animals as food which provide them energy. Similarly electrical and mechanical energies are required by humans to make their tedious tasks easy and efficient. Electrical energy is required for economical growth, poverty eradication and to improve the lifestyle of humans [2]. Despite being the basic necessity for life, surprisingly, electrical energy is yet not conceived as basic human right [3]. There are still areas of the world which lack this basis necessity of life. According to data provided online on the website of "Our World Data" organization, about 14% of the world population is deprived of electrical energy [4]. The data of the world population with and without electricity till 2016 is shown in Fig. 5.1. It can be inferred from the chart in Fig. 5.1 that access to electrical energy is raising globally but at a very low pace. The need of time is to increase the pace of electrical energy access so that everyone around the globe can be benefited. The access rate is even lower in the underdeveloped and developing countries. The main reason for this is the lack in advance technology required for cheap electrical energy production and hence rely on traditional less cost-effective methods. Another reason is that infrastructure especially power supply lines are not upgraded to meet the raising demand of the nation [4].

Traditionally electricity is produced from fossil fuels, but it is harmful for the environment due to the production of copious amount of carbon dioxide. Another reason for the huge demand of alternative sources of energy is that fossil fuels are exhausting at a very high rate compared to their rate of replenishment [5]. One way to overcome the greenhouse effect and shortage of fossil fuels is to use renewable

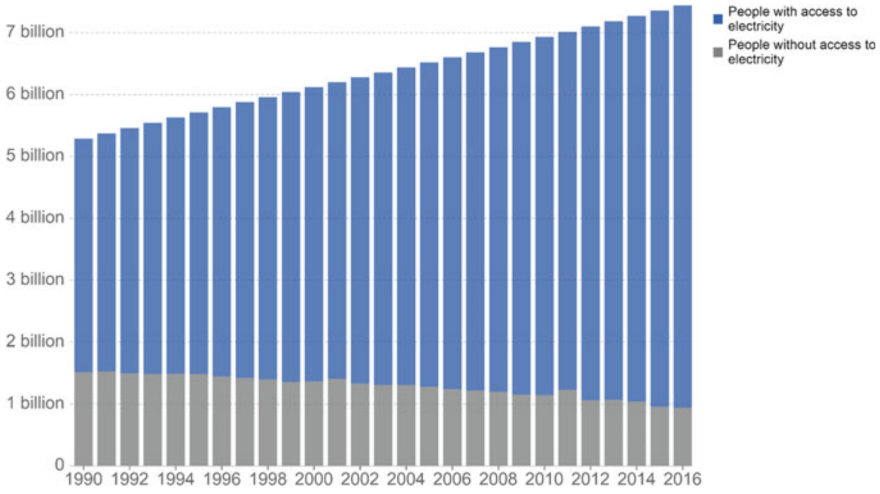

Fig. 5.1 World population with and without access to electrical energy [3]

energy [6], but the transition from fossil fuels to renewable energy is not easy and is one of the biggest challenges of twenty-first century [7]. There are many renewable sources like solar, wind or tides that can be used for the production of clean and green energy. One of the biggest advantages of these renewable sources is that they can be used for electricity production everywhere around the world and all around the year [8]. Research has been carried out on all of the above-mentioned sources but still there is a very small share of the renewable energy in overall energy production. In many developed countries, the renewable energy is contributing more to the overall energy requirements of the country. In United States, renewable energy contribution is 17%. In the undeveloped countries, the contribution of the renewable energy is normally less than 5% [9].

Wind energy is a type of renewable energy resource that is present everywhere around the globe. Optimal harvesting of energy from wind depends upon different factors, the prediction of wind speed and direction is the starting point for selecting a wind turbine for a specific location [10]. The selection of turbine type and size for a specific location play pivotal role in the power system efficiency [11]. For instance, the most widely used three blade horizontal axis wind turbine (HAWT) can generate 50–350 kW power with 45% efficiency. Vertical axis wind turbines (VAWT) are also used but they are not as popular as HAWT due to their certain disadvantages. European countries like Spain, United Kingdom, Germany, and France are leading the world in the energy production from wind [12]. Deep et al. [13], described that wind has become most widely used renewable energy source among all sources present in the nature.

In the current study, the renewable energy sources are presented as a possible remedy for mitigating the effects of the global warming caused due to the excessive emission of the fossil fuels. The various renewable energy sources are discussed in the current study, with a special focus on the wind energy. The structure, merits and demerits of the horizontal and vertical axis wind turbines are also discussed in detail. The renewable energy storage strategies are discussed and finally the role of renewable energy in mitigating the effects of global warming is also discussed.

5.2 Why Electrical Energy is Necessary?

As explained above that electrical energy is very important for human beings. In this section, the various walks and shades of life where electrical energy plays vital role are presented. The electrical energy is used everyday from homes to factories, from toy cars to big ships and aeroplanes, from hospitals to schools, every place uses electrical energy for their daily operations. This is most widely used form of energy around the world. A basic example, the electricity is used at homes for lights, fans, air conditioner and kitchen appliances [14]. Life without electrical energy would be far more difficult and tedious. In certain areas of the world, it will be impossible to survive without using electrical energy for heating or cooling system for houses. Similarly, hospitals are the places where electrical energy is used

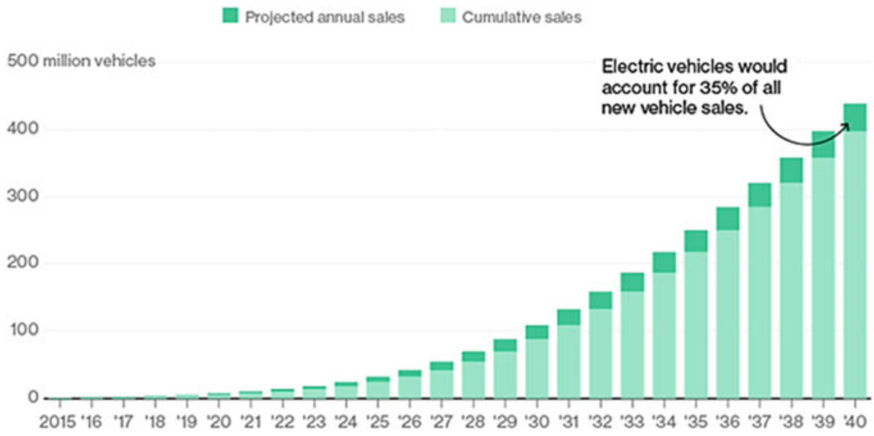

Fig. 5.2 Electrical cars projected sales by 2040 [19]

for saving lives. All appliances in the operation theatres and in the emergency department runs on electrical energy. In 2016 twenty-one patients died in the Ghandi hospital in Hyderabad India due the power cut off [15]. Similar events happen around the globe where many critical patients died due to power failure. Now-a-days electric driven vehicles are becoming famous because they are energy efficient, environment friendly and many other features which traditional vehicles cannot achieve [16–18]. It is predicted by one research conducted by Bloomberg that till 2040 the electrically operated cars will grab the 35% share of the total sales [19]. This is because the price difference between traditional cars and the electrical cars will be reduced to zero. In Fig. 5.2, the data is shown in the form of a bar chart which depicts the sales of the electric cars.

Similarly, there are other areas like agriculture, factories and even space exploration where electrical energy plays a pivotal role.

5.3 Conventional Ways for Electrical Energy Generation

Since the discovery of the electricity by Benjamin Franklin in 1752 with his famous kite flying experiment, there exist multiple ways for its generation. The laws of thermodynamics dictates that all ways of electricity generation are just a fancy way of converting one form of energy to another form, in most cases the heat energy is converted to electrical energy. Conventionally electricity is generated from fossil fuels (Coal, Oil, Natural Gas) or from water. Brief description of each production type is given below.

5.3.1 Fossil Fuel

The basic phenomena to produce electrical energy from fossil fuel is converting water into steam and then running the steam turbine through it which in turn generate electricity. Thermal power plants burn fossil fuel like coal, oil, or natural gas in their furnace to produce heat energy through which water is heated to turn it into steam. These power plants have major disadvantage that they produce copious amount of carbon dioxide. Due to release of CO_2, methane and nitrous oxide, these type of power plants are threat for the environment, because increasing level of CO_2 will cause green house effect. As a result, average temperature of earth climate is raising also known as global warming. World largely rely on the traditional ways of electricity production, that can be proved from the fact that one third of green house gas (CO_2) is produced by thermal power plants. As a results of global warming, polar caps are started melting and the weather pattern of the earth is disturbed. The average temperature of the earth recorded in 2020 is 0.98 °C above the average earth's temperature and it is raising with every passing year. In order to resolve this issue, it is a need of the time to shift from fossil fuels to the renewable energy sources so that the global warming can be mitigated. The fossil CO_2 emission to the atmosphere is the largest among all the greenhouse gases, with a share of 72% among all the greenhouse gases, followed by CH_4 (19%), N_2O (6%) and F-gases (3%) [20–23].

5.3.2 Hydro Power Generation

This method of electricity production uses force of flowing water to rotate the turbine which in turn produce electrical power. As shown in Fig. 5.3, the hydroelectric power plants are used to convert hydro energy into the electrical energy. World first hydroelectric power plant was built on Fox river in Wisconsin USA in 1882. There is indisputable evidence that the dams and reservoirs and other large bodies of freshwater emit two GHGs, namely CO_2 and Methane, although, in the United States, less than 4% of the over 91,000 dams are used for hydroelectric installations [24]. The production of electricity depends upon the following three factors.

a. Water level from ground
b. Volume of water
c. Efficiency of turbine.

The most important advantage of hydro electricity is that it is environment friendly. Secondly, hydro energy can be stored in the reservoir and can be used when required. Moreover, electricity from hydro power plant is produced at constant rate and power plant have sufficient life span. The water from which electricity is produced in the hydro power plant can be further used for irrigation, water sports

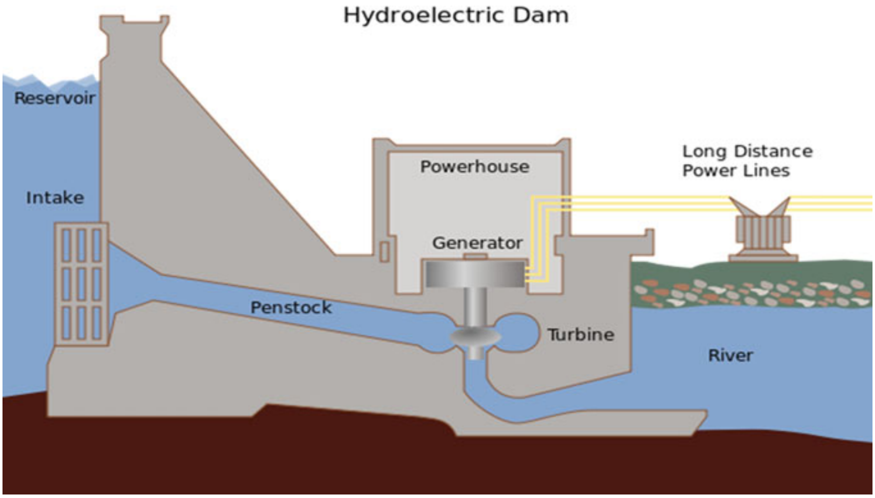

Fig. 5.3 Hydroelectric power plant [25]

or dirking purpose because water physical or chemical properties are not changed. There are few disadvantages of the hydro power plants like the initial construction cost of the plant is sufficiently high. It also requires large area for its construction and may lead to disruption of people lives as they might have to be relocated. Dams built for hydro power plants can cause serious geological damage like Hoover dam of USA caused a number of earthquakes and earth surface of the site is also depressed [26, 27].

5.4 Renewable Energy for Power Generation

Renewable energy serves as supplement to traditional form of energy and in most developed countries they contribute fair share in energy harvesting. Renewable energy is not only used for the production of electrical energy, it is also used to produce thermal energy [28, 29]. In recent times, research and investment is increased in renewable energy, due to the fact that this energy harvesting technique have no negative impact like global warming, as caused by the excessive emission of carbon dioxide into the atmosphere due to the burning of fossil fuels [30, 31]. Another reason for the increased interest of scientists in renewable energy is that they want to get rid of fossil fuel dependency. Fossil fuels are not only dangerous for environment, but they are also decaying at a very fast rate and their replenish rate is very slow or zero in some cases. In Fig. 5.4, the carbon emission is shown from different energy sources [32].

On the other hand, renewable energy sources have the replenish rate greater than energy consumption. Due to numerous advantages of the renewable energy, its use

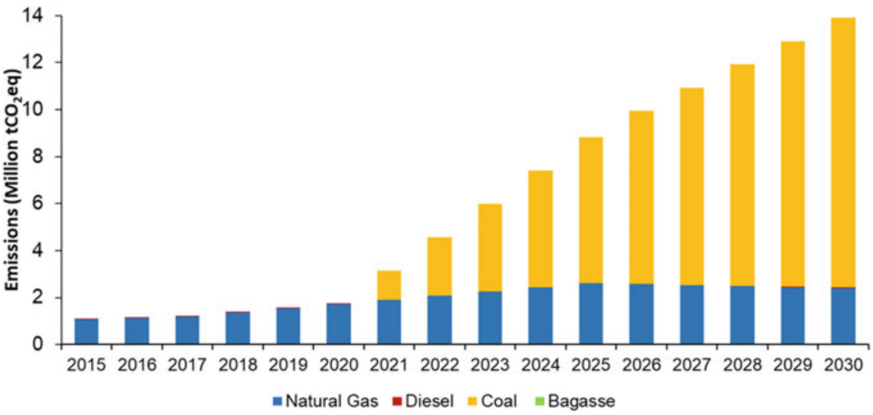

Fig. 5.4 Carbon emission from different sources [32]

is increased in last few decades [33]. It is believed that the use of renewable energy will be increased by 4% in the next decade [34]. There are different types of renewable power sources, some are given below,

a. Solar Energy
b. Wind Energy
c. Biomass
d. Geothermal Energy
e. Tidal Energy.

All above-mentioned sources are naturally replenish at a very high rate and have almost zero green house gases emission.

In order to reduce the carbon emission and to mitigate the global climate issue, it is a need of time to transit from conventional sources of power to renewable sources [35]. Greenhouse gases are having worst impact on the climate due to which average temperature of the earth is raising day by day [36]. This transition will not be easy because of the issues like balancing of load, integration with grid, and energy trading [37]. But these issues are resolvable with some improvement in the technology and with some trade offs.

One of the key elements that effect the growth of renewable energy technology is storage devices. The various strategies that can be used to store renewable energy are batteries [38–40], flywheels [41, 42], to use the excess amount of electricity produced from solar and wind energies for producing the hydrogen fuel [43], phase change materials (PCMs) can be used to store the thermal energy from the solar energy source [44], and unused power from the wind turbines can be used to operate a pumped storage plant (PSP) in order to store the excess electricity [45]. Latest development in the Redox flow batteries provide renewable energy sources with a sustainable storage device. These batteries have advantages like they have independent power and energy density. Similarly, research and development in the lithium-ion batteries have also helped in providing reliable and efficient storage source for renewable technologies. Initially, the cost of the Li-ion batteries was very high as compared to lead acid batteries but now the price is dropped by 80%. These batteries are now becoming very common in developed countries for the electrical energy storage in rural areas. Storage batteries are an important part of the renewable energies, which are not consistent like solar energy because it has power generation only in day time, at night no power will be produced due to unavailability of sunlight. Hence, a reliable storage source is required, for the maximum availability of the electrical energy [46].

5.5 Producing Electricity Through Wind Energy

Wind energy was present since the life came into existence on earth, but it reclaimed its importance in late twentieth century. Precisely, the decade after 1990 gave rebirth to wind energy industry, during this decade the wind energy installed capacity increased five-folds. This all happened due to the following reasons,

a. In the late twentieth century, the adverse effects of the fossil fuels became clear to everyone, and scientist started looking for alternate sources of energy.
b. Wind is type of energy source that is present across the earth and is not confined by the region.
c. Technology development in the twentieth century revolutionized the wind energy industry.

Combing the above factors with vision and political will gave new life to wind power industry. At start, it was not easy because building wind turbine and producing electricity from it was far more expensive than fossil fuels and other sources. Only few developed countries supported the initial research and development for wind energy but after seeing the advantages like low cost and environment friendly source of power, other countries also started joining this activity [47]. According to the report of Zhiyan Consulting Group [48], the average cost of wind energy has touched the same level as of hydro electricity. The heart of the wind energy is wind turbine. Wind turbine is a type of a machine that is used to convert the wind energy into electrical energy. Wind turbines vary in capacity ranging from 1.5 to 5 Mega Watt (MW) [49]. In order to meet the energy requirements, the size of the wind turbine is increasing exponentially [50]. Currently, wind energy is one of the hottest topics in the scientific community [51, 52].

In the recent times, some of the promising research in the wind energy has been conducted like the wind energy harvesting using piezoelectric transduction as an alternative for battery-free portable and wireless electronics [53]. This technology will help the portable devices to go battery-free and will improve their reliability. Similarly, gravity triboelectric nanogenerator are also being used for the conversion of wind energy to electrical energy [54]. Another area which received considerable

Table 5.1 Percentage of installed wind energy of total electricity used by different countries [49–52]

No.	Name of the country	Installed wind power capacity (MW)	Percentage of total electricity (%)
1	China	281,993	38.5
2	USA	117,744	16.1
3	Germany	62,184	8.5
4	India	38,559	5.3
5	Spain	27,089	3.7
6	UK	24,665	3.4
7	France	17,382	2.4

attention by the researchers in the recent past is the selection of the area for harvesting wind energy. Selection of the right area is the first and the most important step of wind energy harvesting [55]. Correct area selection increases the probability of success substantially. The parameters for the selection of area include adequate historic data of wind, containing wind speed and direction information, the average velocity of the wind within a year should be of 20 km/h and power density should be 150 W/m^2. Latest techniques like artificial neural network are also applied for wind energy forecasting [56]. Table 5.1 given that illustrate the percentage of the wind energy produced by different countries in 2020.

There are certain limitations of the wind energy. Firstly, wind cannot be stored, and so it must be used, when available. Due to the intermittent nature of availability, the electrical power produced will be fluctuating. Secondly, it cannot be transported from one place to another, however, power lines can be used to transfer electrical energy from wind turbine to grid station, but wind remain un-transportable. Some of the other challenges for the wind energy sector is the speed fluctuation and load demand variation [57] but this can be resolved by using voltage stabilizer circuits which will provide the steady supply to the load. The following sections will discuss the wind turbines in detail.

5.6 Wind Turbines

As discussed above, wind turbines play pivotal role in the wind energy industry. There are different types of wind turbines used now-a-days, but the basic principle remains the same. Wind is used to rotate the blades of the wind turbine, which consequently, rotates the generator rotors outside, and this action makes a magnetic field, and hence produces the electricity power. Wind turbines can be categorized into different types depending upon multiple parameters like axis of rotation, number of blades, design of the hub and alignment with direction of the wind. In this study, the wind turbines are classified based on their axis of rotation. There are two types of the wind turbines depending upon the axis of rotation [58].

a. Horizontal Axis Wind Turbine (HAWT)
b. Vertical Axis Wind Turbine (VAWT).

5.6.1 Horizontal Axis Wind Turbine

As the name states, this is a type of wind turbine whose axis of rotation is parallel with ground. This type of wind turbine is most widely used in the world. The basis design of the HAWT is same as the windmill but instead of converting wind energy to mechanical energy (in case of windmill), wind turbine converts it to electrical energy. The history of HAWT date back to 1888 when Charles Brush of Ohio built first ancestor of HAWT [48, 59]. Figure 5.5 shows the basic components of the horizontal axis wind turbine their interconnectivity. Rotor that contains blades of the wind turbine is connected to low-speed shaft of the turbine. In order to stop turbine in case of emergency conditions, like extreme gust of wind, the turbine low-speed shaft is provided with mechanical break. Another function of the break is that it acts as a locking system of rotor which is responsible to hold rotor still during repairs. Controller is also coupled with generator that will perform the function of power management of the turbine and it also control the yaw motor in order to set the turbine in the direction of wind. Controller also make sure the safe operation of the turbine under all wind conditions. Controller is connected to the generator and measurement devices to control the yaw and pitch angle of turbine. Controller is provided with Anemometer that sense the direction of the wind and provide the yaw motor the right direction to point turbine for optimal power production. All the components like low speed shaft, gear box, generator, high speed shaft and controller are enclosed in the casing called Nacelle. Yaw drive is important component of the HAWT's yaw system, and it is responsible for the amount of electrical energy produced from the wind. Its function is to keep the rotor of the turbine always in the direction of the wind so the maximum wind energy can be harvested from the wind. Tower is used to support the whole structure of the turbine and provide the required height to the turbine, the taller the tower is, the more wind will be captured by the turbine. The backtracking effect is caused in the wind turbines when the direction of the wind is not perpendicular to the blades of the wind turbine. Backtracking against the wind leads to inherently lower efficiency [58, 59].

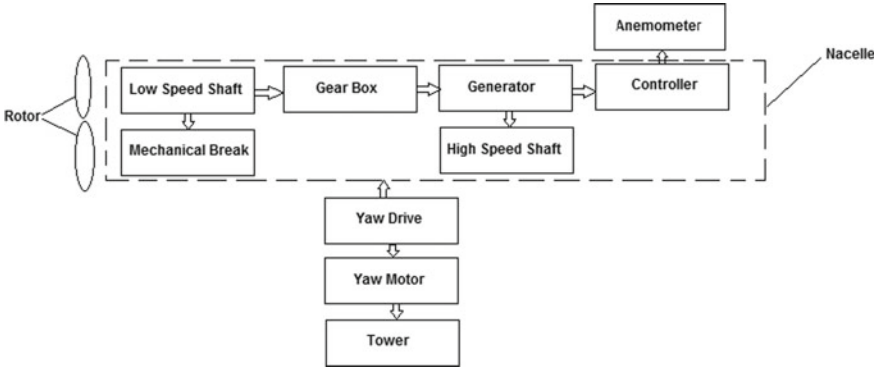

Fig. 5.5 Basic components of horizontal axis wind turbine and their interconnectivity

There are quite a few promising aspects of HAWT, which are highlighted below [58],

a. Horizontal axis wind turbines are the most efficient in terms of energy harvesting.
b. They are not affected by backtracking effect.
c. They are highly reliable.
d. They have high power output.
e. HAWT have high operational wind speed.
f. Their theoretical study is mature.

There are also drawbacks of HAWT, few of them are mentioned below [60].

a. Transportation is difficult due to huge size.
b. They need higher starting wind (about 12–14 km/hour equal to about 3.3–3.8 m/sec depending on their technologies).
c. HAWT need to be inline with the direction of wind for its optimal performance, hence need complex control circuit.
d. Power is used to run turbines yaw system.
e. Not suitable for the regions where wind direction changed frequently.
f. Installation, operation, and maintenance is difficult.

5.6.2 Vertical Axis Wind Turbine

Vertical axis wind turbines have the axis of rotation of the wind turbine perpendicular to surface of earth. Such concept was first presented by a French scientist Georges Darrieus in 1920. This design is most often referred as “Eggbeater windmill”. Figure 5.6 shows the working mechanism of the VAWT. It consists of the rotor that are fixed at top with upper hub and at bottom with lower hub. When

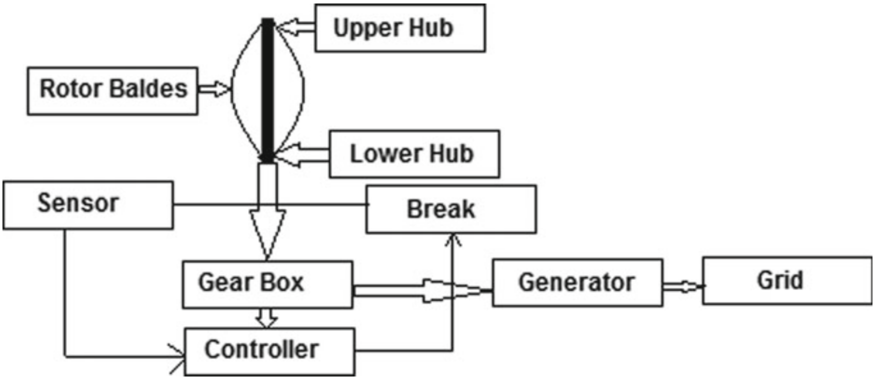

Fig. 5.6 Basic components of vertical axis wind turbine and their interconnectivity

the blades of the turbine rotate due to the action of wind the rotor start rotating but the RPM of the rotor are not adequate for the power production therefore a gear box is required to increase rpm to appropriate level. Mostly helical gears are used because they are quite. Controller of VAWT mostly monitor the wind speed. Sensor provide the controller with the required data that enable it to make decisions depending on the situation like it provide controller information about wind speed on which controller decide stopping of turbine through breaks if the speed is too high to damage the turbine. In most of the small VAWT, centrifugal friction brake system is used. Gearbox of the VAWT is connected with generator which is used to produce electrical power to be added to grid or stored in batteries. There are different types of generators that are used with wind turbines these days, mostly two types of the generators are used which are [60, 61],

a. Squirrel cage induction generator
b. Wound rotor induction generator.

There are mainly two types of vertical axis wind turbine,

a. Darrieus wind turbine
b. Savonius wind turbine.

The basis difference between the two types of the above-mentioned turbines is the way in which their blades use wind for rotation. In Darrieus type turbines, blades are rotated by the action of lift forces whereas in Savonius type turbines, cups of turbine is pushed by the direct action of the wind. Although VAWTS are not as popular as HAWTS but still they have some advantages over the HAWTS which are mentioned below,

a. VAWTS are normally less in height so the heavy components like gearbox and generator can be placed near to ground.
b. One of the most promising advantage of VAWT is that it does not require yaw mechanism.

c. It can harness wind energy from all directions (omni-directional).
d. It has very low wind turbulence so it can be placed closer to each other.
e. It can produce power on low wind speeds.

The structure of the vertical axis wind turbine is normally simpler as compared to the horizontal axis wind turbine. The research has shown that the electricity generated by the vertical axis wind turbines, in locations having low to medium wind speeds, is more as compared to the horizontal axis wind turbines [60–62]. There are certain disadvantages of the VAWT,

a. One of the common disadvantages of the vertical axis wind turbine is that its aerodynamic performance is less efficient as compared to the horizontal axis wind turbines.
b. It does not perform well in gusty winds.
c. It has issues of dynamic stability.
d. The blades of the VAWTS experience much higher fatigue because forces are applied from all directions.
e. Darrieus wind turbine is not self starting so initially it require generator to rotate its rotor.
f. It require the guy wire to support the tower vertical.
g. Less efficient than HAWTS.
h. Their maintenance cost is high as compared to HAWTS.
i. VAWT manufacturing is very low as HAWT dominate the market.
j. It is less reliable as compared to HAWTS.

The comparison between HAWT and VAWT in terms of various parameters are given in Table 5.2 [47–52].

Table 5.2 Comparison of HAWT and VAWT [47–52]

No.	Parameter	HAWT	VAWT
1	Efficiency	70% (Average)	60% (Average)
2	Noise level	60 dB (Max)	10 dB (Max)
3	Maintenance	Difficult	Easy
4	Rotating speed	High	Low
5	Guy wire problem	No	Yes
6	Reliability	More reliable	Less reliable
7	EM Interference	Yes	No
8	Center of gravity	At height	Near to surface
9	Installation cost	High	low
10	Omnidirectional	No	Yes
11	Wind resistance ability	Weak	Strong

5.7 Mitigating Greenhouse Impacts via Renewable Energy

Global warming is becoming one of the biggest threats to the human race. Due to rise in temperature, polar caps are melting which causes the sea level to rise and destroy useable land. The only way to get rid of this problem is to reduce the amount of greenhouse gases (GHGs) being released in the atmosphere. GHGs create an insulation layer in the atmosphere and trap the heat energy by preventing it going back to space, this effect makes the temperature of the globe increase with every passing day. One of the solutions to the global warming issue is using renewable energy for the energy production. Renewable energy is also known as green energy because it produces far less carbon dioxide as compared to other fuels [63]. Table 5.3 summarizes the amount of carbon dioxide equivalent per Kilo watt-hour of different type of fuels [64, 65].

Table 5.3 indicates that use of the renewable energy will significantly reduce the GHGs emission and hence the global warming issue can be reduced. Similar prediction was made by Union of Concerned Scientists (UCS) in 2009 who predicted that by 2025, twenty five percent of the total energy usage will be produced by renewable energy, and it will reduce the emission of GHGs by 227 million metric tons [64]. In the Paris Agreement the target was set to limit the global temperature increase to 2% or possibly to the 1.5% by 2100 [65–67].

Although, generating the total energy required by the world through renewable sources is not possible yet, however, there are other ways to reduce the GHGs like hybridization of the energies. For instance, the areas where the solar energy is sufficient, the domestic electricity can be generated through the integration of solar energy and the grid energy, as shown in Fig. 5.7.

As shown in Fig. 5.7, the power is obtained from two sources, one is the solar panels and other is the grid. During the day time sunlight is enough to run the whole house on solar power and even extra energy may be feed back into the grid. During the night time the loads are operated through the power obtained from the grid. The same system can be improved by adding batteries for the storage of the power at the daytime, although this will increase the installation and maintenance cost, but it will give user an additional source of power. Similar type of setup can be constructed by using wind turbine for the areas which are feasible for the wind energy production.

Hybrid Cars are also helping in the reduction of the GHGs. They have the same principle as explained above, except that the two sources of energy are battery and the fossil fuel. At low speeds, the engine gets power from the battery and as the

Table 5.3 Amount of carbon dioxide equivalent per kilo watt-hour of different type of fuels [64, 65]

No.	Name of the fuel	Amount of CO_2e/kWh (Pounds)
1	Natural gas	0.6–2
2	Coal	1.4–3.6
3	Wind	0.02–0.04
4	Solar	0.02–0.7

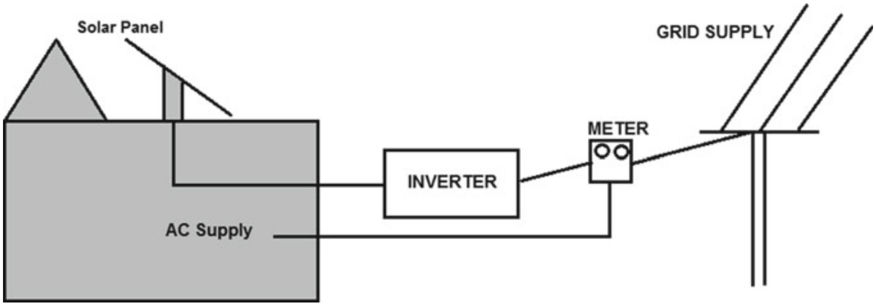

Fig. 5.7 Hybrid domestic supply (solar and grid)

speed passes the threshold, the power is switched to the petrol. Hybrid cars produce 56.1 pounds of carbon dioxide every 100 miles whereas the traditional cars will produce 74.9 pounds for same mileage [68]. Figure 5.8 shown illustrates the basic working mechanism of the hybrid cars.

Negative Emission Technologies (NET) can also play pivot role in the reduction of GHGs. There are two types of the NET based on photosynthesis.

a. Bioenergy with carbon capture and storage (BECCS)
b. Production and sequestration of biochar.

For many years BECCS was considered as only NET technique for the reduction of the carbon dioxide [69]. But BECCS is the time-consuming process and it will not help the mankind to attain the set goals of the GHGs reduction [70–72]. Yang et al. [73], presented biochar technology based on pyrolysis of biomass that can be used for the significant GHGs reduction.

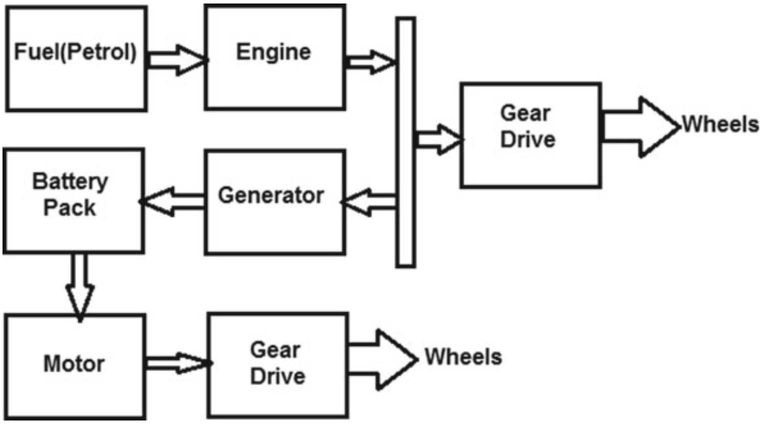

Fig. 5.8 Hybrid cars working mechanism

5.8 Conclusion

In the current study, the renewable energy sources are discussed with an increased emphasis on wind energy. The outcomes of the current study are summarized below:

- The global warming caused due to the excessive emission of the greenhouse gases can be mitigated by replacing the conventional energy sources by renewable energy sources.
- The wind energy is the most efficient and highly researched renewable energy type that has the potential to replace the conventional energy sources around the globe [62].
- As compared to the vertical axis wind turbine, the horizontal axis wind turbine is very efficient. The theoretical study of the horizontal axis wind turbine is also very mature as compared to the vertical axis wind turbines that helps in easily designing the wind turbine blade profile and size selection, based on the wind conditions of a specific location.
- The hybridization of the renewable energy with other conventional sources of energies can help in reducing the dependency on the conventional energy sources and hence will help in reducing the greenhouse gases emission.

5.9 Future Prospects

Almost 26% of the world electricity is currently provided by the renewable energy, but by 2024 the global contribution of the renewable energy will increase up to 30%. The total capacity of the electricity produced from solar energy will reach up to 600 gigawatts (GW) by 2024. Along with the increase in the total capacity, the price of the electricity produced from the solar energy will be reduced by almost 35% by 2024. The capacity of the onshore wind energy will be increased by almost 57% to 850 GW by the year 2024. The capacity of the offshore wind energy is expected to increase to 65 GW by 2024. The global capacity of the electricity produced from the hydro power is expected to increase by 9% by the year 2024. The global capacity of the geothermal energy is expected to increase by 28% by the year 2024. The hybridization of the renewable energy with the conventional sources of energy will be increased even more in the future in order to mitigate the effects of global warming that are caused due to the excessive emissions of the greenhouse gases.

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Chapter 6
Financial Optimization in the Renewable Energy Sector

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Abstract Due to the rapid population growth worldwide, the energy demand increases daily with industrialization, urbanization, and technological development. Electric energy is an indispensable product used in all areas of life for human beings. Although the primary energy source used for electricity generation is fossil fuels, more active use of renewable energy resources has become very important because they are exhausted and the damage they cause to the environment. Many countries encourage electricity suppliers to use renewable energy sources more actively. Since both fossil fuels and renewable energy sources are limited, these resources must be used effectively. Electricity is such a kind of product that must be consumed as soon as it is produced due to limited resources. Therefore, many of the countries are continuously working on regulating their electricity markets in order to improve the effectiveness and the efficiency in the usage of electricity. Electricity suppliers must optimize their generation capacity and bidding strategies in this unregulated market environment. In this empirical study, hydraulic and wind power plants were used to emphasize using renewable energy sources in electricity generation. The mean-variance, mean-absolute deviation optimization models, and Sharpe ratio optimization were applied to Turkish electricity market. Each model has been optimized for two different renewable power plants with four different objective functions (minimum risk portfolio, maximum return portfolio, maximum utility portfolio A = 3, and maximum Sharpe ratio portfolio). All optimization results obtained as a result of the application have been analyzed. The portfolio performances of the models and renewable energy sector were compared with the Sharpe ratio performance criterion. It has been observed that the performance of the optimal portfolios calculated for the hydraulic power plant among the renewable energy sector and the MAD optimal portfolios among the models provide better results.

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Keywords Climate change · Renewable energy · Hydraulic power · Wind power · Portfolio optimization · Mean-variance · Mean-absolute deviation · Sharpe ratio

Abbreviations

DAM	Day-ahead market
DS	Down-side
EPİAŞ	Energy Market Management Company in Turkey
GWh	Gigawatt-hour
HPP	Hydraulic power plant
MAD	Mean-absolute deviation
MaxUP	Maximum utility portfolio
MaxRP	Maximum return portfolio
MCP	Market clearing price
MinRP	Minimum risk portfolio
MPT	Modern portfolio theory
MSRP	Maximum Sharpe ratio portfolio
MV	Mean-variance
MVS	Mean-variance-skewness
MWe	Megawatt electric
OECD	Organization for Economic Cooperation and Development
SR	Sharpe ratio
SV	Semi-variance
WPP	Wind power plant

6.1 Introduction

Today, energy has become one of the most vital needs of the world and humanity. Along with the rapid population growth, the energy demand increases daily with industrialization, urbanization, and technological development.

There are two types of energy sources: non-renewable and renewable. Coal, oil, natural gas, and nuclear power are examples of non-renewable energy resources derived by burning fossil fuels' energies in solid, liquid, and gaseous forms around the world. Renewable energy resources obtained from inexhaustible resources are energy resources that are in a continuous cycle and repeatedly used. Solar, wind, hydraulic, geothermal, wave, and biomass are the primary renewable energy sources [17].

84.3% of the energy resources consumed in the world are provided by fossil fuels [4]. Fossil fuels pose a critical problem as they cause global climate change and environmental problems. Fossil fuels are not endless resources and are in danger of being exhausted. Due to greenhouse gases generated by fossil fuel use in energy production, both climate change and ecological balance deterioration are observed. Because fossil fuel resources are limited, diversification of energy sources is required to ensure energy availability. Turning to new and renewable energy sources is expected to be the best option for meeting future energy demands. The fact that renewable energy sources cause less damage to the environment, do not produce greenhouse gases, and are domestic resources makes them a preferred energy production source [24, 42].

Countries are developing renewable energy policies to increase the use of renewable energy. Within the scope of renewable energy policies; The use of renewable energy can be encouraged by requiring energy companies to follow a renewable energy-oriented path in their targets and investments or by making financial aid. With the purchase guarantee, investors should be cleared by following high policies regarding duration, quantity, and pricing. Thus, the initial investment cost and the economic disadvantage of the high technology used can be eliminated. With the renewable energy policy with increased economic competitiveness, the ecological damages caused by irreversible global warming can be reduced. Supporting energy efficiency and reducing carbon emissions by using energy more effectively and sparingly is another crucial step [22].

Within the scope of these explanations, electricity suppliers should turn to the use of renewable resources. The limitations encountered in electricity generation with fossil resources also apply to electricity generation with renewable resources. Therefore, these limited resources must be used effectively and efficiently. Suppliers in the electricity market should consider operational risks in electricity generation as well as deal with market risks. They should optimize their production capacities and market bid strategies so that they can better manage market risks. They should determine their investment and market strategies, taking into account market conditions and risks.

In the competitive environment in electricity markets, power generation companies' primary purpose is to maximize their profits and minimize market risks. Electricity producers should manage their risks well and establish a good trading strategy before bidding on the spot markets and the bilateral contract market. With a good plan, the main goal is to determine portfolio weights. At this point, portfolio optimization is a necessary requirement.

Portfolio management and optimization in finance literature show developments from past to present. New approaches are developed in the field of securities management. Markowitz made significant contributions to the portfolio management approach with the article "Portfolio Selection" and introduced the Modern Portfolio Theory [20, 21, 39]. While it was argued that the non-systematic risk could be reduced by creating a portfolio basket with a large number of securities in the classical portfolio approach, there was no consideration of the correlation between the assets in the portfolio [7, 20, 44]. Markowitz stated that diversification and correlation between assets are also crucial for reducing portfolio risk [20, 35, 39].

In MPT, it was stated that the risk should be minimized, and mean-variance was used as the risk measure, and it was named as Mean-Variance Optimization. Konno and Yamazaki continued their optimization studies and used mean absolute deviation to measure risk [33]. With this study, the concept of Mean-Absolute Deviation Optimization has been brought to the literature [33]. The terrestrial programming method suggested in MV for the portfolio selection model problem has been transformed into a linear program with MAD [43]. With the MAD model, which enables portfolio optimization with linear programming, such issues as operation difficulties and extended problem solving are eliminated. Simultaneously, since the MAD model does not have normal distribution and assumptions that investors avoid risk, it has been proposed as an alternative model to MV [28, 29]. In financial markets, both models were used with frequency, and the pairwise comparison results were shared with market players [28, 30].

This empirical study aims to encourage electricity producers that produce electricity using fossil fuels to add renewable energy sources to their electricity generation portfolio. This study also describes how a market bid strategy should be built by applying MV and MAD optimization models and SR optimization to Turkey's electricity market. For each model, a total of 16 optimizations were made by using four different objective functions (MinRP, MaxRP, MaxUP A = 3, and MSRP) for two different types of renewable power plants. All calculated optimization results were analyzed. Portfolio performances of models and renewable energy sector were compared with the Sharpe ratio performance criterion. Suggestions were made to the electricity market decision-makers about adding renewable energy resources to their generation portfolios.

6.2 Literature Review

With the MPT put forward by Markowitz, portfolio optimization studies have increased, and scientists have created different optimization models. Some of the portfolio optimization models frequently used in the finance sector have become available in various sectors such as electricity markets. With the application of these models to the electricity markets, electricity suppliers can model their sales portfolios for their production.

When looking at the literature, it is clear that the application of portfolio optimization models to electricity markets has increased after 2000. Some of the work was done since 2000 is given below.

Byström [6] conducted a study that minimizes the variance in the Nord Pool electricity market. Dahlgren et al. [10] SP15 optimized the California PX electricity market using VaR/CVaR (95, 99%) models. Liu [34] made portfolio optimization between bilateral agreement and spot market with MV model in California ISO and PJM electricity markets. Liu and Wu [35] applied the MV model to the California electricity market. Liu and Wu [36] again applied the MV model to the PJM electricity market, and made portfolio optimization. Liu and Wu [37] again used PJM electricity market data and optimized it with the VaR model.

Feng et al. [18] applied the MV optimization model to the PJM electricity market. Munoz et al. [40] made MV optimization using Spanish electricity market data and determined the renewable energy resources included in the investment portfolio. Pindoriya et al. [41] applied the MVS model to the PJM electricity market and realized portfolio optimization. Kazempour and Moghaddam [31] applied variance, covariance, and CVaR optimization models to the Spanish electricity market.

Bhattacharya and Kojima [2] applied the MV optimization model to the Japanese electricity market. They showed that Japan's renewable energy portfolio could be up to 9% due to the application. Suksonghong et al. [45] applied the MVS model to the PJM electricity market and performed multi-objective optimization. Boroumand [5] applied VaR and CVaR optimization models to the French electricity market. Gökgöz and Atmaca [20, 21] implemented the MV, the DS, and SV optimization models to the Turkey's electricity market.

As can be seen from the literature, portfolio optimization models have been applied to electricity markets by researchers after 2000. In this context, researchers have applied the MV, the VaR, the CVaR, the MVS, and the DS and SV portfolio optimization models to the Nord Pool, the California, the PJM, the Spain, the Japan, and the France and Turkey electricity markets.

Turkey produced 78.104 GWh of electrical energy from hydraulic sources at the end of 2020. Hydraulic resources were used to generate 25.59% of the electricity. Hydroelectric power plants account for the majority of electricity generation. In Turkey, hydraulic resources account for the majority of renewable energy sources. Turkey has 1.5% of the world's hydropower potential [13, 15].

Turkey produced 24.760 GWh of electricity from wind power plants at the end of 2020. Wind energy accounted for 8.11% of total electricity generation. Turkey has the highest wind energy potential among the OECD nations. Due to its geopolitical location, Turkey's wind energy potential is enormous [14, 15, 26].

In this empirical study is MV, MAD optimization models, and SR optimization were applied to two renewable energy power plants in Turkey's electricity market. Unit electricity generation costs of hydraulic and wind power plants were used. 4 different objective functions—MinRP, MaxRP, MSRP, and MaxUP—have been implemented for the models. Eight optimization studies were carried out separately for hydraulic and wind power plants, and 16 optimization studies. The MV and the MAD optimization models were compared in detail, and recommendations were made to electricity market decision-makers to establish a decision support system. It is thought that this study on renewable energy sources will provide an idea for electricity producers to add renewable energy resources to their electricity generation portfolio. The optimization results carried out in the study were compared in terms of both models and renewable energy sector. In this context, the comparison of both models and sectors would make significant contributions to the literature on portfolio optimization in electricity markets.

6.2.1 MPT and Optimization Models of MV

It is stated in classical portfolio theory that risk can be reduced by diversification regardless of the correlation between the assets that make up the portfolio [7, 20]. Markowitz opposed this theory and stated that risk should not only be looked at with diversification but also the correlation between the assets in the portfolio created by diversification and laid the foundation of MPT [20, 35, 39]. MPT seeks effective portfolios that provide the maximum return for the desired risk value or the minimum risk for the desired level of return [19, 21]. It is based on MV optimization in which the correlation between assets is calculated, and the assets with high correlation are removed from the portfolio, and the risk is minimized. MPT's assumptions are as follows [11, 21, 23]:

- There are no transaction fees or taxes.
- Investors only consider risky assets' expected returns, variances, and covariances.
- The expected returns of assets are normally distributed.
- Investors have all of the information they need about expected returns, variances, and risky asset buckets.
- All investors try to avoid taking risks.

According to MPT, the distribution of portfolio options' returns can be created using only average returns and variances. Considering this rule, variances, average returns, and covariance matrix of assets should be made to optimize MPT based on MV optimization [20, 21].

Markowitz brought the definitions of effective portfolio and effective boundaries to the literature. Portfolios that provide the maximum return at the desired risk level or have the minimum risk at the desired return level are defined as effective portfolios. In the expected return and expected risk graph, the curve combining efficient portfolios is defined as an efficient frontier [7, 28].

In the optimization using the minimum risk objective function, a portfolio with minimum risk created with assets is calculated. After the minimum risk portfolio is found on the efficient frontier curve, the part remaining on this portfolio constitutes the effective result set. Portfolios below the minimum risk portfolio are not taken into account as they do not yield effective results. As seen in Fig. 6.1, portfolios under efficient frontier are called inefficient portfolios.

In order to make MV optimization, the variance, covariance, and expected return of the assets that make up the portfolio should be calculated. The calculations are shown with the following formulas in order [12, 20, 21, 23, 46]:

$$Variance - \sigma_p^2 = \sum_{i=1}^{n} \sum_{j=1}^{n} Wt_i Wt_j \sigma_{ij} \tag{6.1}$$

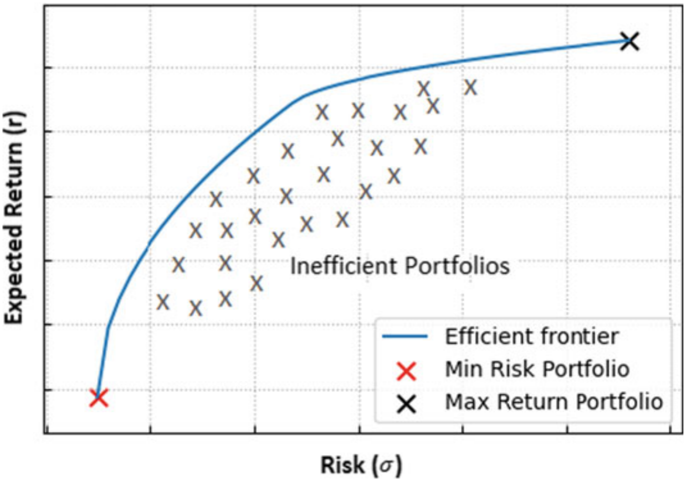

Fig. 6.1 The MV model's efficient frontier

$$Covariance\ Matrix = \begin{bmatrix} \sigma_1^2 & \sigma_{1,2} & \dots & \sigma_{1,n} \\ \sigma_{2,1} & \sigma_2^2 & & \\ \vdots & & \ddots & \\ \sigma_{n,1} & & & \sigma_n^2 \end{bmatrix} \tag{6.2}$$

$$Expected\ Return - E\left(Rn_p\right) = \sum_{i=1}^{n} Wt_i Rn_i \tag{6.3}$$

n is the number of current risky assets, Wt_i is the asset i's weight in the portfolio, Wt_j is the asset j's weight in the portfolio, Rn_i is the asset i's return, σ_{ij} is the value of covariance between assets i and j, $E\left(Rn_p\right)$ is the portfolio's expected return, σ_p^2 is the portfolio's variance.

6.2.1.1 Minimum Risk Optimization via MV Model

The minimum risk objective function is used in the MV optimization model to find the minimum risky portfolio. An investor who does not like risk prefers a portfolio with minimum risk. In the MV model, MinRP is calculated as stated in the following formulas [20, 21, 23]:

$$Min.\left(\sigma_p^2\right) = \sum_{i=1}^{n}\sum_{j=1}^{n} Wt_i Wt_j \sigma_{ij} \tag{6.4}$$

s.t.

$$\sum_{i=1}^{n} Wt_i Rn_i = Rn_{target} \tag{6.5}$$

$$\sum_{i=1}^{n} Wt_i = 1 \tag{6.6}$$

$$0 \leq Wt_i \leq 1, \ [i = 1, 2, \ldots, \mathrm{n}] \tag{6.7}$$

By using Eqs. 6.4–6.7, portfolio risk can be minimized, and MinRP can be calculated for an investor who does not like risk.

6.2.1.2 Maximum Return Optimization via MV Model

In the MV optimization model, the maximum return objective function is used to find the portfolio with maximum return. The risk-loving investor prefers the portfolio with the maximum return. In the MV model, MaxRP is calculated as stated in the formulas below [19, 25]:

$$Max.E\left(Rn_p\right) = \sum_{i=1}^{n} Wt_i Rn_i \tag{6.8}$$

s.t.

$$\sum_{i=1}^{n} Wt_i = 1 \tag{6.9}$$

$$0 \leq Wt_i \leq 1, \ [i = 1, 2, \ldots, \mathrm{n}] \tag{6.10}$$

By using Eqs. 6.8–6.10, portfolio return can be maximized, and MaxRP can be calculated for an investor who likes risk and wants to maximize the portfolio's return.

6.2.1.3 Maximum Utility Optimization via MV Model

In the MV optimization model, the maximum utility objective function is used to find the portfolio that will maximize the utility according to the investor's risk aversion level. In the MV model, MaxUP is calculated as indicated in the following formulas [12, 20, 23, 34–36, 46]:

$$Max.(U) = E\left(Rn_p\right) - \frac{1}{2}A\sigma_p^2 \tag{6.11}$$

s.t.

$$\sum_{i=1}^{n} Wt_i = 1 \tag{6.12}$$

$$0 \leq Wt_i \leq 1,\ [i = 1, 2, \ldots, \mathrm{n}] \tag{6.13}$$

The purpose here is to maximize the utility function indicated by U in Eq. 6.11 according to the coefficient “A,” which shows the investor’s risk aversion level. As the “A” coefficient increases, the investor avoids risk, and as it decreases, he prefers risky investments. The average risk aversion coefficient is accepted as three according to financial studies [21]. If the average risk aversion coefficient is greater than 3, it is understood that the investor avoids more risk than usual. If the coefficient A is taken too large, the portfolio to be obtained converges to the minimum risk portfolio. If the average risk aversion coefficient is lower than 3, it is understood that the investor likes the risk above normal [21, 36].

By using Eq. 6.11–6.13, the utility to be obtained by the investor in the MV model according to the risk aversion request can be maximized.

6.2.2 Optimization Models of MAD

The MAD portfolio optimization model was introduced by Konno and Yamazaki as an alternative to the MV portfolio optimization model discussed by Markowitz in MPT [33, 39]. Instead of the MV’s risk measure variance, the MAD optimization model uses the mean-absolute deviation as the risk measure. Portfolio optimization has shifted from quadratic to linear programming with mean-absolute deviation as a risk measure in MAD. Thus, the difficulties of quadratic programming in solving the portfolio selection model problem were overcome with the ease of linear programming in problem-solving [33, 43].

While there is an assumption that assets show a normal distribution in the MV model, there is no distribution assumption in the MAD model, including a normal distribution. In order to create the MAD model, it is unnecessary to create variance and covariance matrices as in the MV model. Therefore, portfolio optimization with MAD is done with linear programming, and the solution to the portfolio selection problem is more straightforward. When new assets are added to the model, updating the model is simpler [28, 29, 33]. In addition to the advantage of the ease of operation, there are also opinions that it causes excellent estimation risks [28, 29]. Even if all returns of the assets included in the MAD optimization model are negative within the same period, the model can always produce solutions [28, 29].

Table 6.1 The comparison of MV and MAD optimization models

MV model	MAD model
Non-linear programming	Linear programming
Assets are assumed to be normally distributed	No assumption of distribution among assets
Variance, covariance matrices are created	Variance, covariance matrices do not need to be created
Model is difficult to update	Model is easy to update
The portfolio selection problem is difficult to solve	The portfolio selection problem is easy to solve

The optimal solution achieved with MAD portfolio optimization can maximize the expected benefit. While it makes the expected benefit the highest, it is not concerned with distributing returns [28, 29]. In the optimal portfolio solution found due to the MAD model's optimization, the portfolio cannot contain more than 2T + 2 assets. Therefore, T can be used as a control variable to limit the number of assets in the portfolio [28, 29]. Table 6.1 shows a summary comparison of the MV and MAD optimization models.

Konno and Yamazaki calculated the mean-absolute deviation used as a risk measure and the expected return of the portfolio in the MAD optimization model that they brought to the literature [33]:

$$E(Rn(v)) = \sum_{j=1}^{n} Rn_j v_j \tag{6.14}$$

$$w(v) = E\left[\left|\sum_{j=1}^{n} Rn_j v_j - E\left[\sum_{j=1}^{n} Rn_j v_j\right]\right|\right] \tag{6.15}$$

$E(Rn(v))$ represents the portfolio's expected return, Rn_j represents the asset j's return, v_j represents the asset j's weight in the portfolio, and $w(v)$ represents the mean-absolute deviation value.

6.2.2.1 Minimum Risk Optimization via MAD Model

In order to find the minimum risky portfolio in the MAD optimization model, the minimum risk objective function is used. An investor who does not like risk prefers a portfolio with minimum risk. In the MAD model, MinRP is calculated as specified in the following formulas [33]:

$$Min.w(v) = E\left[\left|\sum_{j=1}^{n} Rn_j v_j - E\left[\sum_{j=1}^{n} Rn_j v_j\right]\right|\right] \tag{6.16}$$

s.t.

$$\sum_{j=1}^{n} E(Rn_j)v_j \geq Rn_{target} \tag{6.17}$$

$$\sum_{j=1}^{n} v_j = 1 \tag{6.18}$$

$$0 \leq v_j \leq 1,\ [j = 1, 2, \ldots, \mathrm{n}] \tag{6.19}$$

Rn_{target} represents the minimum rate of return the investor is targeting, $E(Rn_j)$ represents the expected rate of return on asset j.

r_{jt}; time t is the yield obtained for (t = 1, 2, …, T). It's believed that r_{jt} can be calculated using historical data or forecasts for the future. Furthermore, the expected value of the random variable is supposed to converge with the data's average.

$$r_j = E(Rn_j) = \sum_{t=1}^{T} r_{jt}/T \tag{6.20}$$

In this case, $w(v)$ is converged as follows.

$$w(v) = E\left[\left|\sum_{j=1}^{n} R_j v_j - E\left[\sum_{j=1}^{n} R_j v_j\right]\right|\right] = \frac{1}{T}\sum_{t=1}^{T}\left|\sum_{j=1}^{n}\left(r_{jt} - r_j\right)v_j\right| \tag{6.21}$$

$a_{jt} = r_{jt} - r_j$; j = 1, 2, …, n; For t = 1,2, …, T, the minimum risk objective function is calculated as follows:

$$Min.w(x) = \sum_{t=1}^{T}\left|\sum_{j=1}^{n} a_{jt}x_j\right|/T \tag{6.22}$$

s.t.

$$\sum_{j=1}^{n} r_j v_j \geq Rn_{target} \tag{6.23}$$

$$\sum_{j=1}^{n} v_j = 1 \tag{6.24}$$

$$0 \leq v_j \leq 1,\ [j = 1, 2, \ldots, \mathrm{n}] \tag{6.25}$$

As a result of the definitions, the minimal risk objective function has become linear. The linear programming model that follows is similar to the model above [33]:

$$Min.w(v) = \sum_{t=1}^{T} y_t / T \tag{6.26}$$

s.t.

$$y_t + \sum_{j=1}^{n} a_{jt} v_j \geq 0,\ t = 1, 2, \ldots, T \tag{6.27}$$

$$y_t - \sum_{j=1}^{n} a_{jt} v_j \geq 0,\ t = 1, 2, \ldots, T \tag{6.28}$$

$$\sum_{j=1}^{n} r_j v_j \geq Rn_{target} \tag{6.29}$$

$$\sum_{j=1}^{n} v_j = 1 \tag{6.30}$$

$$0 \leq v_j \leq 1,\ [j = 1, 2, \ldots, \mathrm{n}] \tag{6.31}$$

6.2.2.2 Maximum Return Optimization via MAD Model

In the MAD optimization model, the maximum return objective function is used to find the portfolio with maximum return. The risk-loving investor prefers the portfolio with the maximum return. In the MAD model, MaxRP is calculated as indicated in the formulas below:

$$Max.E(Rn(v)) = \sum_{j=1}^{n} Rn_j v_j \tag{6.32}$$

s.t.

$$\sum_{j=1}^{n} v_j = 1 \tag{6.33}$$

$$0 \le v_j \le 1, \ [j = 1, 2, \ldots, \mathrm{n}] \tag{6.34}$$

Portfolio return can be maximized in the MAD model by using Eq. 6.32–6.34. MaxRP can be calculated for an investor who likes risk and wants to maximize his return.

6.2.2.3 Maximum Utility Optimization via MAD Model

In the MAD optimization model, the maximum utility objective function is used to find the portfolio to maximize the utility according to the investor's risk aversion level. In the MAD model, MaxUP is calculated as indicated in the formulas below.

$$Max.(U) = E(Rn(v)) - \frac{1}{2} w(v) \tag{6.35}$$

s.t.

$$\sum_{j=1}^{n} v_j = 1 \tag{6.36}$$

$$0 \le v_j \le 1, \ [j = 1, 2, \ldots, \mathrm{n}] \tag{6.37}$$

By using Eqs. 6.35–6.37, the utility to be obtained by the investor according to the risk aversion request can be maximized in the MAD model.

6.2.3 Optimization via SR Approach

Investors want to evaluate the performance of the portfolio they have created. There are multiple approaches used for portfolio performance measurement in the literature. The investor can choose one of these performance measurement approaches or use more than one approach according to their needs. SR portfolio performance evaluation model, which has been brought to the literature by W.F. Sharpe, is a performance indicator preferred by investors and used frequently. When performing performance evaluation, it takes into account the portfolio's expected return, the risk-free asset's return, and the portfolio's risk [9, 19]. The SR represents the extra return that the investor demands at the risk-free interest rate in response to the real risk of creating the portfolio. A high SR indicates that the performance of the investment is suitable based on risk-based return, while a low ratio indicates an unsuccessful performance. Since it is the ratio used to measure the performance according to the risk taken by investors, it allows investment by choosing a portfolio with high performance. SR is calculated as specified in the formula:

$$SR_p = \frac{r_p - r_f}{\sigma_p} \tag{6.38}$$

"SR_p" represents the portfolio's Sharpe ratio, "r_p" represents the portfolio's return, "r_f" represents the risk-free asset's return, "σ_p" represents the risk of the portfolio.

6.2.3.1 MSRP Optimization via MV Model

In the MV optimization model, the objective function is used to maximize the Sharpe ratio in order to find the portfolio with the highest Sharpe ratio. The MSRP in the MV model is calculated as stated in the following formulas for an investor who wishes to invest in the portfolio with the highest Sharpe ratio [9, 12, 36, 48]:

$$Max.(SR) = \frac{E\left(Rn_p\right) - r_f}{\sigma_p^2} \tag{6.39}$$

s.t.

$$\sum_{i=1}^{n} Wt_i = 1 \tag{6.40}$$

$$0 \leq Wt_i \leq 1, \; [i = 1, 2, \ldots, \mathrm{n}] \tag{6.41}$$

r_f represents the rate of the risk-free asset's return.

Using Eqs. 6.39–6.41, the portfolio's Sharpe ratio can be maximized in the MV model. The MSRP can be calculated for the investor who prefers the portfolio maximizes the Sharpe ratio.

6.2.3.2 MSRP Optimization via MAD Model

In order to find the portfolio with the maximum Sharpe ratio in the MAD optimization model, the objective function is used to maximize the Sharpe ratio. For the investor who wants to invest in the portfolio with the highest Sharpe ratio, the MSRP in the MAD model is calculated as indicated in the formulas below:

$$Max.(SR) = \frac{E(Rn(v)) - r_f}{w(v)} \tag{6.42}$$

s.t.

$$\sum_{j=1}^{n} v_j = 1 \tag{6.43}$$

$$0 \leq v_j \leq 1, \ [j = 1, 2, \ldots, \mathrm{n}] \tag{6.44}$$

r_f represents the rate of the risk-free asset's return.

Using Eqs. 6.42–6.44, the portfolio's Sharpe ratio can be maximized in the MV model, and the MSRP can be calculated for the investor who prefers the portfolio that maximizes the Sharpe ratio.

6.3 Renewable Energy Potential of Turkey

A large proportion of Turkey's energy demand is based on fossil resources such as oil, natural gas, and coal. However, due to being away from fossil resources to meet all our needs and not cause environmental pollution globally, Turkey has become a topical issue. Turkey does not have adequate reserves of fossil resources. Therefore, it is dependent on the outside in energy. Increasing environmental awareness and sensitivity to energy supply security have made renewable energy sources necessary [26].

Turkey has assessed the possible extent to add value to the various renewable energy sources' economy. The fact that the potential is not fully utilized puts pressure on the country's economy and causes adverse effects on the ecosystem, especially air pollution and climate change [27].

Turkey's total installed capacity of 48.546 MWe power plants generating electricity with renewable resources. The total installed power of the power plants where fossil resources are used is 46.255 MWe. As can be seen, 51.2% of the total installed electrical energy power belongs to renewable energy resources [15].

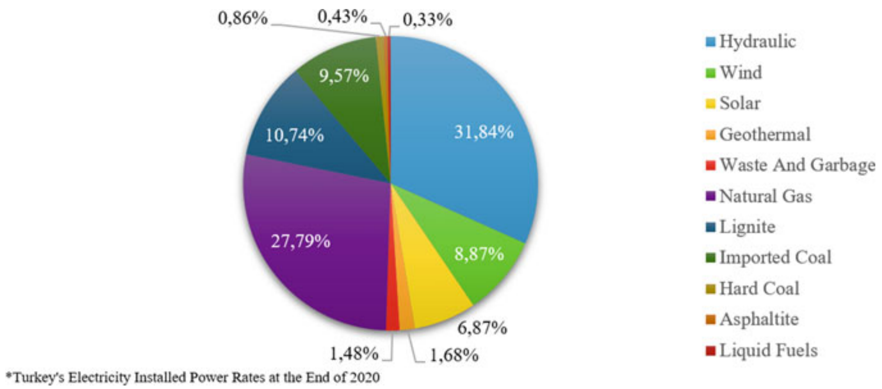

Fig. 6.2 Electricity installed power rates of Turkey by resources [15]

As seen in Fig. 6.2, electricity power installed power plants' capacity in Turkey, the highest type 31.84% (30.548 MWe) with hydraulic power plants. Considering the installed power of renewable energy sources, after hydraulic power plants, the installed power ratio of wind power plants is 8.87% (8.507 MWe), the installed power ratio of solar power plants is 6.87% (6.513 MWe), the installed power ratio of geothermal power plants is 1.68% (1.556 MWe), and the installed power ratio of power plants where waste resources are used is 1.48% (1.422 MWe). The installed power ratio of power plants producing electricity with fossil fuels is 48.8% [15].

By the end of 2020, electricity produced from renewable energy sources in Turkey is 129.358 GWh. The amount of electricity obtained by using fossil resources is 175.810 GWh. 42.38% of the total electricity generation was provided by renewable resources [15]. Electricity generation rates according to sources are shown in Fig. 6.3.

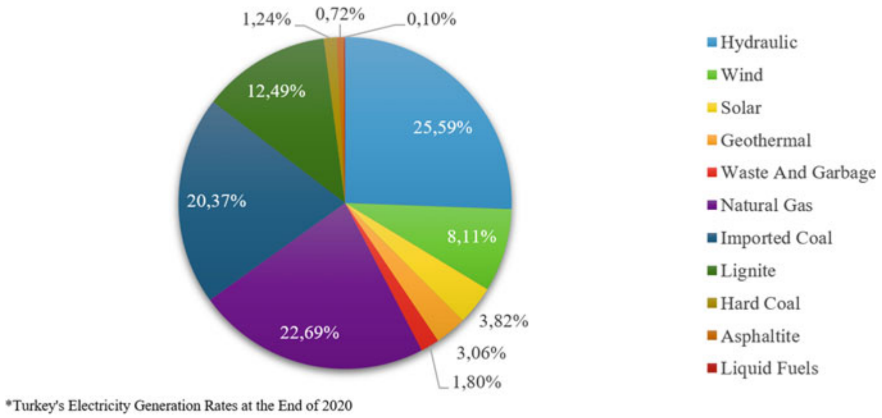

Fig. 6.3 Electricity generation rates of Turkey by resources [15]

Figure 6.3 shows that the plant type that the highest electricity generation in Turkey is hydraulic power plants with generation 78.104 GWh (25.59%). The second was wind power plants with 24.760 GWh (8.11%), the third was solar power plants with 11.645 GWh (3.82%), fourth was geothermal power plants with 9.344 GWh (3.06%), and last was waste power plant 5.505 GWh (1.08%). 42.38% of the total electrical energy was produced from renewable energy sources and 58.62% from non-renewable energy sources [15]. With incentives, electricity generation from renewable energy sources is rising day by day, and climate change is tried to be prevented with environmentally friendly resources.

6.3.1 Hydraulic Energy Resources in Turkey

Hydraulic energy is among the renewable energy resources used to generate electricity from the existing potential energy of water by accumulating the river in reservoirs through power plants [1]. The most widespread use of hydroelectric energy, a renewable energy source, is to accumulate water in a large area by building dams on rivers and generating electrical energy by using the energy caused by water [26].

Hydraulic power plants have advantages such as low operating cost and no waste or CO_2 emissions. It contributes significantly to global electricity generation [8].

Turkey has 1.5% of the hydropower potential in the world. This potential has turned into an advantage during the production phase. Hydraulic resources are the most significant share of renewable energy sources in Turkey. Hydroelectricity has a price-balancing role in producing expensive electricity cheaply. This renewable energy, a non-imported renewable energy source, has an important place in meeting the country's energy needs [26].

As seen in Table 6.2, 78.104 GWh of electrical energy using hydraulic sources by the end of 2020 is manufactured in Turkey. 25.59% of the electricity production was produced by using hydraulic resources. The most significant proportion of electricity generation belongs to hydraulic power plants using renewable energy sources. The ratio of hydraulic power plants to the total installed power is 31.84%, and their total installed power is 30.548 MWe. The number of the registered hydraulic power plant in Turkey is 672 [13, 15].

Table 6.2 HPP profile of Turkey [13, 15]

Number of registered power plants	672
HPP installed power	30.548 MWe
Installed power ratio	31.84%
Annual electricity generation	~78.104 GWh
The ratio of generation to consumption	25.59%

6.3.2 Wind Energy Resources in Turkey

Wind energy, which is the fastest-growing renewable energy source in recent years, does not cause warming in the atmosphere. CO_2 and other harmful gases cause acid rain to enter the atmosphere. It is a vital resource that does not cause climate change and does not affect natural vegetation and human life. It also reduces the use of fossil resources that have harmful effects. Wind energy, which does not create a radioactive effect, is clean and at the same time an endless source of energy. In addition to all these advantages, wind energy is produced through turbines that can be assembled and disassembled quickly and is a rapidly developing resource [47]. Wind, one of the essential sources among renewable energy sources due to these features, is a type of energy caused by the sun's radiation creating extra heat on different ground surfaces. The resulting temperature differences result in the movement of the air mass and cause the formation of wind. The wind is the flow of air from high-pressure regions to low-pressure regions. The conversion of this current into electrical energy is carried out by wind turbines [32].

Wind energy, which is accepted as an indirect product of the sun, consists of 2% of the solar energy coming to the earth. Wind turbines used to provide the energy obtained from the airflow have a life of around 25 years. Productivity needs to be produced by paying attention to factors such as the wind speed above a certain level in order to be able to make products and being located close to the transformer centers or lines used to transmit energy [47].

The wind is an inexhaustible source of energy that is not affected by fluctuations in fuel prices. This feature provides a substantial advantage that can contribute to the energy security of countries. Wind energy is among the alternative sources that will diversify the electricity supply portfolios, which can mean that it can lead to relatively more stable energy prices and offer cheaper electricity use for end-users in the long run [38].

Peninsula, which is in a good position in geopolitical terms of wind energy potential in Turkey. Among OECD countries, Turkey is the highest wind energy potential. Turkey's ground level in areas 50 m height 7.5 m/s wind speed above has established and can wind power plants of 5 MW per square kilometer in these areas [26].

As seen in Table 6.3, 24.760 GWh of electricity from wind power plants by the end of 2020 is manufactured in Turkey. 8.11% of the electricity production was produced from wind energy. The ratio of wind power plants to total installed power is 8.87%, and their total installed power is 8.507 MWe. The registered number of wind power plants in Turkey is 258 [14, 15].

Table 6.3 WPP profile of Turkey [14, 15]

Number of registered power plants	258
WPP installed power	8.507 MWe
Installed power ratio	8.87%
Annual electricity generation	~24.760 GWh
The ratio of generation to consumption	8.11%

6.4 Data and Analysis

Hydraulic and wind power plants were used in the study to encourage electricity suppliers to add renewable resources to their generation portfolio and thus contribute to the prevention of climate change. The MV and MAD optimization models and SR optimization have been applied to specific hydraulic and wind power plants in the Turkey electricity market. For optimization, EPİAŞ DAM MCP data were used.

For the last five years (01.01.2016–31.12.2020), actual MCP data, a total of 1827 days, were used in the study [16]. Since there are different spot sales prices for 24 h a day, 24 h, 24 other risky assets have been selected to solve the portfolio selection problem. The total number of data used for optimizations is 43.848.

Before starting the optimization studies, statistical analysis was made for 24 risky assets. Within the scope of the analysis, mean, std. deviation, skewness, kurtosis, and median values were calculated and shown in Table 6.4.

Hydraulic and wind power plant unit production costs are used to calculate the return rate for each risky asset. Hourly rate of return to be used for optimization with MCP data and unit production costs, different from finance literature Liu and Wu, Gökgöz and Atmaca, and deLlano-Paz et al. regarding approaches previously applied for electricity markets [12, 20, 21, 36].

$$rt_{n,m} = \frac{\left(a_{n,m} - C_{h,w}\right)}{C_{h,w}},\ (n = 1, \ldots, 24),\ (m = 1, \ldots, 1827) \tag{6.45}$$

$a_{n,m}$ represents nth hour of mth day day-ahead price, $C_{h,w}$ represents the average generation cost for hydraulic and wind power plants, and $rt_{n,m}$ represents the hourly rate of return for the electric spot market.

$$\overrightarrow{rt_1} = \begin{bmatrix} rt_{1,1} \\ rt_{1,2} \\ \vdots \\ \vdots \\ rt_{1,1827} \end{bmatrix},\ \overrightarrow{rt_2} = \begin{bmatrix} rt_{2,1} \\ rt_{2,2} \\ \vdots \\ \vdots \\ rt_{3,1827} \end{bmatrix},\ \overrightarrow{rt_3} = \begin{bmatrix} rt_{3,1} \\ rt_{3,2} \\ \vdots \\ \vdots \\ rt_{3,1827} \end{bmatrix}, \cdots,\ \overrightarrow{rt_{24}} = \begin{bmatrix} rt_{24,1} \\ rt_{24,2} \\ \vdots \\ \vdots \\ rt_{24,1827} \end{bmatrix} \tag{6.46}$$

$\overrightarrow{rt_n}\,[n = 1, \ldots, 24]$ represents the vector of the rate of return for each hour.

As shown in Eqs. 6.39, and 6.40, the rate of return in the electricity markets is calculated using actual DAM MCP data and the unit electricity generation costs of hydraulic and wind power plants that generate electricity with renewable energy sources. The expected return rate, standard deviation, and covariance matrix for

Table 6.4 The risky assets' descriptive statistics

Hour	Mean $/MWh	Std. deviation	Skewness	Kurtosis	Median $/MWh
0	44.85	11.55	−0.903	2.304	45.11
1	43.41	10.76	−1.029	2.846	43.79
2	39.22	11.69	−0.750	1.411	39.63
3	35.06	13.01	−0.736	0.715	36.16
4	33.28	13.33	−0.676	0.450	34.47
5	33.22	13.36	−0.592	0.502	33.66
6	34.05	15.12	−0.696	0.150	35.66
7	39.59	14.32	−1.053	1.007	41.87
8	45.96	13.87	−1.388	2.283	49.17
9	49.02	15.22	−0.703	7.551	53.93
10	50.50	14.95	1.312	35.709	54.07
11	52.12	14.95	2.926	68.334	54.62
12	46.21	14.81	1.615	37.934	46.89
13	47.64	14.27	0.425	16.404	48.7
14	50.35	18.34	11.385	297.218	52.26
15	49.14	16.07	6.737	169.894	50.81
16	49.41	13.68	0.718	19.374	51.07
17	49.08	14.55	4.734	93.052	50.18
18	48.94	11.79	1.234	28.573	50.15
19	49.95	9.47	0.353	9.699	51.03
20	50.49	8.20	0.767	10.167	51.43
21	49.27	7.89	−0.192	0.736	49.58
22	46.30	9.38	−0.421	1.454	46.41
23	42.26	10.97	−0.812	1.780	42.46

Source Descriptive statistics depends upon Authors' calculations

each risky asset are calculated as follows by taking into account the studies of Gökgöz and Atmaca [20, 21].

$$\overline{rt_n} = \frac{1}{1827}\left(\sum_{m=1}^{1827} rt_{n,m}\right) \tag{6.47}$$

$$\sigma_n = \sqrt{\frac{1}{1827}\sum_{m=1}^{1827}\left(rt_{n,m} - \overline{rt_n}\right)^2} \tag{6.48}$$

$$\sigma_{x,y} = \frac{1}{1827}\sum_{m=1}^{1827}\left(rt_{x,m} - \overline{rt_x}\right)\left(rt_{y,m} - \overline{rt_y}\right) \tag{6.49}$$

$$Covariance\ Matrix = \begin{bmatrix} \sigma_1^2 & \sigma_{1,2} & \cdots & \sigma_{1,24} \\ \sigma_{2,1} & \sigma_2^2 & & \\ \vdots & & \ddots & \\ \sigma_{24,1} & & & \sigma_{24}^2 \end{bmatrix} \tag{6.50}$$

This study produces electricity with renewable energy sources in Turkey's electricity market for hydraulic and wind power plants, the MV and MAD optimization models and SR optimization are performed. For the optimization results to be reliable, MCP data of the last five years (01.01.2016–31.12.2020) in total were used for 1827 days. Since they are treated as risky assets 24 h a day, 43.848 actual sales price data are used. Using MV and MAD models, minimum risk, maximum return, and maximum utility A = 3 portfolios are calculated for both power plant types. Within the SR optimization scope, MV and MAD models and maximum Sharpe ratio portfolios were calculated for both power plant types. Within the study's content, a total of 16 portfolios were optimized, and the performance of the optimal portfolios found was calculated with the Sharpe ratio. Table 6.5 shows the qualifications of the empirical study.

The assumptions in the study are listed below:

- HPP unit electricity generation cost has been assumed to be 20 \$/MWh;
- WPP unit electricity generation cost has been assumed to be 35 \$/MWh;
- Optimizations for HPP and WPP are considered as case study 1 and case study 2, respectively.
- For seven days, both weekdays and weekends, electricity can be traded;
- For 24 h a day, electricity can be traded;
- A power outage does not exist.

Additionally, the cost of producing electricity is fixed, and electricity transmission is not tricky or congested. The market receives both bids. The system's price is unaffected by the amount of energy supplied to the market by the investor. Investors prefer a less volatile portfolio while maintaining the same level of return

Table 6.5 The qualifications of the empirical study

Theme	MV technique	MAD technique	SR technique
Investment days	Monday, Tuesday, Wednesday, Thursday, Friday, Saturday, Sunday		
Power plant types	HPP and WPP		
Generation cost of HPP	20 $/MWh [3]		
Generation cost of WPP	35 $/MWh [3]		
Market data	EPIAŞ DAM (01.01.2016–31.12.2020) 1827 days and total of 43.848 data [16]		
Risky asset's number	24		
Objective functions	MinRP, MaxRP, MSRP, MaxUP A = 3		

instead of a more volatile portfolio while retaining the same level of risk. Bids can be broken down into an infinite number of smaller bits [21].

6.4.1 Case Study 1: Optimization for HPP

As part of case study 1, portfolio optimization was performed for HPP with the MV and MAD optimization models and SR optimization. A total of 8 optimizations have been made, and the calculated optimal portfolios are presented. With this presentation, ideas were given to the electricity market decision-makers about adding hydraulic resources to their generation portfolio.

Using the HPP production cost C_h (20 \$/MWh), the average return rates and standard deviations for 24 risky assets are calculated as follows with the formulas specified in Eqs. 6.47, and 6.48.

Expected returns and standard deviations of 24 risky assets are shown in Table 6.6. When risky assets are evaluated according to their returns and risks, the following results have been reached:

- The asset with the maximum return is at the 11th hour, and the minimum return asset is at the 5th hour.
- The maximum risky asset was obtained as 14th hour and minimum risky assets as 21st hour.
- When the 24 risky assets that can form a portfolio are analyzed based on return and risk, the most productive assets are at the 19th, 20th, and 21st hours.

Table 6.6 Returns and std. deviations of the risky assets for HPP generation cost

Hour	Return (%)	Std. deviation (%)	Hour	Return (%)	Std. deviation (%)
0	124.23	57.74	12	131.05	74.05
1	117.06	53.80	13	138.22	71.32
2	96.09	58.45	14	151.77	91.67
3	75.30	65.03	15	145.71	80.32
4	66.38	66.64	16	147.07	68.40
5	66.08	66.78	17	145.40	72.72
6	70.25	75.59	18	144.69	58.93
7	97.95	71.56	19	149.77	47.32
8	129.78	69.31	20	152.45	40.98
9	145.10	76.07	21	146.36	39.46
10	152.49	74.75	22	131.47	46.87
11	160.58	74.75	23	111.31	54.85

Source Authors' calculations

6.4.1.1 MV Optimization for HPP

The MV optimization model was created for HPP using 24 risk assets. SR optimization was made with the MV optimization model, and MSRP was obtained. Besides, optimizations were made for the other three objective functions (MinRP, MaxRP, and MaxUP), and optimal portfolios were calculated. Figure 6.4 shows the effective frontier chart obtained using the MV optimization model for HPP.

As seen in Fig. 6.4, four different objective functions were applied to the MV optimization model for HPP, and four portfolios were calculated. These four portfolios are shown on an efficient frontier. The asset weights, risk, return, and Sharpe ratios of the optimal portfolios obtained are shown in Table 6.7.

For the hydraulic power plant electricity producer, four different objective functions have been applied with the MV optimization model, and the results are shown in Table 6.7.

When the producer wants to minimize the risk, he should prefer MinRP. MinRP should invest in 9 assets out of 24 risk assets according to its preference. It is required to sell 37.30% of the electricity produced by hydraulic sources in the 21st hour, 27.12% at the 20th hour, 9.20% at the 19th hour, 8.48% at the 0th hour, 6.95% at the 8th hour, 3.88% at the 4th hour, 3.51% at the 1st hour, 2.61% at the 2nd hour, 0.94% at the 6th hour. The risk value of MinRP was calculated as 36.71%, return rate 139.14%, and Sharpe ratio 3.7894.

When the producer wants to maximize its return, it should choose MaxRP. According to the MaxRP preference, it must sell 100.00% of its production at the 11th hour. As can be seen from Table 6.6, the asset with the maximum return

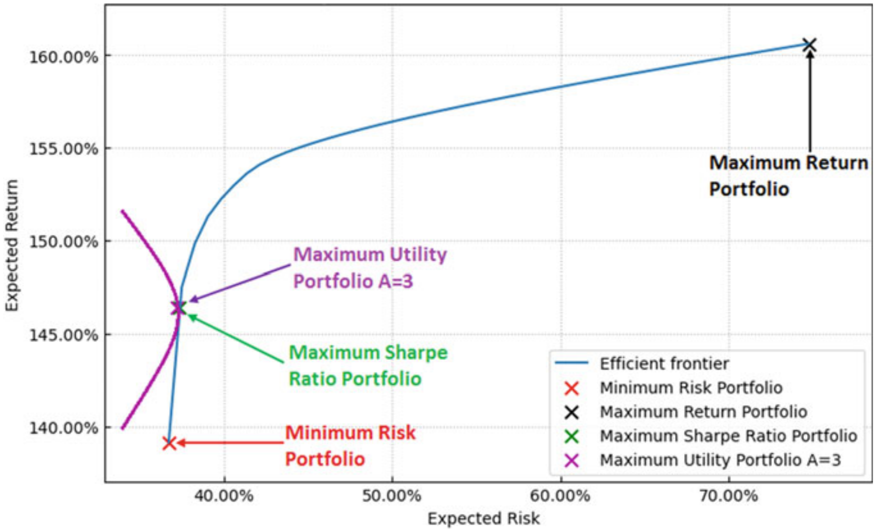

Fig. 6.4 The efficient frontier of MV and optimal portfolios for HPP. *Source* Authors' calculations

Table 6.7 MinRP, MaxRP, MSRP and MaxUP A = 3 weights, risk, return and Sharpe ratio in MV optimization model for HPP

Hour	MinRP	MaxRP	MSRP	MaxUP A = 3
0	8.48%	–	6.38%	7.49%
1	3.51%	–	–	–
2	2.61%	–	–	–
3	–	–	–	–
4	3.88%	–	–	–
5	–	–	–	–
6	0.94%	–	–	–
7	–	–	–	–
8	6.95%	–	4.31%	5.07%
9–10	–	–	–	–
11	–	100.00%	0.74%	–
12–18	–	–	–	–
19	9.20%	–	11.66%	11.63%
20	27.12%	–	36.31%	35.26%
21	37.30%	–	40.59%	40.54%
22–23	–	–	–	–
Risk	36.71%	74.75%	37.34%	37.21%
Return	139.14%	160.58%	146.95%	146.40%
Sharpe ratio	3.7894	2.1482	3.9352	3.9344

Source Authors' calculations

is the 11th hour. The risk value of MaxRP was calculated as 74.75%, return rate 160.58%, and Sharpe ratio 2.1482.

If the producer wishes to choose a portfolio with reference to the Sharpe ratio, he should prefer the MSRP that maximizes the Sharpe ratio. According to the MSRP results, it should invest in 6 assets out of 24 risky assets. 40.59% of the electricity produced by hydraulic sources at the 21st hour, 36.31% at the 20th hour, 11.66% at the 19th hour, 6.38% at the 0th hour, 4.31% at the 8th hour, 0.74% at 11 It has to sell on the hour. The risk value of the MSRP was calculated as 37.34%, the return rate as 146.95%, and the Sharpe ratio as 3.9352.

If a producer who avoids risk at an average level wants to choose a portfolio that will maximize his benefit for A = 3 level, he should prefer MaxUP. MaxUP should invest five assets out of 24 risky assets according to A = 3 results. It is required to sell 40.54% of the electricity produced by hydraulic sources at 21st hours, 35.26% at 20th hours, 11.63% at 19th hours, 7.49% at 0th hours, and 5.07% at 8th hours. The risk value of the MaxUP was calculated as 37.21%, the return rate as 149.40%, and the Sharpe ratio as 3.9344.

When four different optimal portfolios are examined, it is seen that the highest investments are made in the 19th, 20th, and 21st hours among the three optimal portfolios except for MaxRP. As shown in Table 6.6, these three risky assets are specified as the most efficient assets.

MaxUP A = 3 and MSRP optimal portfolios gave almost the same results. The MSRP's risk value and return rate are very close to the MaxUP A = 3 portfolios.

The rate of return of the MaxRP optimal portfolio has the highest rate of return as expected. The rate of return is calculated as 160.58%. However, the risk value (74.75%) is estimated to be relatively high. Therefore, the lowest Sharpe ratio among the four optimal portfolios calculated belongs to the MaxRP portfolio. The electricity producer that chooses the MaxRP portfolio has to accept the high risk.

The four optimal portfolios calculated were evaluated according to the Sharpe ratio performance criterion. As expected, according to the evaluation results, the MSRP portfolio showed the best performance with 3.9352 Sharpe ratio. According to portfolio performances, MaxUP A = 3 came second, MinRP third, and MaxRP fourth.

6.4.1.2 MAD Optimization for HPP

The MAD optimization model was created for HPP using 24 risk assets. SR optimization was made with the MAD optimization model, and MSRP was obtained. Also, MinRP, MaxRP, and MaxUP A = 3 objective functions were made optimizations, and optimal portfolios were calculated. The efficient frontier chart received when the MAD optimization model is applied for HPP is formed in Fig. 6.5.

As seen in Fig. 6.5, four different objective functions were applied to the HPP MAD optimization model, and four portfolios were calculated. These four portfolios are shown on an efficient frontier. The asset weights, risk, return, and Sharpe ratios of the optimal portfolios obtained are shown in Table 6.8.

For the hydraulic power plant electricity producer, four different objective functions have been applied with the MAD optimization model, and the results are shown in Table 6.8.

When the producer wants to minimize the risk, he should prefer MinRP. MinRP should invest in 10 assets out of 24 risk assets according to its preference. It is required to sell 31.19% of the electricity produced by hydraulic sources at the 20th hour, 26.96% at the 21st hour, 10.91% at the 4th hour, 10.88% at the 19th hour, 6.71% at the 0th hour, 5.52% at the 2nd 4.22% at the 8th hour, 3.04% at the 9th hour, 0.33% at the 11th hour and 0.25% at the 6th hour. The risk value of MinRP was calculated as 29.11%, return rate 134.76%, and Sharpe ratio 4.6298.

When the producer wants to maximize its return, it should choose MaxRP. According to the MaxRP preference, it must sell 100.00% of its production at the 11th hour. As can be seen from Table 6.6, the asset with the maximum return is the 11th hour. The risk value of MaxRP was calculated as 47.52%, return rate 160.58%, and Sharpe ratio 3.3787.

If the producer wishes to choose a portfolio regarding the Sharpe ratio, he should prefer the MSRP that maximizes the Sharpe ratio. According to the MSRP results, it should invest in 5 assets out of 24 risk assets. It is required to sell 37.86% of the electricity produced by hydraulic resources at 21st hours, 30.27% at 20th hours,

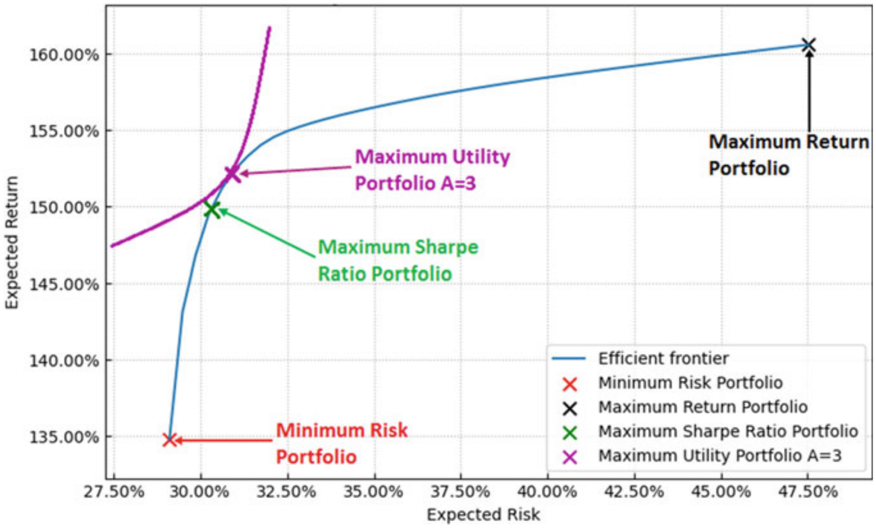

Fig. 6.5 The efficient frontier of MAD and optimal portfolios for HPP. *Source* Authors' calculations

Table 6.8 MinRP, MaxRP, MSRP and MaxUP A = 3 weights, risk, return and Sharpe ratio in MAD optimization model for HPP

Hour	MinRP	MaxRP	MSRP	MaxUP A = 3
0	6.71%	–	4.93%	–
1	–	–	–	–
2	5.52%	–	–	–
3	–	–	–	–
4	10.91%	–	–	–
5	–	–	–	–
6	0.25%	–	–	–
7	–	–	–	–
8	4.22%	–	–	–
9	3.04%	–	–	–
10	–	–	–	–
11	0.33%	100.00%	12.88%	16.67%
12–18	–	–	–	–
19	10.88%	–	14.06%	9.44%
20	31.19%	–	37.86%	50.46%
21	26.96%	–	30.27%	23.44%
22–23	–	–	–	–
Risk	29.11%	47.52%	30.31%	30.89%
Return	134.76%	160.58%	149.88%	152.12%
Sharpe ratio	4.6298	3.3787	4.9439	4.9245

Source Authors' calculations

14.06% at 19th hours, 12.88% at 11th hours, and 4.93% at 0th hours. The risk value of the MSRP has been calculated as 30.31%, the return rate as 149.88%, and the Sharpe ratio as 4.9439.

If a producer who avoids risk at an average level wants to choose a portfolio that will maximize his benefit for A = 3 level, he should prefer MaxUP. It should invest in 4 assets out of 24 risky assets according to MaxUP A = 3 results. It is required to sell 50.46% of the electricity produced by hydraulic sources at the 20th hour, 23.44% at the 21st hour, 9.44% at the 19th hour, and 16.67% at the 11th hour. The risk value of the MaxUP is calculated as 30.89%, the return rate as 152.12%, and the Sharpe rate as 4.6298.

The rate of return of the MaxRP optimal portfolio has the highest rate of return as expected. The rate of return is calculated as 160.58%. However, the risk value (47.52%) is calculated to be relatively high. Therefore, the lowest Sharpe ratio among the four optimal portfolios calculated belongs to the MaxRP portfolio. The electricity producer that chooses the MaxRP portfolio has to accept the high risk.

The four optimal portfolios calculated were evaluated according to the Sharpe ratio performance criterion. As expected, according to the evaluation results, the MSRP portfolio showed the best performance with a ratio of 4.9439 Sharpe. According to portfolio performances, MaxUP A = 3 came second, MinRP third, and MaxRP fourth.

6.4.2 *Case Study 2: Optimization for WPP*

Within the scope of case study 2, portfolio optimization was performed for WPP with the MV and the MAD and SR optimization models. A total of 8 optimizations have been made, and the calculated optimal portfolios are presented. With this presentation, ideas were given to electricity market decision-makers about adding wind energy to their generation portfolio.

Using the WPP production cost C_w (35 \$/MWh), the average return rates and standard deviations for 24 risky assets are calculated with the formulas specified in Eqs. 6.47 and 6.48.

Table 6.9 shows the expected returns and standard deviations of 24 risky assets. When risky assets are evaluated according to their returns and risks, the following results have been reached:

- Assets with the maximum return are calculated as 11th hour, and assets with minimum returns are calculated as 5th and 4th hours.
- The maximum risky asset is calculated as the 14th hour and the minimum risky asset as the 21st hour.
- When the 24 risky assets that can form a portfolio are analyzed based on return and risk, the most productive assets are at the 19th, 20th, and 21st hours.
- The 4th, 5th, and 6th hours bring negative returns.

Table 6.9 Returns and std. deviations of the risky assets for WPP generation cost

Hour	Return (%)	Std. deviation (%)	Hour	Return (%)	Std. deviation (%)
0	28.13	32.99	12	32.03	42.31
1	24.03	30.74	13	36.12	40.75
2	12.05	33.40	14	43.86	52.38
3	0.00	37.16	15	40.41	45.89
4	−0.05	38.08	16	41.18	39.08
5	−0.05	38.16	17	40.23	41.55
6	−0.02	43.19	18	39.82	33.67
7	13.11	40.89	19	42.72	27.04
8	31.30	39.60	20	44.26	23.41
9	40.06	43.47	21	40.77	22.54
10	44.28	42.71	22	32.27	26.78
11	48.90	42.71	23	20.75	31.34

Source Authors' calculations

6.4.2.1 MV Optimization for WPP

The MV optimization model was created for WPP using 24 risk assets. SR optimization was made with the MV optimization model, and MSRP was obtained. Besides, optimizations were made for the other three objective functions (MinRP, MaxRP, and MaxUP), and optimal portfolios were calculated. The efficient frontier graph obtained when the MV optimization model is applied for WPP is formed in Fig. 6.6.

As seen in Fig. 6.6, four different objective functions were applied to the MV optimization model for WPP, and four portfolios were calculated. These four optimal portfolios are shown on the efficient frontier. The asset weights, risk, return, and Sharpe ratios of the optimal portfolios obtained are shown in Table 6.10.

For the wind power plant electricity producer, four different purpose functions have been applied with the MV optimization model, and the results are shown in Table 6.10.

The electricity producer who does not like the risk and wants to minimize the risk should prefer MinRP. MinRP should invest in 9 assets out of 24 risk assets according to its preference. It should sell 37.30% of the electricity generated by wind at 21st hour, 27.12% at 20th hour, 9.20% at 19th hour, 8.48% at 0th hour, 6.95% at 8th hour, 3.88% at 4th hour. 3.51% at the 1st hour, 2.61% at the 2nd hour, 0.94% at the 6th hour. The risk value of MinRP is calculated as 20.98%, return rate 36.65%, and Sharpe ratio 1.7468.

The electricity producer who wants to maximize its return should prefer MaxRP. According to the MaxRP preference, it is required to sell 100.00% of its production at the 11th hour. As can be seen from Table 6.9, the asset with the maximum return is the 11th hour. The risk value of MaxRP was calculated as 42.71%, return rate 48.90%, and Sharpe ratio 1.1449.

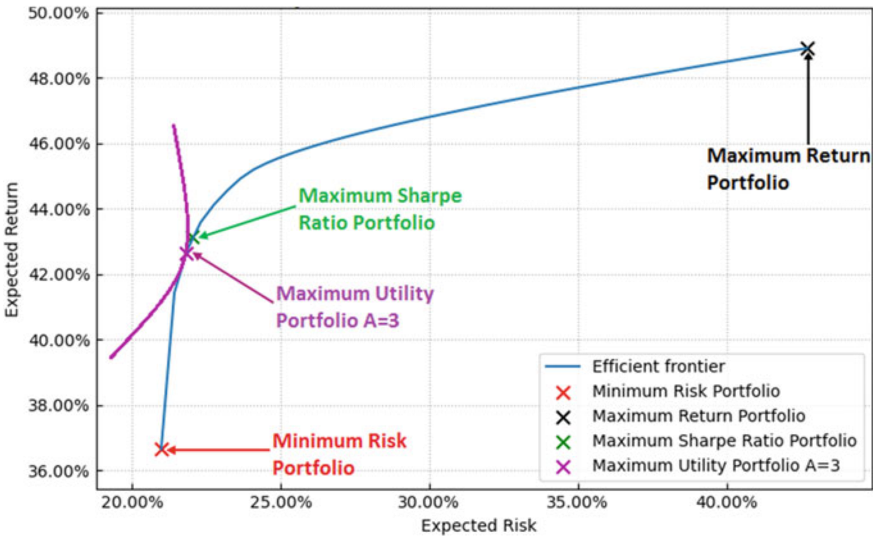

Fig. 6.6 The efficient frontier of MV and optimal portfolios for WPP. *Source* Authors' calculations

Table 6.10 MinRP, MaxRP, MSRP and MaxUP A = 3 weights, risk, return and Sharpe ratio in MV optimization model for WPP

Hour	MinRP	MaxRP	MSRP	MaxUP A = 3
0	8.48%	–	–	1.12%
1	3.51%	–	–	–
2	2.61%	–	–	–
3	–	–	–	–
4	3.88%	–	–	–
5	–	–	–	–
6	0.94%	–	–	–
7	–	–	–	–
8	6.95%	–	–	0.36%
9–10	–	–	–	–
11	–	100.00%	6.89%	5.26%
12–18	–	–	–	–
19	9.20%	–	10.53%	11.79%
20	27.12%	–	45.89%	40.15%
21	37.30%	–	36.69%	41.32%
22–23	–	–	–	–
Risk	20.98%	42.71%	22.03%	21.83%
Return	36.65%	48.90%	43.14%	42.65%
Sharpe ratio	1.7468	1.1449	1.9578	1.9540

Source Authors' calculations

According to the Sharpe ratio, the electricity producer who wants to choose the portfolio with the best performance should prefer MSRP. According to the MSRP results, it should invest in 4 assets out of 24 risky assets. It is required to sell 45.89% of the electricity produced by the wind at the 20th hour, 36.69% at the 21st hour, 10.53% at the 19th hour, and 6.89% at the 11th hour. The risk value of the MSRP is calculated as 22.03%, return rate 43.14%, and Sharpe ratio 1.9578.

If the electricity producer wants to maximize its utility for A = 3 level, it should prefer MaxUP. MaxUP should invest 6 assets out of 24 risky assets according to A = 3 results. It should sell 41.32% of the electricity generated by the wind at 21st hour, 40.15% at 20th hour, 11.79% at 19th hour, 5.26% at 11th hour, 1.12% at 0th hour, and 0.36% at 8th hour. The risk value of the MaxUP was calculated as 21.83%, the return rate as 42.65%, and the Sharpe ratio as 1.9540.

The four optimal portfolios calculated were evaluated according to the Sharpe ratio performance criterion. As expected, according to the evaluation results, the MSRP portfolio showed the best performance with a ratio of 1.9578 Sharpe. Performance of MaxUP A = 3 was very close to MSRP. According to portfolio performances, MaxUP A = 3 came second, MinRP third, and MaxRP fourth.

6.4.2.2 MAD Optimization for WPP

The MAD optimization model was created for WPP using 24 risk assets. SR optimization was made with the MAD optimization model, and MSRP was obtained. Also, MinRP, MaxRP, and MaxUP A = 3 objective functions were made optimization, and optimal portfolios were calculated. The efficient frontier graph obtained when the MAD optimization model is applied for WPP is formed in Fig. 6.7.

As seen in Fig. 6.7, four different objective functions were applied to the MAD optimization model for WPP, and four portfolios were calculated. These four portfolios are shown on the efficient frontier. The asset weights, risk, return, and Sharpe ratios of the optimal portfolios obtained are shown in Table 6.11.

For the wind power plant electricity producer, four different objective functions have been applied with the MAD optimization model, and the results are shown in Table 6.11.

The electricity producer who wants to invest in a portfolio with minimum risk should prefer MinRP. MinRP should invest in 10 assets out of 24 risk assets according to its preference. It should sell 31.19% of the electricity generated by wind at the 20th hour, 26.96% at the 21st hour, 10.91% at the 4th hour, 10.88% at the 19th hour, 6.71% at the 0th hour, 5.52% at the 2nd hour. It should sell 4.22% at the 8th hour, 3.04% at the 9th hour, 0.33% at the 11th hour, and 0.25% at the 6th hour. The risk value of MinRP was calculated as 16.63%, return rate 34.15%, and Sharpe ratio 2.0532.

The electricity producer that wants maximum return should prefer MaxRP. According to the MaxRP preference, it is required to sell 100.00% of its

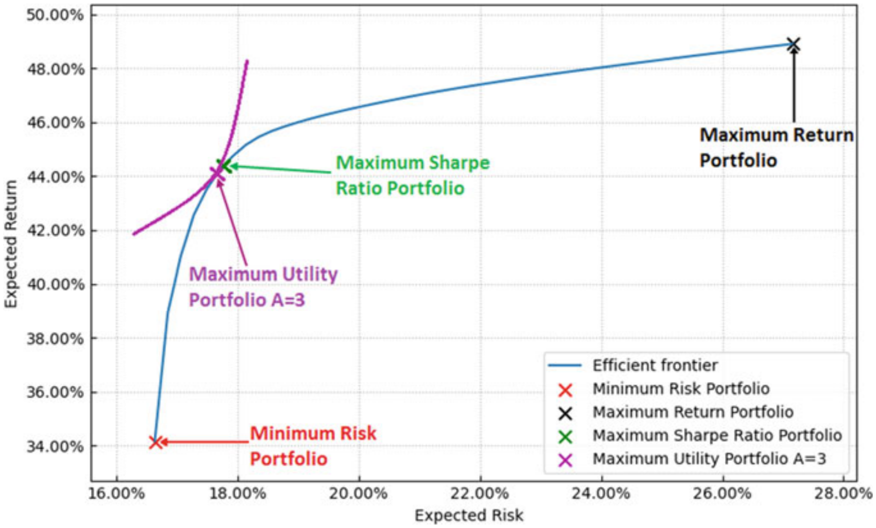

Fig. 6.7 The efficient frontier of MAD and optimal portfolios for WPP. *Source* Authors' calculations

Table 6.11 MinRP, MaxRP, MSRP and MaxUP A = 3 weights, risk, return and Sharpe ratio in MAD optimization model for WPP

Hour	MinRP	MaxRP	MSRP	MaxUP A = 3
0	6.71%	–	–	–
1	–	–	–	–
2	5.52%	–	–	–
3	–	–	–	–
4	10.91%	–	–	–
5	–	–	–	–
6	0.25%	–	–	–
7	–	–	–	–
8	4.22%	–	–	–
9	3.04%	–	–	–
10	–	–	–	–
11	0.33%	100.00%	17.86%	16.67%
12–18	–	–	–	–
19	10.88%	–	8.61%	9.44%
20	31.19%	–	56.89%	50.46%
21	26.96%	–	16.64%	23.44%
22–23	–	–	–	–
Risk	16.63%	27.15%	17.76%	17.65%
Return	34.15%	48.90%	44.37%	44.07%
Sharpe ratio	2.0532	1.8007	2.4981	2.4965

Source Authors' calculations

production at the 11th hour. The risk value of MaxRP was calculated as 27.15%, return rate 48.90%, and Sharpe rate 1.8007.

The electricity producer who wants to maximize the Sharpe ratio should prefer MSRP. According to the MSRP results, it should invest in 4 assets out of 24 risky assets. It is required to sell 56.89% of the electricity produced by the wind at the 20th hour, 16.64% at the 21st hour, 17.86% at the 11th hour, and 8.61% at the 19th hour. The risk value of the MSRP is 17.76%, the return rate is 44.37%, and the Sharpe ratio is 2.4981.

If the electricity producer with A = 3 risk aversion level wants to maximize its benefit, it should choose MaxUP. MaxUP should invest in 4 assets out of 24 risky assets according to A = 3 results. It should sell 50.46% of the electricity produced by the wind at the 20th hour, 23.44% at the 21st hour, 16.67% at the 11th hour, and 9.44% at the 19th hour. The risk value of MaxUP is calculated as 17.65%, return rate 44.07%, and Sharpe ratio 2.4965.

The four optimal portfolios calculated were evaluated according to the Sharpe ratio performance criterion. As expected, the MSRP portfolio showed the best performance with a Sharpe ratio of 4.4981, as was the MV optimization case. According to portfolio performances, MaxUP A = 3 came second, MinRP third, and MaxRP fourth.

6.4.3 Comparing the Optimal Portfolios Performances

For electricity suppliers with HPP and WPP in their electricity generation portfolio, 16 different optimizations in total were made with MV and MAD optimization models and four different objective functions (MinRP, MaxRP, MSRP, and MaxUP A = 3). The optimal portfolios' performance obtained as a result of the optimizations was measured with the Sharpe ratio. 24 risky assets were used in the study, risk-free assets (bilateral contracts) were not included. Therefore, r_f is taken "0" in the calculations. Optimal portfolios were compared according to renewable electricity generation sources (HPP and WPP) and optimization models (MV and MAD).

6.4.3.1 Comparing the Optimal Portfolios Performances for HPP and WPP

In the study, a total of 16 optimizations were performed for HPP and WPP using MV and MAD optimization models separately. Sharpe ratios of 16 optimal portfolios obtained due to the optimizations were calculated and shown in Table 6.12.

Table 6.12 The Sharpe ratios of the HPP and WPP optimal portfolios

Optimal portfolios	HPP	WPP
MinRP − MV	3.7894	1.7468
MinRP − MAD	4.6298	2.0532
MaxRP − MV	2.1482	1.1449
MaxRP − MAD	3.3787	1.8007
MaxUP A = 3 − MV	3.9344	1.9540
MaxUP A = 3 − MAD	4.9245	2.4967
MSRP − MV	3.9352	1.9578
MSRP − MAD	4.9439	2.4981
Average Sharpe ratio	3.9605	1.9565

Source Authors' calculations

Performance comparisons of portfolios calculated for HPP and WPP according to Table 6.12 are as follows:

- Among the optimizations made for HPP and WPP, MSRP, which maximizes the Sharpe ratio, showed the best performance as expected.
- HPP results gave better results in all eight optimizations made separately for HPP and WPP.
- The lowest performance portfolio for HPP and WPP is MaxRP realized with the MV model.
- The highest performance portfolio for HPP and WPP is MSRP realized with the MAD model.
- HPP optimal portfolios performed better than WPP optimal portfolios. The average Sharpe ratio performance of the eight optimal portfolios shown in Table 6.12 is 3.9605 for HPP and 1.9565 for WPP. As a result, HPP optimal portfolios are more efficient than WPP optimal portfolios.
- HPP unit electricity production cost is lower than WPP. Portfolio performance decreases when the cost of electricity generation increases. The cost of electricity generation and portfolio performance are inversely proportional.

6.4.3.2 Comparing the MV and MAD Optimal Portfolios Performances

In the study, MV and MAD optimization models were applied with four different objective functions for HPP and WPP. In total, 16 optimizations were carried out. The Sharpe ratios of 16 optimal portfolios obtained due to the optimizations were calculated and shown in Table 6.13.

Table 6.13 The Sharpe ratios of the MV and MAD optimal portfolios

Optimal portfolios	MV Model	MAD Model
MinRP − HPP	3.7894	4.6298
MinRP − WPP	1.7468	2.0532
MaxRP − HPP	2.1482	3.3787
MaxRP − WPP	1.1449	1.8007
MaxUP A = 3 − HPP	3.9344	4.9245
MaxUP A = 3 − WPP	1.9540	2.4967
MSRP − HPP	3.9352	4.9439
MSRP − WPP	1.9578	2.4981
Average Sharpe ratio	2.5763	3.3407

Source Authors' calculations

Performance comparisons of portfolios calculated for MV and MAD according to Table 6.13 are as follows:

- The portfolios with the highest performance among MV and MAD optimizations are MSRP as expected.
- Among MV and MAD optimizations, the portfolio with the lowest performance is MaxRP − WPP.
- Among MV and MAD optimizations, the portfolio with the highest performance is MSRP − HPP.
- MSRP and MaxUP A = 3 performances gave very similar results in MV and MAD optimizations. An average risk-averse investor's portfolio preferences and an investor who wants to maximize the Sharpe ratio are very close.
- MAD optimal portfolios performed better than MV optimal portfolios. The average Sharpe Ratio performance of the eight optimal portfolios shown in Table 6.13 is calculated as 2.5763 for MV and 3.3407 for MAD. As a result, MAD optimal portfolios are more efficient than the MV model.

6.5 Conclusion

Electric energy is an indispensable product for human life. Fossil and renewable energy sources are used for electricity generation. Electricity generated by both types of sources cannot be stored. Therefore, electricity must be used effectively and efficiently. Electricity producers face operational and market risks. They should determine their market and investment policies well, taking into account the market conditions and risks. They should optimize their production capacities and market bid strategies with the determined policies.

The damage caused by the electricity generated by using fossil sources to the environment causes climate change. Besides, since fossil resources are depleted resources, many countries encourage electricity market decision makers to add renewable energy resources to their generation portfolios. Therefore, HPP and WPP were used in the study to emphasize the importance of using renewable energy sources in electricity generation.

In this empirical study, the MV and MAD optimization models and SR optimization were applied in the Turkish electricity market. A total of 16 optimizations were performed with four different objective functions (MinRP, MaxRP, and MSRP and MaxUP $A = 3$) for HPP and WPP with both models. Ideas are presented in the study so that electricity producers who add HPP and WPP to their generation portfolio can determine their bidding strategies.

The following are the findings of the empirical study:

- The portfolios obtained as a result of 16 optimizations were analyzed. The weights of the portfolios that make up the portfolios and the portfolios' risks and returns were shown in the study. It has been observed that the optimal portfolio solutions obtained with two different optimization models differ according to the four different objective functions offered to electricity generators. It is thought that showing these changes will contribute to the decision-making process of decision-makers.
- Portfolio performances separately for both models and both power plants were measured with SR and compared with each other. As a result of the comparison between models, it has been shown in an empirical study that MAD optimal portfolios and HPP based on power plants give better results.
- In the study, MV and MAD models were applied using HPP and WPP unit electricity generation cost, and ideas were given to the electricity producers to decide. These models can also be applied to power plants with different unit electricity generation costs, and by evaluating the results, electricity producers can contribute to shaping their generation portfolios.

As a result, in this empirical study, it has been shown that the MV and MAD optimization models and SR optimization used for portfolio optimization in finance literature can be adapted to electricity markets. It is explained in detail that these models, which are adapted to the electricity markets, will provide many benefits to the energy market players at the point of decision-making. The study's findings would make significant contributions to the literature on portfolio optimization in electricity markets.

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Chapter 7
Policy Responses to Climate Change: Lessons from Covid and Other Historical Crises

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Abstract This chapter examines the likelihood that policy makers—particularly in the United States—will be able to proactively take effective steps to minimize the adverse effects of global climate change. Through the examination of historical case studies, and an in-depth examination of policy responses to the ongoing Covid-19 pandemic, we argue that crisis situations are often the most effective drivers of transformative policy action. Only when the populace perceives climate change as an immediate existential crisis will they demand immediate effective action. At that point, solar radiation management (SRM) will likely be the only solution that will offer immediate results in addressing the long-term problem of atmospheric global heating.

Keywords Climate crisis · Climate change · Covid-19 · Pandemic · Vaccines · Policy · Anti-Slavery · Abolition movement · US Civil War · Emancipation · Geoengineering · Solar Radiation Management/SRM

7.1 Introduction

Scientists largely agree that anthropogenic global warming, or climate change, threatens to severely impact and disrupt human societies as this century progresses. Environmental activists, along with segments of the global policy community, have been calling for strong proactive measures to either prevent or mitigate the worst effects of this crisis. Technological and policy solutions to address the crisis exist. The fundamental question is, will policy makers adopt and implement these solutions in a timely and effective way? Or will this threat be more or less ignored until it reaches catastrophic proportions? At that point, how will policy makers respond

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to the imperative to respond to the immediate crisis? Is the geoengineering approach of altering the atmosphere to block a portion of the incoming solar heating (referred to as Solar Radiation Management or SRM) likely to be adopted as a technological solution?

We start by surveying the way that scientists became aware of the problem of accumulating atmospheric greenhouse gases causing global climate change and briefly consider how this is likely to become a major crisis in the coming decades. We then examine a series of historical case studies to evaluate the processes and outcomes that occur when human societies confront crises. Our analysis concentrates on two cases: the process of emancipating the enslaved people in nineteenth-century America, and the responses to the recent (and ongoing) Covid-19 global pandemic. Our analysis of these cases finds that human systems respond to crises in a variety of ways that are often suboptimal. Demands for radical and immediate transformation of societies are difficult to fulfill and often encounter fierce resistance. The Covid-19 response demonstrates that proactive measures that demand significant societal or personal sacrifices are often avoided in favor of seeking technologies that offer the promise of relatively painless quick fixes. In the case of the pandemic, the vaccine program is this type of technological solution. Even though the development of the mRNA vaccine technology represents the culmination of a decades-long research program [17], it is generally perceived by the public as a quick and simple solution. This leads to our conclusion that when climate change is perceived to have reached a crisis point, policy makers will respond to the imperative demands of the people by seeking to implement an immediate technological solution. Geoengineering, specifically SRM, despite the ethical and environmental concerns associated with it, will likely offer an appealing, indeed compelling, technological solution to an existential crisis. It is not our purpose in this chapter to advocate for SRM, but to raise awareness that it very well may come to be seen in the future as the only viable solution to an immediate crisis of potentially catastrophic proportions.

Our analysis concentrates on the United States because it is a leading global power in economic, political, and technological terms. It will remain a significant global actor in these areas for the foreseeable future. But many of the lessons we draw are likely applicable to other political regimes in other nation states.

7.2 Climate Change as a Crisis

7.2.1 The Problem of Anthropogenic Climate Change

Scientists have known of the potential atmospheric impacts of man-made carbon dioxide (CO_2) since the late nineteenth century [112]. In the past 50 years, scientists have been issuing warnings of the need to reduce carbon emissions and greenhouse gases (GHGs) [84]. In addition to CO_2, there are several other problematic GHGs.[1] Methane (CH_4) is the most prevalent and most potent of them. Like CO_2, Methane concentrations in the atmosphere have grown significantly over the last 200 years, due to human causes [28]. As the effects of climate change have become more noticeable, scientists and environmentalists have made progressively more urgent calls for action [32, 48, 72]. Arguably, however, there has been relatively little progress in reducing carbon emissions globally. Though most countries signed on to the Paris Climate Treaty in 2015, the target for the goal of net zero emissions is 2050 [108]. Currently, the world is on a path that would likely lead to an increase of 3–5 °C in average global temperature in the twenty-first century [8]. The latest climate research projects the global temperature to increase by two degrees prior to reaching the Paris deadline of 2050. By then, tipping points may well have passed which will lock in systemic feedbacks that lead to ongoing warming. This out-of-control process may well result in a "Hothouse Earth," regardless of human interventions [95, 96].

Long before reaching three degrees of global temperature rise, human populations across the planet will experience a tsunami of catastrophic crises [65]. Even just a two-degree increase will result in significant upheavals and difficulties. These impacts include the effects of greater temperature extremes, droughts and water scarcity, ocean level rise, and increasingly severe storms (see for example, [10, 23, 65]). Avoiding these will require massive societal transformation, rarely attempted in human history [94]. Net carbon emissions of zero by 2050 is required to keep global warming below 2 °C by the end of this century [108]. To achieve net zero carbon emissions by the mid-century will require a total transformation—a complete revolution—in our production and consumption systems; a type of revolution that has rarely been attempted previously [89].

Western society is founded on cheap energy and disposable consumerism, driven by technological innovations and cheap capital. Society will need to move to an energy system based on non-carbon sources, which requires a replacement of 80% of our current energy generation capacity (i.e., eliminating the use of carbon sources unless offset elsewhere in the system) and a commitment that any growth in the system will come only from non-carbon sources [94]. Nuclear power and renewable energy (i.e., Solar, Wind. Geothermal, and Hydro) are the only non-carbon sources available and they do not currently have the capacity to meet global energy needs, nor are they likely to reach this capacity by 2050 [91]. Society would need to move to a maintenance mindset for products and infrastructure, which it does not currently have (see for example, [87]. We would need to eliminate the obsession with continual growth and unlimited innovation (see for example, Vinsel and Russell [111]).

One of the difficulties is that societies have rarely set out with the goal of attempting large scale social, political, and economic change. Societies have experienced revolutions in the past, from technological revolutions to social and

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[1] The technical literature often aggregates the concentration of CO_2 and the other GHGs as CO_{2e} or CO_2 equivalents.

political revolutions. The closest representations of this kind of change that is required are found in the historic examples of the French Revolution (1789), the emancipation of African-American slaves during the American Civil War (1863), the Russian Revolution (1917), and the Chinese Revolution (1949). These transformations were surrounded by significant struggles and bloodshed, and they were followed by decades (if not centuries) of rippling effects. That is to say that significant societal transformations are accompanied by considerable conflict and pain. Technological revolutions are typically organic and the result of many different inventions coming together [88]. They are not generally planned ex-ante (i.e., in advance). Social and political revolutions often begin with a vision of transformation and society must grapple with this vision and its implementation.

History shows us the difficulties that governments, policy makers, institutions, companies, and individuals have in making proactive change. For governments, acting effectively can be difficult, even when they are confronted with crises and emergencies. Working to proactively prevent future problems has proven nearly impossible. Instead, governments typically do not act until demands from citizens create significant pressures for change. Significant action seems to only take place when there is a significant crisis.

However, the effects of climate change are very real, and they are accelerating. The magnitude of climate change is enormous, but it has been developing over a relatively long period of time, especially compared to short election cycles and the careers of individual politicians. In this chapter, we argue that the steps needed to mitigate climate change proactively are going to be very difficult. If the historic pattern holds, it is highly unlikely that Western democracies will take the necessary steps to address the climate crisis until a sufficient number of citizens decide that it poses a dire and immediate threat to themselves and their loved ones. By that point, unfortunately, preemptive and considered action to reduce or eliminate carbon emissions will be viewed as ineffective and impotent, because of the long time-lags that exist within the atmospheric climate system. The crisis will demand immediate action and policies that take time to implement will be discarded in preference for urgent measures to address the immediate danger. By the time that citizens demand action, policy makers will be left with few options for mitigating climate change.

In the next section, we examine two cases of crises and how policy makers have dealt with them. We look specifically at the case of emancipation in the nineteenth century in the United States and the response to the Covid pandemic in 2020. We also briefly survey other cases for comparative purposes. We then discuss the lessons from these cases for mitigating Climate Change.

7.3 Historic Responses to Crises, Disruptions and Transformations

In this section, we examine historical cases of disruptions, crises, and transformations, in the US, especially focusing on the way that policy makers have responded to extreme events. This anyalsis provides insights into patterns of behavior when political and social systems are confronted with crises. These patterns are likely to continue to hold as the problems associated with climate change become more severe. First we examine these patterns, particularly looking at the process of ending chattel slavery. Then we undertake a detailed examination of how the US has reponded to the Covid-19 pandemic (to date) as the most recent case of a political and social response to a severe and far-reaching crisis. Historical cases can be useful in discerning patterns of how human individuals, groups, and societies respond to disruptive situations. Humorist and author Mark Twain has been credited with coining the aphorism, “History doesn’t repeat itself, but it often rhymes.” Geophysical modelling, verified by records of past climate patterns, is an effective means of forecasting climate trends [6]. Historical case analysis does not offer the same precision in predicting future human actions, but it is useful given the absence of superior methods.

7.3.1 Crisis Responses and Transformation in United States History

In their 2019 evaluation of possible US responses to the climate crisis, Leech and Schuelke-Leech [62] briefly surveyed nine events that were either actual or perceived crises. These events created oportunities for political leaders to act desively in ways that would not have been possible had it not been for the groundswell of popular support that sprang from the urgent desire to see these crises addressed. These events, which are a selected sample, span the chronology of US history from the nineteenth century to the present. They range from the incidents in the disputed area of the Texas-Mexico border that led to the Mexican–American War of 1848, through the 1941 Japanese attack on Pearl Harbor, and the Gulf of Tonkin “incident” of 1964, to the flurry of executive and legislative actions that were taken in the wake of the 2008 financial crisis. In addition to identifying these nine events, we also provided more detailed surveys of three other cases: Abraham Lincoln’s launching of full-scale military operations against the rebellious states of the Confederacy, following their attack upon the Federal installation at Fort Sumter, in 1861; the massive commitment undertaken by the US to win the “Space Race” following the launch of Sputnik by the Soviet Union in 1957; and the launching of the “War on Terror” in response to the Al Qaeda attacks of September 11, 2001. The details of all these events differed, as did the extent to which they constituted actual crises. But they shared several commonalties. The precipitating events were perceived throughout the American public sphere as genuine crises. Political leaders were able to leverage popular support for policy responses that under other circumstances would not have been paletable. And, the responses grew and evolved over time to a larger magnitude then could have been foreseen at the advent of each original crisis. While each of these crises had significant impacts on society, none of them, regardless of their severity, was sufficient in themselves to provoke a massive and fundemental restructuring of American society and political economy.

The one crisis that did rise to the magnitude of a revolution in the US was the Civil War that resulted in the emancipation of the enslaved population. This is an example of an attempt at a proactive large-scale social and economic change. We employ this case to illustrate the complicated, difficult, and often violent paths that often accompany major transformations of human societies.

7.3.2 The Historical Process of Ending Slavery in the United States

An examination of the process whereby chattel slavery was eventually eliminated in the US, beginning around 1850, illustrates one way that a society went through a series of crises that led to a radical transformation. It also demonstrates how a transformation can be messy, violently contested, and stretch out in a state of partial completion for decades or even generations. The process whereby a strong anti-slavery party arose in the north, the way that this led to the crisis of the Union, and the eventual emancipation of enslaved peoples is a useful case to consider the complexity of transformative processes. It also illustrates the way that reforming activists can leverage perceived crises to gain popular support. In doing so, reformers can also provoke severe backlashes from entrenched interests that are committed to maintaining the status quo. This case is also an illustration of the way that major historical transformations do not tend to be peaceful, straight-forward, linear processes. Here we focus attention on four significant aspects: the rise of a strong anti-slavery movement in the northern United States that was spurred to action by perceived crises; the violent backlash against it; how that backlash led the Republican political leadership to endorse and enforce emancipation, and in the process, transform the country; and finally, the linked problems of racial inequality and anti-Black violence that continue today as legacies of an incomplete revolution.

From the early 1700s, prior to the founding of the American republic, individuals and groups expressed anti-slavery sentiments. There were moments when anti-slavery activists made some inroads into the political process. For instance, in 1808, the US outlawed the international slave trade (with support from domestic slave traders), the Missouri Compromise of 1820 limited the territorial extent of slavery, and the underground railroad assisted individuals and families escaping from slavery. The formation of the American Anti-Slavery Society in 1831, marked a high point in abolitionist activism [42]. Despite occasional modest successes, the early abolitionists did not significantly alter the trajectory of political support for the institution of racialized chattel slavery, because the economic benefits of slavery to the white ruling classes were too great [3]. Like the environmental activists and climate scientists who began warning of global warming decades ago, the abolitionists persisted in advocating against slavery despite the apparent disregard of the surrounding society.

Starting around 1850, that began to change as a series of events took place that gave the abolition movement new life and vitality, eventually propelling it into an effective political alliance with the newly-emergent Republican Party in the north. Some of these key events were political, while others were cultural and social. In 1850, the US Congress passed the Fugitive Slave Act, which compelled authorities in the free states to assist in returning people who had escaped from slavery. This forced northerners to confront their own complicity in the institution of slavery. This complicity was further magnified when Harriet Beecher Stowe began publishing *Uncle Tom's Cabin* as a magazine serial in 1851, and she published it as a book in 1852. The story was subsequently dramatized in plays that toured northern cities, so that both the reading and the theater-going public encountered this vivid, heart-wrenching depiction of enslaved people. Historian John Brooke argues that encountering this depiction of slavery strongly influenced northern public opinion. People who had been able to ignore slavery as a southern institution, that was detached from their daily lives suddenly began seeing it as a horrible moral blot on the nation [7]. In 1854, Congress passed the Kansas-Nebraska Act, which was drafted by Senator Stephen Douglas. It organized the two new territories, and it rejected the Missouri Compromise of 1820, by establishing the principle of popular sovereignty, whereby the voters within a territory could determine whether it would be admitted as a free state or slave state. This led to a small-scale civil war in Kansas as supporters of slavery fought with abolitionists, turning the territory into "Bleeding Kansas." In the 1857 Dred Scott decision, the Supreme Court ruled that an enslaved person remained in a state of slavery, even if their master transported them into a territory or state that did not permit slavery. Each of these events served to galvanize anti-slavery sentiments in the north. They also strengthened the growing Republican Party, which was not committed as a party to the immediate abolition of slavery, but it was determined to stop its expansion.

The abolition movement was never monolithic. There were always internal personality conflicts along with debates over goals, strategies, and tactics. Radicals called for immediate emancipation while moderates advocated for containing slavery as a pathway to gradual emancipation. They also debated about how newly-freed people should be treated after emancipation—whether they should be immediately integrated into white society or separated. Many abolitionists employed methods of peaceful protest, advocacy, and political lobbying, while a small minority embraced violence to fight the scourge of slavery [93].

In 1859, the militant abolitionist John Brown led a raid on the Federal Armory at Harper's Ferry, Virginia.[2] This uprising was quickly suppressed, and Brown was subsequently executed for treason. But southern slaveholders perceived this event as a crisis. They had always been haunted by their fear of slave revolts [52], and they felt especially threatened in that moment, because many in the north viewed Brown as a martyr to freedom rather than a dangerous madman. Each of these events were perceived as crises by various individuals and groups of people, but none of them were sufficiently powerful, by themselves, to spur radical shifts in the political, economic, and social orders of the nation. It was the confluence of these various types of events in relatively quick succession that combined to form a national crisis.

As the southern slaveholders saw it, the growing abolitionist movement in the north posed a significant threat to their economic survival. In their view, this threat became an existential crisis when Republican Abraham Lincoln won the presidential election of 1860. Lincoln did not at that point support government action to abolish slavery, but his platform, which was committed to restricting its spread, was anathema to the slaveholders. Despite deeply divided public opinion, several southern states seceded from the Union in the aftermath of Lincoln's election [59]. Even then, northern public opinion remained deeply divided as to the best way to deal with the crisis. Lincoln was convinced that he had to bring the southern states back into the Union, but he lacked political support for using force against them. Only after the attack on Fort Sumter did northern citizens unite in a commitment to use military force to end the rebellion [18]. But the northern commitment to war was not immediately matched by a consensus that the war ought to also end slavery.

Lincoln entered the war with the overarching goal of defeating the rebels and re-uniting the states. He was initially ambivalent as to whether the war should also end slavery. He was especially concerned that the few slave states that had remained loyal would join the rebellion if he pushed an abolitionist agenda. He also had to ensure the support of northern whites who were willing to fight to preserve the Union but resisted the idea of sacrificing on behalf of enslaved Blacks. Throughout his political career, Lincoln viewed the Constitution as a document of freedom [74]. From the beginning of the war, enslaved people took the opportunity to seize their freedom, and they were aided by supportive Union officers such as Benjamin Butler and John C. Fremont. In essence, Lincoln's Emancipation Proclamation of 1863 was catching up with the reality on the ground. While never completely unified about it, northerners came to see the Civil War as a fight to establish nation-wide freedom [73]. Even after the rebellion was defeated on the battlefield, emancipation had to be enforced by federal troops occupying southern communities [22].

When representatives and senators from the seceding states withdrew from Congress, at the start of 1861, the Republican party was left to dominate the federal government. They seized the opportunity to fundamentally redefine the role of that

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[2] Now Harpers Ferry, West Virginia.

government in national life. They accelerated the suppression of western Native Americans, established a system of funding for state universities, opened the west to white settlement through the Homestead Act and railroad subsidies, all in addition to amending the Constitution to outlaw slavery and establish universal male suffrage [33]. The Republicans grasped the crisis of the Civil War as an opportunity to fundamentally recreate the United States.

Yet the aspirations of the second American revolution have never been fully realized. The rebellious enslavers grudgingly accepted military defeat, but they never accepted the reality that it was necessary for them to radically change their attitudes towards and treatment of African Americans. Even prior to the end of the military occupation of the south, they were taking steps to perpetuate and entrench a white supremacist society. That legacy of suppression of Black people's civil and economic rights, along with violence against them, has continued through the Jim Crow era down to the tragic pattern of racist police violence that motivates the Black Lives Matter movement of today [54].

The process of emancipation that began around 1850 can be summed up as following the typical pattern of crisis-driven transformation. A series of events are perceived as crises, galvanizing a segment of society to agitate for radical change. This provokes a conservative backlash which further exacerbates the crisis. In dealing with the emerging situation, political leaders are compelled to ratify societal changes, and they take advantage of the turbulent situation to enact other parts of their agenda. As the situation reaches a new equilibrium, conservative forces continue to resist the most revolutionary aspects of the transformation, but they are unable to fully return to the status quo.

7.3.3 Covid Response

The SARS-CoV-2 Coronavirus pandemic presents a contemporary case of how various governments and populations are responding to a crisis that has a global reach. Preliminary information from this case does not give much cause to be optimistic that governments will respond effectively to the climate crisis in ways that are proactive and gives priority to scientific evidence in decision-making.

For years, public health experts and epidemic disease specialists have been warning that it was only a matter of time before a major outbreak of an airborne viral infection occurred [71]. While these warnings received occasional attention from policy makers and the news media, they were largely ignored by society at large. This follows the historic pattern of the abolitionists being largely ignored prior to the series of crises that began unfolding around 1850, and the lack of substantial action on climate despite decades of warning from activists and climate scientists. The outbreak of the Covid-19 pandemic, along with the deaths and severe illnesses the disease causes, led to much more strident demands for action. Policy makers, though initially ill-prepared, have taken a wide variety of steps to respond to the crisis, and demonstrate to the public that they are taking the urgency of the situation seriously.

Initial reports of a new coronavirus first emerged globally in late 2019. The virus was quickly named Covid-19, identifying the year in which is was discovered. By the end of January 2020, cases were starting to show up globally. Within a few months, Covid-19 had spread around the world and countries were beginning to see significant numbers of cases [114]. The United States has a very high number of cases and deaths relative to its population, and it is useful to use their numbers and policy response as our case study because of the importance in the US in addressing global policy problems.

The US recorded its first case in January and its first death in February 2020 [78]. Despite increasingly dire warnings, many policy makers did not heed the best advice of technical and scientific experts. Warnings in advance of the pandemic were dismissed as being exaggerated [21]. Programs designed to prepare for pandemics were defunded and plans were discarded [63]. The leader of the pandemic-readiness office in the Trump Whitehouse was dismissed in early 2018 and the office was closed [21]. In spite of these failures, many public agencies and organizations were engaged in ensuring US preparedness for a pandemic and these plans should have enabled better responses [31].

Public servants that had spent their careers working in public health administration seemed completely unable to manage the unfolding crisis. In addition to senior leadership that was uninterested in dealing with the pandemic when it began, they faced conflicting programs and competing managers all claiming ownership and priority [31]. Disinformation campaigns, media skepticism, and social media drove a parallel crisis, an infodemic [70]. Many recommendations, such as wearing masks and physically distancing from other people, were simply ignored. Other policies, such as extensive testing and contact tracing, were viewed as impractical, while others were not implemented because they were not considered practical or economically feasible. The spread of the Coronavirus and the correponding public health crisis unfolding in early 2020 quickly became politicized and subject to debate, much like Climate Change. The Trump administration shifted the burden of dealing with the health crisis to state and local governments. The administration blamed the World Health Organization and the Chinese, rather than looking to improve their own response [46]. State and local governments floundered, struggling to acquire the resources that they needed to address the crisis [118]. Some states made policy decisions, such as New York and New Jersey's decision to require long-term care and nursing homes to take Covid patients from hospitals, that created new loci of crises [31].

There were factors beyond the response of governments that exacerbated the effects of the pandemic in the US. Global supply chains that had had the advantage of lowering costs and increasing product offerings, now became liabilities. Many Western countries had become dependent on China and other countries for medical supplies, pharmaceutical manufacturing, and protective equipment [76]. Once it became clear that there were significant shortages in critical equipment, President Trump invoked the Defense Production Act to force domestic manufacturers to develop and produce essential healthcare equipment [49]. Trump appointed General Gustave Perna as the chief operating officer and Moncef Slaoui as chief scientist of Operation Warp Speed to oversee the development of a vaccine [15, 46]. Countries and states began competing for future access to possibly successful vaccines [113].

By the time that it became clear that ignoring the virus was not going to be a successful strategy, the virus was spreading rapidly and drastic steps were required. Severe lockdowns in some jurisdications were imposed to try to halt community transmission. More than 26 million people lost their jobs and the unemployment rate increased to 14.7% [118]. The US closed its borders to international travel, as did many other countries. They also instituted export restrictions and other protectionist measures [46].

Over the previous decades, Health Management Organizations (HMO's), insurance companies, and hospitals made cutting costs, reducing waste, and improving efficency major priorities for their operations. They adopted the model of lean engineering that was, and is, prevalent in manufacturing firms [1, 20]. This left many healthcare organizations without any extra capacity, facilities, staff, or equipment to deal with the increased demands for healthcare services when the pandemic hit [76].

The US also failed to develop an alternative accurate diagnostic test, leaving health officials unable to effectively identify infected patients and, thus, to stop further community transmission [118]. The administration also refused to accept the coronavirus diagnostic test that the WHO made available internationally [31]. Without the availability of reliable tests in the US, the ability to acurately track the transmission of the disease was severely hampered.

Novel corona viruses have been known for years. They were responsible for the SARS pandemic in 2003 and the MERS epidemic in 2014. But, under-funding of research and development for diseases and viruses that are considered rare is a common problem [76]. Public health organizations have also struggled with chronic underfunding, creating significant public vulnerabilities [118]. Likewise, the persistent neglect and underfunding of long-term care homes and prisons weakened the healthcare system, making it more difficult to deal with the stresses on the existing resources during the pandemic [118].

Many Americans refuse to comply with policy recommendations. In late 2020, approximately 20% of Americans indicated their refusal to wear masks [110], and they did not plan to take available Covid vaccinations [36]. That proportion has held roughly steady through May 2021 [53]. Political affiliation and media consumption (particularly of Fox News) is strongly associated with greater reluctance to follow policy guidelines around Covid [38, 39].

Partly due to this ideological opposition to following policies by some Americans, there was a focus on finding a technological solution, in this case, a vaccine, and in providing some economic support to businesses and individuals. Developing and distributing vaccines has become essential in dealing with the Covid crisis [68]. In addition, this search focused on public–private partnerships, and governments supporting the private sector in providing a solution [30]. The quest to rapidly develop and distribute a vaccine became the preferred policy choice, because it did not impose restrictions on individual freedom and offered the promise of minimizing economic consequences. Even with this choice, which neglected other beneficial public health measures, limitations on distribution of vaccines abroad, and critical ingredients, risks extending the pandemic (see for example, [100, 104]), increasing the likelihood of vaccine-resistant variants emerging.

In 2005, the US Congress passed the Public Readiness and Emergency Preparedness Act. It gives companies that develop treatments/vaccines in public health emergency complete shielding from legal liablity—but only within the US [104]. This type of blanket protection for companies is unprecedented outside the US. The Trump administration did not push pharmaceutical companies to permit overseas distribution, in contrast to negotiations that the Obama administration conducted to ensure global donations of H1N1 flu vaccines in 2009 [24]. So this became another convenient opportunity to push the Trump "America First" agenda rather than something that would have been impossible for the government to negotiate with the companies. This severely hampered the Biden administration in its vaccine distribution efforts during the early months of 2021. It quickly began working on ways of getting around the contracts, such as "loans" of AstraZeneca to Canada and Mexico [34]. The US is also working as part of a Quad Alliance with Australia, India, Japan, and to ramp up distribution in India. But global sharing remains far less than what is needed [24]. The vaccine offers a technological solution to the crisis, but political and economic considerations hamper the world-wide distribution that would lead to optimal benefits.

Operation Warp Speed led to the creation and approval of vaccines in under a year—something which can take up to ten years under normal conditions. "According to contract language *Vanity Fair* has obtained, the agreements with Pfizer, Moderna, AstraZeneca, and Janssen state: 'The Government may not use, or authorize the use of, any products or materials provided under this Project Agreement, unless such use occurs in the United States' or US territories." [24] This Trump-era contract language continues to impede the Biden administration's efforts to share vaccines around the world. On March 2, 2021, under the Defense Production Act, Merck agreed to repurpose two of its US facilites to produce the Johnson and Johnson, which could yield a billion doses annually. This creates the potential for the US to become a major supplier for the rest of the world. Department of Defense, which negotiated the Operation Warp Speed contracts, refused to even attend meetings on international sharing that were called in July of 2020 by Trump's Secretary of Health and Human Services Alex Azar and the US Agency for International Development (USAID). On January 5, 2021, Deputy National Security Advisor Matthew Pottinger received the draft of The Framework for International Access that had been negotiated within the administration over the previous months. Then in the wake of the January 6, 2021 insurrection at the US Capitol, Pottinger resigned without acting on the framework [16]. In a March 31, 2021 meeting at the White House, the Biden adminstration decided to postpone action on the Framework, because the US appeared to be headed into another surge in cases. This was despite the urgency of public health officials who understand that the sooner vaccines are widely distributed around the world the greater possibility of avoiding the development of dangerous mutant varients of the virus [24]. In June 2021, the Biden administration announced plans to buy 500 million doses of the Pfizer vaccine for distribution around the world [79].

One of the other responses to the pandemic was for governments to attempt to mitigate the pain of the economic downturn that occurred as businesses and borders closed. In the United States, the federal government passed several stimulus bills, giving individual citizens a total of $8000 in 2020–2021, enhanced unemployment benefits, business loans, and other aid [86]. This spending was achieved through debt, resulting in the largest deficit in U.S. history at $3.1 Trillion and record high debt levels [97].

The response of the United States to close its borders and look to protect its own citizens first should not be surprising. Many countries responded exactly the same way. Earlier pandemics saw similar nationally-focused responses [2]. Upon occasion, nations have taken coordinated measures to address pandemics [12] More frequently, when confronted with an emergency which severly threatens a nation's coping capacity, countries turn inwards. This response is especially common when a contagious disease appears to be a threat to national security [82]. It appears that the US will have a huge vaccine surplus by the summer of 2021, while other parts of the world are still struggling with severe outbreaks and vaccine shortages. On May 5, 2021, the Biden administration indicated support for Intellectual Property waivers to allow for the local manufacturing of Covid vaccines [98].

It can be argued that the Trump adminstration was uniquely ill-suited for dealing with a pandemic crisis. But other nations with other governments have also struggled to cope effectively with this crisis. Hoping that future leaders will be better-equiped to respond to crises is not a satisfactory strategy. While experts generally consider Trump to have been an extremely bad president, the same experts rate Lincoln very highly [92]. Yet, despite his strengths, Lincoln's options for dealing with the crisis of the 1860s were significantly circumscribed. He could not prevent enslaved people from emancipating themselves, he could not compel reluctant generals to take aggressive action, and he had to take constant care to avoid losing public support for his agenda. In 1865, the assasin's bullet stopped him from taking further action—an ultimate expression of conservative backlash.

7.4 What This Means for Climate Change Mitigation

For many years, environmentalists have been sounding the alarm about climate change and the need to transform society's production and consumption patterns. Though climate change is viewed as a serious crisis–even an impending catastrophe–by some, for others, it is not a serious problem at all.

The need to address the sustainability of our world came into greater public consciousness in the 1970's and 1980's, following the publication of Rachel Carson's *Silent Spring* [11], the first Earth Day on April 22, 1970, the 1987

Brundtland Report *Our Common Future* [9], and subsequently, Frances Lappé *Diet for a Small Planet* [61]. These events and publications led to greater recognition of the fragility of the earth's environment and the need to change the prevailing industrial food and energy productions systems, and the consumerism that drove the need for massive global transportation network and ever cheaper production of goods.

The international community followed up with a series of global summits, starting with the Earth Summit in Rio de Janerio in 1992. This work culminated in the development and adoption of the 17 United Nations Sustainable Development Goals, which envision a world that not only addresses climate change and environmental issues, but also eliminates inequality, poverty, discrimination, hunger, economic insecurity, and other social problems [109].

There has been some progress in implementing environmental policies and increasing sustainability awareness, in the United States. In 1963, the US introduced the Clean Air Act. In 1965, they introduced the Motor Vehicle Air Pollution Control Act and in 1967, the Air Quality Act. These policies, coupled with modifiations and additional legislation, have significantly reduced the levels of NO_x (Nitrogen Oxides) and VOC (Volatile Organic Compounds) emissions. Per capita emissions are now lower than 1970 levels [37]. Lead was banned as an additive to gasoline in the United States in the 1990's [26]. The international community agreed to ban ozone depleting substances, which were damaging the ozone layer, in 1987 [107]. The efforts to restore the ozone layer have been an environmental success and it is expected to be fully restored by the middle of the twenty-first century after significant degradation in the twentieth century [27]. Though renewable sources of energy are still a relatively small portion of the total energy produced in the United States, renewables are forecast to be the largest portion of new electricity generation capacity in 2021 [106].

Despite this progress, meaningful policies to deal with climate change have been slow. As with Covid-19, misinformation, fake news, and obfuscation have been common. Fossil fuel companies and advocates have made deliberate attempts to distract and deny the urgency of the situation [75]. This creates confusion for the public as to what actions are required.

Both companies, policy makers, and other stakeholders have waffled on what actions could or should be taken. This uncertainty has been aggravated by environmental and sustainability advocates as well. Different social activists have advocated for differing goals and demands. Many of the calls for addressing and mitigating climate change are now coupled with calls for equality of economic opportunity, racial and social justice, and the elimination of poverty and extreme income disparities. These calls are demonstrated in the Green New Deal (GND) legislation proposed in different jurisdictions, such as United States and Europe. Both the American and the EC version of the Green New Deal propose more than simply achieving net zero emissions. Instead, they proffer a vision of society that is socially just, equitable, and sustainable. Both incorporate components of the United Nations Sustainable Development Goals (UN SDG) and the United Nations 2030 Agenda, which call for societies to eliminate greenhouse gas emissions, guarantee a healthy and sustainable lifestyle to all citizens, including access to clean water, healthy food, clean air, and economic and physical security [109]. Thus, there is a plethora of different ideas of what should be done and how it should be done. This diversity makes it difficult to establish consensus and formulate consistent policies.

These conflicting views are inherent in complex political situations, illustrated in the drive for emancipation and the Covid pandemic. Large scale policy changes are extremely difficult. When the calls for change were originally made in the 1970’s, it may have been possible that relatively gradual, incremental changes would have resulted in sufficient progress towards reducing GHGs and carbon emissions that drastic and disruptive changes would not have been necessary.

There are still claims that addressing climate change can be done through market-based solutions or with new technologies so that disruptive societal changes will not required.

7.4.1 Can Market-Based Mechanisms Address Climate Change?

Certainly, market-based approaches and solutions may be a part of the solution. They allow people to make choices based on their preferences relative to the price of a good or service. However, the market price of a good or service does not always reflect its full costs or benefits. This is one reason that society uses public policies, both to regulate the production of goods and services, and to force price adjustments to account for the costs and benefits not priced by the market. These extra costs and benefits are called *externalities*. Externalities can be either positive or negative. For instance, pollution that is just released into the environment without charge to the polluter is a commonly cited negative externality since people in society have to bear the costs, while the producer and product consumer gets the good at a “reduced” price. Public education is generally considered to produce positive externalities for society since people in society benefit from there being an educated population, even if individuals do not use or pay for public education directly. Thus, it is unlikely that the market can determine the right level of pollution simply through pricing in the market. Additionally, companies driven by markets and share prices, as has become the norm since the 1970s [90], are forced to try to maximize the use of their resources, even if that is detrimental to the environment. Oil and gas companies are continuing to increase production, despite the damage that those resources (i.e., fossil fuels) do to the environment [99]. Thus, unregulated, competitive markets are not able to produce solutions that will address the problems of carbon emissions because the benefits of reducing and eliminating carbon emissions are not embedded in market prices.

There are various policy mechanisms for helping to address externalities. Carbon pricing is generally seen as an effective way to reduce the demand for carbon (i.e., fossil fuels). There are two dominant mechanism for putting a price on carbon. The first is a limit on carbon emissions and a corresponding trading system (i.e., a cap-and-trade or emissions permitting system), where emission producers purchase offsetting credits from emissions absorbers. This allows for policymakers to establish a specific level of emissions. Cap-and-trade systems have been used for many years, including to address acid rain through a cap on the emissions of sulphur dioxide in the United States [44]. The EU has instituted a cap system with a penalty for emissions above the cap level, known as the EU Emissions Trading System (EU ETS). The EU ETS is credited with reducing carbon emissions by 35% between 2005 and 2019 [29]. The second system is a carbon tax in which a price is placed on carbon emissions [116]. Globally, there are approximately 40 national governments and over 20 sub-national governmants that have instituted some form of carbon pricing [117]. For instance, Canada has a price on carbon. The policy allows provinces to institute their own carbon pricing system or to default to the federal price [40]. In addition to participating in the EU Emissions Trading System, Germany initiated a carbon pricing of approximately €25 per tonne of carbon on fossil fuels at the beginning to 2021 to try to encourage consumers to reduce carbon consumption [56]. Research shows that carbon pricing can help to reduce carbon emissions. Economists consider carbon pricing, either in the form of a tax on carbon or emissions trading, as one of the best ways to incentivize the reduction in consumption of carbon and to drive innovation towards lowering carbon emissions [5, 80]. It drives the externalities in the use of carbon into the cost of carbon. For instance, Sweden instituted a carbon tax in 1991, and over the past 30 years, its overall carbon emissions have declined by approximately 27%, primarily since 2000 [51]. Other policies include subsidizing non-carbon energy sources, such as wind and solar power, or subsidizing improvement in energy efficiency. These policies can help to reduce carbon emissions and to reduce the demand for fossil fuels. Unfortunately, there is no general agreement about what policies are most effective and the current policies do not appear sufficient. Even if countries manage to meet carbon emission targets established in the 2015 Paris Agreement, there is very little likelihood of keeping average global warming below the 2 °C target [64].

7.4.2 *Can New Technological Innovations Address Climate Change?*

Clearly, technologies and innovations can help a lot by providing desired products and services more efficiently or sustainably or by helping to mitigate the effects of pollution and carbon emissions. However, it is rare that new technologies have not arisen without public support. Public education, research and development funding, business loans and grants, and public procurement are some of the ways that governments assist in the development and deployment of new technologies. Even innovation during the high growth (and high prosperity) period after World War II when the United States provided much of the world's manufactured goods was the outcome of substantial public spending [90].

Additionally, technologies require energy—for manufacturing and operating. For instance, one data center can require as much as 100 MW of energy to handle the data of tens of thousands of devices [25]. In 2018, data centers globally required an estimated 205 Terrawatt-hours (TWh) of power, or approximately 1 percent of all global electricity [66]. In truth, this is a low proportion of energy relatively to other activities. There is also evidence that electricity use per household in the United States has decreased in the past 2 decades [19]. Nevertheless, total energy production and consumption have grown significantly. In 1990, the US consumed approximately 85 quadrillion BTUs of energy. By 2019, that had grown to approximately 100 quadrillion BTUs [105]. As the number of devices and data generation, transmission, and use continue to increase, the energy needs for devices and data, will also continue to grow. Though the energy efficiency of any single technology may increase, only a portion of new technologies actually replace old, less efficient units. Rather, often newer technologies displace older units without actually eliminating the employment of the older one. One study from Canada showed that about 50% of the homeowners that replaced their primary refrigerator actually kept the older one and continued using it as a secondary refrigerator [119]. That is, even though the new refrigerator may have been more energy efficient, rather than a newer technology replacing the older one, it simply supplemented it resulting in increased total energy consumption.

In summary, market-based solutions and technological innovations alone cannot address climate change. Thus effective public policies are critical elements needed for making the necessary transformation.

Large scale changes in policies are relatively rare. Jones et al. [50, 102] theorized that policy changes go through periods of relative stability (i.e., equilibrium), punctuated by significant and relatively swift changes. Kingdon [57] observed that even if policies appear to change relatively quickly, change actually requires the convergence of three factors: the public's attention on the policy issue, the presence of a feasible alternative; and general acceptance of the proposed solution. However, there is also a belief that getting the public's attention really requires a crisis. Some leaders actively wait for some crises to implement policies that would otherwise be distasteful and experience significant resistance without the crisis [60]. Noted economist Milton Friedman claimed that real change could only come at times of crisis [35]. It often takes a major emergency before governments will commit sizeable resources to addressing it.

Governments have a wide range of tools and mechanisms that they can use to accomplish their policy goals. For example, they can directly administer programs and provide services; they can also use their fiscal powers (i.e., taxation and expenditures); they can implement laws and regulations; and they can use coercion and force [55]. The substantial monopoly power that is vested in the public sector has been a cause for concern in democracies, who generally grapple with the trade-off between individual rights and collective (i.e., the "public") good. However, not every policy works for every situation. Instead, policy makers use the mechanisms that they think are likely to be the most effective and best tolerated (hopefully supported) by the public.

Transitioning to the kind of economic and social systems required to address climate change will require a significant disruption to our society. Without some substantial policies that change our production, consumption, and energy systems, we will not meet carbon emission targets and we will not mitigate global warming. Unfortunately, energy consumption and carbon emissions are continuing to grow. Even if we achieve net zero emissions by 2050, global warming will continue through the twenty-first century. Currently, we are on the path to realize 3 °C of warming by the end of the twenty-first century [8]. If the atmosphere warms as it is forecast, we are going to enter a point of global crisis. As the case studies demonstrate, policy makers typically will not, and cannot, take drastic measures until confronted with a crisis.

7.4.3 Dealing with Climate Change

Policy makers are impelled to respond to the will of the masses. Even in autocracies, public unrest can present major threats to those in power. Therefore, policy makers are only able to undertake actions that are widely supported (or at least widely tolerated). So, it is reasonable to ask whether it is possible to rely on market-based mechanisms or new technological innovations to address climate change without major policy intervention?

Public interventions and policies have costs beyond the obvious fiscal ones. Interventions in the market can result in distortions and unintended consequences. As there is no connection between the costs and the prices of public services, policy makers have very little way to measure the relative benefits and opportunity costs relative to actual expenditures. Since they cannot use market demand, policy makers rely on other signals to determine service requirements and levels. Typically, this means a sufficient demand from voters. Once established, it is very difficult to reduce or eliminate services. People may want an absolute cut in the overall government budget, but they generally cannot agree on what needs to be cut [14].

While elected officials receive their mandate from voters, public organizations receive their mandates through the legislation that these elected officials enact. In democracies, elected officials decide what services are needed and how much they are prepared to pay for these services (via the budget process). Oversight of public organizations is also done through the legislature, who must decide how they want oversight, transparency, and accountability to be done. The two mechanisms that legislatures use are proactive monitoring (sometimes called police patrols) and reactive response (called fire alarms) [67]. Legislatures often prefer to use reactive response for several reasons. First, it is less costly and takes less time. Second, policy makers can institute a response aligned with the problem. With proactive monitoring, policy makers must lay out both the potential violation and the consequence (i.e., the crime and the penalty). With reactive responses, they can wait to determine how much response is actually demanded before instituting the penalty. This generally allows policy makers to mitigate their responses to public pressures, implying that the response is more “democratic”.

Governments are used to mitigating short-term pain through public policies, but public institutions are not designed to promote or support radical change or revolution. Governments in general are intended to promote stability. Public policies must typically be proportional to the challenge being faced. However, as was evident with the plans and programs for dealing with a pandemic, when there is no impending emergency, it can be tempting to dismiss warnings and neglect advanced preparations.

Despite the successes in creating and implementating environmental polices and the development of global goals for a sustainable and equitable world, sustainability has not been realized. Instead, the world continues to struggle with carbon emissions, pollution, waste, and many social problems. Countries are looking at additional policies to address climate change.

Notwithstanding the consensus by scientists and environmentalists on the causes and implications of climate change, this consensus has not been accepted completely by the general population. There is a sizeable minority of Americans that do not believe in climate change and they do not see the necessity to change their behavior. It seems that there has not yet been an event analogous to John Brown’s raid on Harper’s Ferry or even *Uncle Tom’s Cabin* in Americans’ consciousness of climate change.

Even if people believe that climate change is happening, there are often significant incentives to use the commons (i.e., to continue behaving the same way, hoping that others will mitigate their behavior sufficiently so that the problem will get solved by others); the classical “free rider problem.” Elinor Ostrom discussed how any common resource will tend to get abused as each individual has an incentive to use as much of the resource as possible, relying on others to limit their use. Unfortunately, as Ostrom points out, the “tragedy of the commons” results because there is no individual incentive to preserve the resource even though there is a collective incentive to do it [77].

Many countries have chosen to be environmental free riders to a certain extent. Though there is a general acceptance that there needs to be a change in energy consumption patterns and sources, it is easier to hope that other countries will change their behavior sufficiently so as to eliminate the need for policy makers to convince their own citizens to make necessary sacrifices.

Though some progress has been made, overall, the general population of the United States does not agree on the need for policies to address climate change. Thus, there have not been sufficiently strong calls for policies where politicians and policy makers feel unambiguous pressure to act. With the change in administration in 2021, there has been some progress towards an acknowledgement of the realities of climate change and the need to implement some kind of policies. President Joe Biden has laid out aggressive climate change goals, including a 50–52% reduction in US carbon emissions from 2005 levels by 2030 [101]. The Green New Deal introduced into Congress in 2019 similarly proposed significant measures to address a variety of environmental and social problems, which would have resulted in a significant transformation to society and the economy [45] However, Congress remains sharply divided. On May 5, 2021, Republican Senate Leader Mitch McConnel announced that his whole focus is to block the Biden administration's agenda [115]. Vested interests devote considerable political and financial capital to maintaining the status quo. Thus, it is unlikely that the needed policies will be enacted to avoid the serious consequences of rising global temperatures.

As with other massive crises, the United States seems unlikely to respond proactively with sufficient policies to mitigate climate change or to address the costs of policy responses through some means other than deficit spending. Only once there is a strong and vocal public consensus about the need for action will political leaders feel compelled to act. This is likely to require some catastrophic incident, on a scale larger than anything that we have witnessed up to now. With the crisis demanding a response, citizens will demand *immediate* action, despite years of relative inaction. It is likely that policy makers will feel the need to adopt some policy which demonstrates their commitment take immediate, tangible action. A technological solution, along the lines of a crash program to develop vaccines for a pandemic disease is likely to be extremely appealing under those circumstances.

Solar Radiation Management (SRM), more generally called geoengineering, is one such solution.[3] The most commonly discussed approaches to SRM propose imitating the effects of volcanic eruptions that spew sulfate particles and gases into the upper atmosphere thereby blocking a certain amount of sunlight from penetrating deeper into the atmosphere and thus cooling the climate [83]. These techniques would involve the injection of reflective materials into the atmosphere. Preferably the injection point would be high in the stratosphere to achieve the largest effect and sustain the reflective particles in the atmosphere for the longest time before they precipitate out, losing their effectiveness. This intervention would have both regional and global effects [58].

SRM is a relatively immediate way to reduce the amount of sunlight that passes through the atmosphere [58]. It would therefore be a way of demonstrating to the public that effective action is being taken. Unlike many policies, SRM does not necessarily require consensus for implementation [103]. The decision to use SRM can be made by a relatively small group of people and it can be implemented with a comparatively small expenditure of resources. Given its likelihood of implementation, it is essential that some national and international agreements be established for its use [62]. Current efforts to do this have been growing and need to be increased [4, 13, 41, 43, 47, 81].

In Kim Stanley Robinson's recent fictionalized account of the effects and policy reactions to global warming, *The Ministry for the Future*, [85] he begins with a

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[3] From a technical standpoint, geoengineering refers to any of a wide variety of techniques to intentionally alter some aspect of the earth system in order to achieve a beneficial effect. It is often assumed that reference to the term geoengineering specifically means the employment of SRM techniques.

catastrophic deadly heat wave in India. This drives the Indian government to implement solar radiation management in an attempt to slow the rate of temperature rise and give themselves (and the global community) some time to respond. The Indian government feels compelled to this action to respond to the catastrophe, despite it violating international law. One nation is powerless to unilaterally reduce global greenhouse gas emissions, but a single nation has the potential to distribute sulfate particles into the stratosphere. Due to the circumstances, the international community is generally sympathetic. Whether India would ever undertake such a step remains in the realm of speculative fiction, but our analysis of US history and policy strongly suggest that under similar circumstance, US policy makers would be compelled to take similar immediate actions. Thus, the novel is a useful parable for our time. Perhaps it, or another fictional work addressing the same issues, will grow to have an impact analogous to *Uncle Tom's Cabin* in nineteenth century America.

Solar Radiation Management would be a global experiment. It has significant ethical, political, and social implications. First and foremost, the results of the use of SRM is not clear. Putting small particles in the atmosphere to try to reduce the amount of sunlight getting through to the earth's surface may alter the atmosphere in unanticipated ways. For instance, local and regional weather patterns may be altered, the particulates may lead to ozone degradation, there may be unanticipated health impacts, and there may be a renewed increase in "acid rain."[4] SRM also only provides a short reprieve. It does not solve climate change. It also does not address the other problems of surplus Carbon Dioxide in the atmosphere, such as ocean acidification. The use of SRM may lead to a moral hazard problem, in which the use of SRM is taken to be a "fix" or permanent solution, resulting in avoidance of making the required long-term systemic changes. The risks and uncertainties surrounding SRM make it a highly-undesirable solution [69]. Despite these risks and uncertainties, demand for implementing SRM in response to a crisis may be irresistible.

Currently, there are no international agreements about the use of SRM. Even with such agreements, there is no guarantee that when there is a serious crisis, everyone would continue to abide by those agreements, particularly as citizens demand significant climate change action. Thus, there is a real need for investigations of the consequences of SRM, including looking at SRM methods and techniques. Countries, and the international community, need to establish guidelines based on scientific research. Even with these, the Covid pandemic has shown us that plans and agreements can be disregarded or displaced in an emergency.

Those with good understanding of the scientific issues of climate change and knowledge of potential mitigating techniques need to be advocates, working to inform the public and policy makers. The more positive change can be accomplished, and the more positive trends can be put in place before climate events

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[4] Acid rain is the general term for precipitation with a lowered pH due to the water reacting with either Sulphur dioxide or nitrous oxides present in the atmosphere.

become identified in the public sphere as an immediate, existential crisis, the greater the likelihood that they will be adopted and amplified when popular demand for immediate action will inevitably emerge.

Advocates, policy makers, and members of the scientific and scholarly community need to push for realistic attitudes and policies regarding SRM. This will require some to abandon their taboo against even discussing the topic. As stated above, further research into methods and techniques need to go with establishing international agreements and norms covering experimentation and employment of the technologies. Rather than advocating against any use of SRM, the better course will be to firmly establish within the public sphere the understanding that this is not a solution but a temporary expedient that can only be used under the direst circumstances and only for a limited period of time. If used to buy time, SRM can offer temporary breathing space to enable the world to take the long-term steps that are necessary to reduce the adverse impacts of climate change. But this can only happen if there is, ahead of time, a realistic appraisal of what SRM can offer and what its pitfalls are. In other words, policy makers and the general public need to be very clear that if SRM is to be used, it should only be permitted for a relatively short period of time, to relieve suffering while longer-term solutions are implemented.

7.5 Conclusions

Our analysis of both the historical case of revolutionary change in the midst of crisis and the contemporary crisis of the Covid-19 pandemic lead us to several conclusions and recommendations. The most obvious conclusion is there is no simple, straightforward pathway forward. Crises are going to come, and addressing them will be fraught with difficulties. The magnitude of the climate problem is huge, as are the transformations that are necessary to deal with it.

Confronting crises is hard, but these events can open opportunities to transform society that do not tend to be available under ordinary circumstances. When significant elements of the populace demand immediate relief, policy makers can struggle to present the right solution, especially when that solution requires patience and forethought for successful implementation.

Several important lessons from our analysis are evident:

- Consensus that some policy action needs to be taken does not necessarily mean that there is consensus about *what* policy needs to be implemented. There was significant consensus among northern abolitionists that enslaved people needed to be free. However, there was little consensus about how to do this or what should happen to them after emancipation. Arguably this waffling made it more difficult to come to agreement on action before violent conflict erupted. The lack of a feasible plan for post-emancipation integration opened the door for renewed oppression of African Americans after the American Civil War.

- Significant societal change can take a long time to accomplish, and it can be chaotic and acrimonious, even violent. Emancipation took decades and, arguably, complete equality is still unrealized.
- The kind of societal transformation that is called for to limit global warming to less than 2° by the end of the century should not be downplayed or underestimated. We cannot maintain our current production and consumption patterns and achieve our climate goals. Incremental policies are not going to be effective.
- Even when plans and organizations are in place for crisis, as was the case in the United States before the Covid-19 pandemic, the crisis will unfold in unexpected ways. Even though there were public health agencies and individuals devoted to mitigating and addressing contagious diseases, when Covid-19 struck, there were many failures that exacerbated the pandemic. There was chaos in public organizations, a lack of leadership, human errors in decision making, people unwilling to follow guidelines, and organizations and people undermining public health messages. None of these were anticipated in the plans for dealing with a global pandemic, though maybe they should have been. Simply having plans does not guarantee that they can be effectively implemented. While Solar Radiation Management is viewed by some as a possible mitigating mechanism, which would provide some pause in global warming while more significant steps are taken, it is not a panacea or long-term fix.
- Though proactive actions can be avoided for a while, the nature of climate change means that eventually people are going to require significant actions to address the catastrophes and chaos that result from increased wildfires, flooding, droughts, heat waves, severe storms, increased climate migration, and property losses. While policy plans may not be implemented as desired, some plan is better than having none at all.

Solar Radiation Management appears to offer an easy, stop-gap solution, but this may prove to be a mirage:

- The adverse side-effects of SRM may turn out to be worse than the problem it is designed to address.
- Unless SRM is accompanied by a comprehensive program that effectively addresses the problem of atmospheric GHGs, it will need to be continued indefinitely.
- Just because we have plan for SRM, does not mean it is going to work.

Public advocacy for proactive policymaking is worthwhile, even though proactive policymaking represents a divergence from the historical pattern of reactive policies. If our political processes can be transformed, so that governments anticipate future problems and address them proactively, that can potentially have many positive impacts beyond addressing the particular problem of climate change. To accomplish this, it will be necessary to build much more trust in both political leadership and government institutions. It will also be necessary to strengthen accountability to ensure that this model of proactive policy making does not lead to autocracy.

The problem of how mis-information and conspiracy theories lead people to dismiss and ignore scientific findings and recommendations urgently needs to be addressed. Purveyors of falsehoods need to be muted, while consumers of information need to be provided with tools and encouragement to critically evaluate information that is presented to them to be able to determine its validity.

Responding to climate change will likely require a mobilization akin to that needed for total war, but it will need to last for generations. Either we will do it to mitigate the impacts, or we will need to do it just to cope with the cascading crises (or possibly both). We will need to deal with cutting emissions, while dealing with the effects of global warming, all while fighting the resistance to changing our social, political, and economic structures. This raises the specter of having to fight the equivalent of a multi-front war against multiple enemies that do not follow the same rules. Unfortunately, we have passed the point where the status quo or incremental actions will suffice.

A generational mobilization will lead to habits becoming ingrained in people who do not remember any other way of life, thus establishing a "new normal," just as people adjusted to the restrictions required during the pandemic. The age of consumption will come to be seen as the aberration. Sustainable avenues for production and consumption will need to replace the disposal and cheap patterns that we currently hold. Our drive for continuous improvement and innovation will need to be targeted towards climate change mitigation and adaption.

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Chapter 8
An Energy-Efficient Green Design and Modelling of a Health Clinic Located in a Cold Climatic Zone

Figen Balo, Hazal Boydak, and Hasan Polat

Abstract The building industry's high-energy usage and greenhouse gas emissions have given rise to the improvement of more easy methods to accomplish low-carbon structures. Nowadays, the use of the building information model in the engineering, architecture, operation and construction industries is constantly increasing and it takes this relationship into account when analyzing the energy of buildings. Thus, this paper aims to investigate the feasibility of using Building Information Modeling to simulate and manage the energy of a health clinic in a cold region, and to compare it to a customized natural Andezit stone sandwich wall structure from Kayseri city and a green wall module for energy performance evaluation of constructions. Type 2 was designed by adding a green wall layer to the outermost layer of the wall, which was planned as Type 1. Among the existing building external wall types, the lowest energy use intensities determined as 110,738 kWh at Type 1. In this wall type, the largest and least energy use intensity values obtained as 76,809 (space heat) and 12,529 (misc. equipment) kWh, respectively. A health clinic Building Information Modeling was improved in Autodesk-Revit displaying its benefit when used as a presence for organizing and storing energy-based information. The effects of the add-on green wall settlement on energy performance for the health clinic, which located in a cold zone, were examined in Autodesk Green Building Studio using energy data from Building Energy Modelling and Building Information Modeling.

Keywords Autodesk revit · Energy analysis · Revit · Green building studio · Energy efficiency · Natural stone · Green wall

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8.1 Introduction

The construction industry is responsible for nearly 40% of world greenhouse gases and 36% of global energy consumption [1]. Throughout the world, this industry's energy consumption has increased by one percent per year during the building's operation stage [2]. A significant portion of this energy is depleted for the indoor thermal comfort of the building's occupants [3]. The Increased access to energy resources has caused the housing industry to release the gases into atmosphere, affecting the greenhouse effect and depleting extreme energy.

Policymakers should now convince the constructors to develop structures based on maintainability standards that adequately address the community's economic, social, and environmental contexts. As a result, the structure planning is optimized for energy and resource use [4]. The energy expenditure of structures has been widely classified into two categories: first, embodied energy, which is correlated with product subtraction at the structure stage, and second, present energy, which is used throughout the structure's whole life cycle after the structure is completed [5]. The majority of the research has focused on reducing operating energy while ignoring the substantial effect of embodied energy on environmental implications [6]. A few studies have been conducted to investigate the impact of diverse structure components on energy consumption such as thermal masses, ceilings, external shadings, doors, windows, vents, insulation, floors, and wall panels [7]. Throughout its operation stage, it has been obtained that the acceptance of proper planning policies can save up to 37% of the maximum energy load [8]. Because of the huge advantages in developing structure efficiency, energy analysis databases have placed significance in optimal planning implementations. These optimal planning implementations include characteristics like structure façade's thermo-physical features, building geometry, building layout, and closing air leaks [9]. The building information model proposes the arena in the structure platform to contain related events, allowing us to improve collaboration in planning and structure technics [10, 11]. Aside from that, energy sorting simulation is a database that is being developed in order to comprehensively capture the variation in energy usage at the operating stage due to differences in materials, climatic conditions, and geographical locations. The proper energy information from the operating stage can be correlated with the overall building structure operation to forecast the effect of its correspond to embodied energy. Building information modelling contributes to the solution by strengthening the extra plug-in simulation to install correlations between embodied stages and operations to ensure an equivalent, fast, and meaningful resolution for maintainable structure planning [12]. Using Building information modeling (Autodesk Revit), Java-Script-Object Notation, Gerrish and his coworkers defined the obstacles that can be facilitated by binding between building information modeling and another tool to allow effective use of operational and design information in structure efficiency administration studies. According to this study, the proper planning of structures' energy consumption is not possible through building information modeling without linking the zone's standardized data

[13]. Cavalliere and his colleagues proposed using MS Excel to evaluate the ecological effects of embodied energies from various steps of fabrication, extraction, transportation, and to the structure location as a grade of improvement. The effects of operation and construction are completely disregarded in this study. The investigation did not consider alternative planning options [14]. Mukkavaara and Shadram developed a system to assist planners in making accurate decisions by incorporating embodied and operating energies through a multi objective optimisation strategy into a building information modeling driven planning process using Dynamo, Octopus, Energy Plus, and Autodesk Revit. In this study, the planning variables such as structure geometry, environmental impacts, and structure materials are disregarded to maximize the planning. Sensitivity and uncertainty evaluation for planning elements would have simplified the optimization problem and reduced computation time [15]. Nizam and his co-workers integrated the energy evaluation tool Standard Development Kit as well as the Inventory of Carbon and Energy tool into the building information modelling-based planning to anticipate embodied energy inputs from diverse stages of material transportation, fabrication, extraction, and structure. All of the equipment used in the structure stage is included. The research focused solely on commercial structure, and did not consider the trade-offs of the option designs or the operational stage [11]. Rather than using an industrial tool, Shadram and his colleagues presented a life cycle assessment-BIM framework (Environmental Product Declarations database, Power Pivot, Autodesk Revit) to support decision-making based on embodied energy correlate with defined products of the Environmental Product Declarations database. The investigation disregards the service life evaluation. Because of the developed planning method, interconnected embodied energy was not considered in conjunction with sensitivity and uncertainty analyses [16]. According to Habibi, the contemporaneous implementation of building performance simulation (Daysim and Ecotect) and BIM databases is beneficial for solely optimizing operational energy. It is possible to collaborate to make the retrofit and design of energy-efficient constructions easier. The sensitivity and uncertainty evaluation may have been considered for the structure's passive planning. The embodied energy of the materials has not been accounted for the preferential planning operation [17]. Henry and his coworkers evaluated the emissions and embodied energy of two different types of residence's construction materials: cement-block and mud-brick. Building information modeling was used for quantization, material scheduling, and extraction. The inventory of energy and carbon coefficients supported in calculating emissions and energy for designed products and recommending alternative planning. Because of the manual strategy, the subsequent process was prone to mistakes. The operational energy and ecological effects of materials were unobserved [18]. Najjar and his colleagues assessed the life cycle assessment of a multi-story structure planning by using the Revit database as the Green Building Studio and building information modeling arena, and Tally as the modulus to anticipate energy and emissions. In the course of optimal evaluation, proper materials selection, changing planning characteristics, transportation, and the impact of the structure are not taken into account. More detailed investigation into indefiniteness and

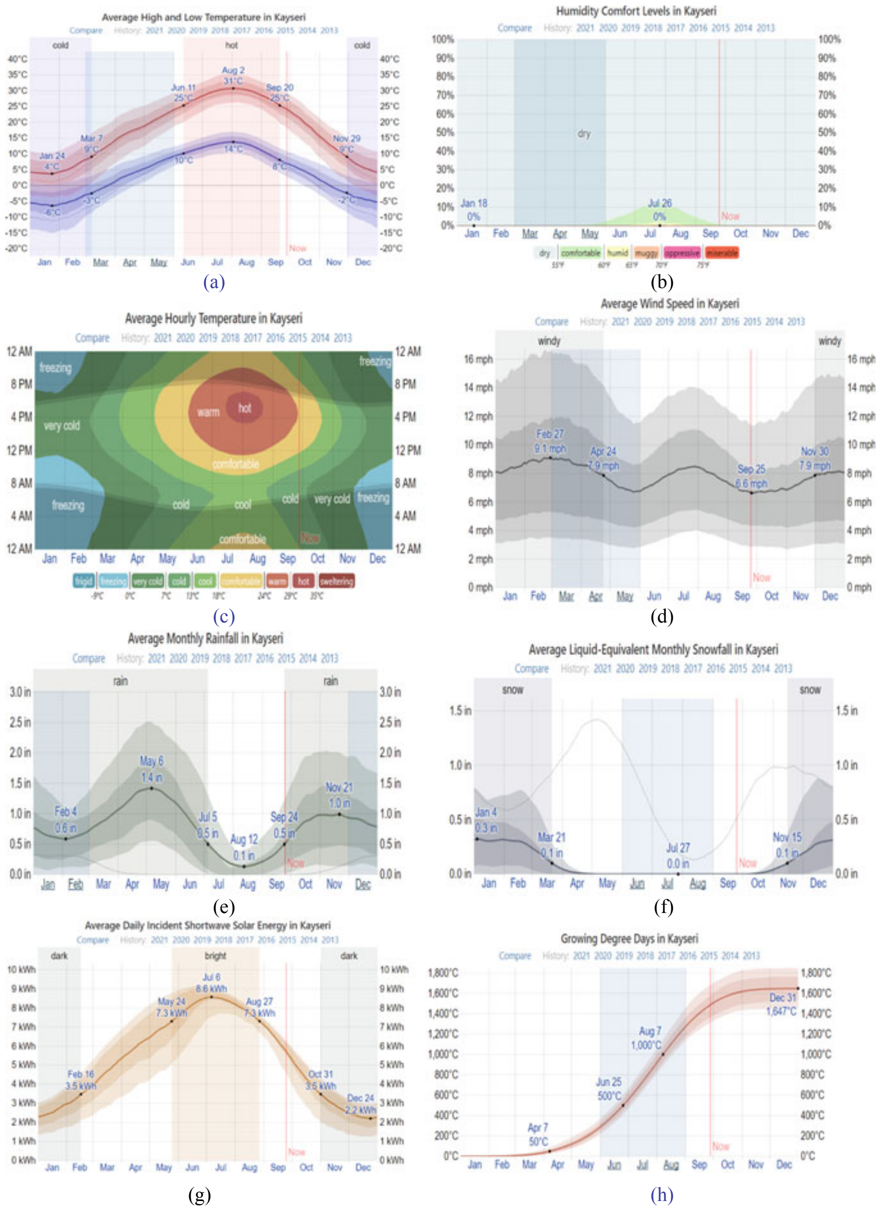
responsiveness may be developed for optimization [19]. Zhang predicted embodied energy using plug-in simulation software, which was then linked into the building information modeling arena for more detailed examination based on the products removed. Scripts for varied construction and transportation integrations are used. The work analysis constructions in the project also demonstrate a principle for the equipment's use for different structural events. Multi planning scripts have not been recognized. The investigation did not produce any significant recommendations for improving construction and building design maintainability [20]. Rock and his coworkers created a work-flow that included building information modeling and life-cycle evaluation using a unique information construction. Building information modelling defined specific planning particular matters that can be imagined in the Dynamo to associate embodied energy for life cycle assessment. The analysis disregards the responsiveness of alternative planning options, specific structure factors, physical criteria such as thermal and structural features, and structure material options [21].

Several researchers go through the methodology and administration of building information modeling and building energy modeling in the design phase. Korkmaz and his colleagues [22] and Koppinen and his colleagues [23] propose a description of the planning process for building information modeling-building energy modeling, which includes the essential determination matters, data demands, and data resources for each of the planning stages. Likewise, Lee [24], Attia and his colleagues [25], Wong and his colleagues [26], and Tuomas Laine [27] define the needed data for diverse planning stages in order to achieve a high-efficiency construction. Jabi proposed a new technical strategy [28] for building information modeling-building energy modeling, in which the distributed dynamical modeling combination methodology is used to combine databases for building information modeling and building energy modeling. For Open Studio, a simulation enhancement kit [29] is being investigated as a middleware to connect EnergyPlus and 3Ds-MAX [30]. The use of building information modeling for effective green construction evaluation necessitates only a minor difference between structured construction and building information modeling. As a result, the improvement of a standard tool is essential to the assessment process. These tools, as suggested in, can be classified as increased, functional, or external [31]. Building information modeling software such as IES-VE, Autodesk Revit, and ArchiCAD include an embedded library of construction elements [32]. Revit database was defined to ensure an application programming interface for expanding functionalities. These application programming interfaces ensure opportunities for future research in improving plug-ins to assess the ground-based augmentation system criteria. With a well-installed and improved tool, the resources and materials criteria can be evaluated within the building information modeling.

This paper is proposing to explore according to the changing health clinic wall envelope the conventional settlement's energy performance. For this aim, two diverse wall envelopes in health clinic building were assessed in terms of energy performance according to the green walls in the external wall envelope. In this way, the effect of the added green component in the building form on decreasing the energy consumption in the first wall component was analyzed. Today, there are a lot of researches purposing to obtain the energy consumption amount of the any building's current state. In addition, there are lesser researches assessing the needed energy consumption of a specific structure over time in the literature, depending on the requirements and needs. In this area, this research is important because it is an exemplary research to assess how the cooling-heating loads and energy needs of the building external wall components according to added green component to building.

8.2 The Climatic Data in Kayseri City

In Kayseri, the cool months last from November to March. The hot months last from June to September. The summer months are dry, clear, and warm throughout the year, while the winter months are partly cloudy and overly cold. The temperature usually ranges between 31 and 4 °C (Fig. 8.1a). In Kayseri, the annual humid period lasts for 3 months. The dew point determines the moisture comfort level. Unlike temperature, which fluctuates significantly between day and night, dew point appears to fluctuate slowly (Fig. 8.1b). Annual compact characterisation of hourly mean temperatures is shown in Fig. 8.1c. The day's hour is on the vertical axis, the year's day is on the horizontal axis, and the color represents the mean temperature for that day and hour. At 10 m height. The wind speed is heavily influenced by the topography of the region. In Kayseri, the hourly mean wind velocity experiences slight seasonal change throughout the year. The intense wind lasts from March to May. On an hourly basis, the main wind speed in August is 3.5 m/s at its strongest (Fig. 8.1d). The amount of rain that fell over a 31-day period is shown in Fig. 8.1e as an annual average for each day. The liquid-equal amount of sliding monthly snowfall in Kayseri does not change significantly throughout the year. The average liquid-equal snowfall collected over a sliding monthly period, centered on the daily basis, with 10th to 90th and 25th to 75th percent bands (Fig. 8.1f). Figure 8.1g displays the total daily event short-wave sun power arriving at the superficies of the ground on a broad field, taking into account seasonal changes in day length. The sun's position on the horizon, as well as adsorption through clouds and other environmental factors. Short-wave irradiation includes ultraviolet irradiation and visible light. The year's brighter duration continues for 3 months, between May and August, with daily a mean event short-wave power on 7.3 kWh/m^2. The growing degree-days in Kayseri are represented in Fig. 8.1h. These are a measure of annual thermal build-up, and identified as the warmth's essential on a base temperature, discarding any excess on a maximum temperature [33].



Average High and Low Temperature in Kayseri

Humidity Comfort Levels in Kayseri

(a) (b)

Average Hourly Temperature in Kayseri

Average Wind Speed in Kayseri

(c) (d)

Average Monthly Rainfall in Kayseri

Average Liquid-Equivalent Monthly Snowfall in Kayseri

(e) (f)

Average Daily Incident Shortwave Solar Energy in Kayseri

Growing Degree Days in Kayseri

(g) (h)

Fig. 8.1 The climatic data in Kayseri city

8.3 Building Information Modeling

Revit database is building information modelling simulation for designers, structural engineers, landscape architects, contractors, MEP engineers, and architects. This software was improved by Charles River. It was acquired by Autodesk in 2002. The Revit database allows users to plan a structure and building and its elements in three dimensions, annotate the modeling with two-dimensional drawing components, and access construction data from the building modeling database. Revit database is a four-dimensional building information modeling tool that works with databases to track and plan different stages of a building's life cycle, from planning to structure and then demolition and maintenance. In Revit, energy analysis can be performed by energy simulation for itemized architectural modellings and conceptual shapes formed. The simulation outputs are used to understand construction energy consumption, and then iterate the plannings to develop their maintainability. The created energy modeling can be displayed in the Revit database, allowing it to be observed and confirmed that the energy modeling was used.

The ideal workflow between energy tools and building information modeling has been defined as 6 steps [34]. These steps are as follows:

- defining the building's location so that weather data can be connected to it
- defining the structures, materials, geometry and a building's space types
- assigning gaps as thermal regions
- assigning gaps to appliances, lighting loads, and occupants
- identifying the heating, ventilating and air conditioning system and its elements in detail
- operating an energy software.

8.4 The Structure Components and Project of Designed Health Clinic

See Table 8.1 and Figs. 8.2, 8.3.

Table 8.1 The thermal conductivity values of wall material at designed health clinic [35, 36]

Materials	Thermal conductivity (W/(m K))
Kayseri andesite stone	1.3200
XPS	0.0360
Exterior plaster	0.4
Interior plaster	0.4

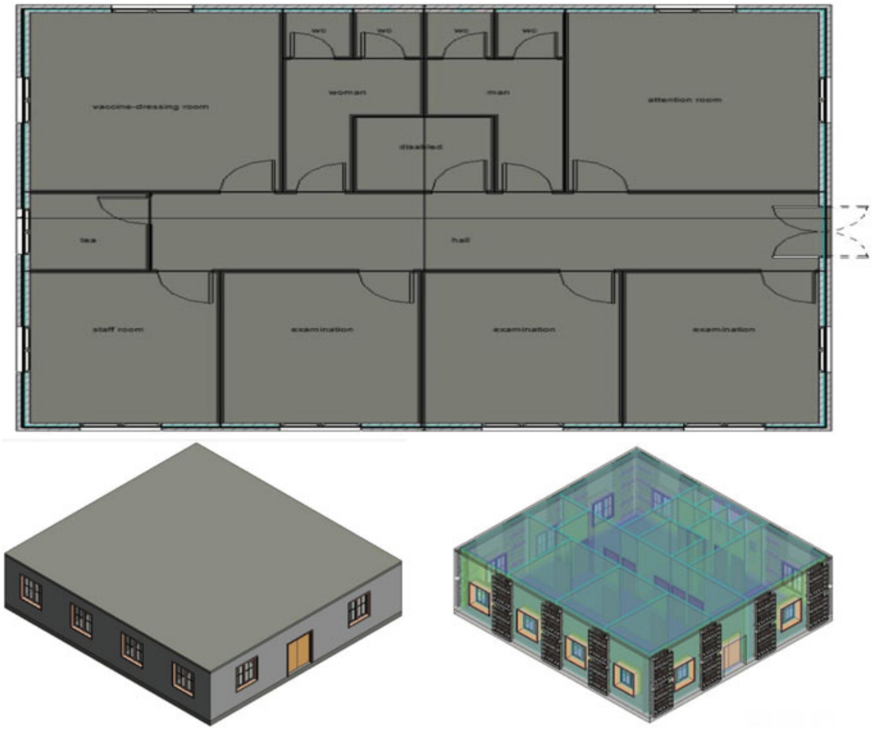
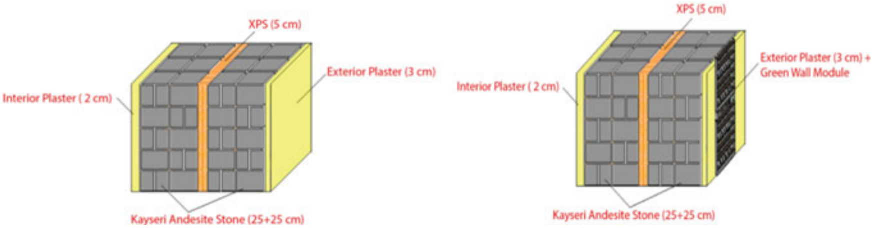


Fig. 8.2 The project of designed health clinic



(a) (b)

Fig. 8.3 The wall structures for Type 1 (**a**) and Type 2 (**b**)

8.5 Energy Simulation Modelling for Analyzed Health Clinic

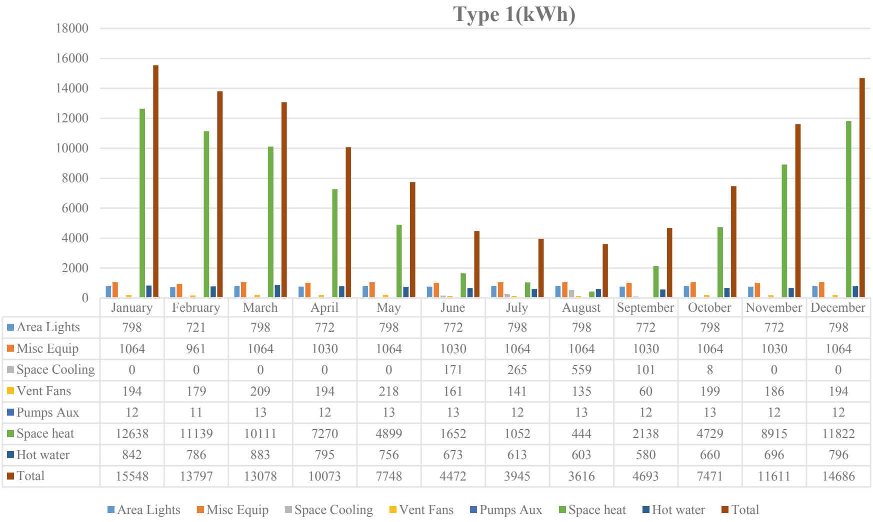
The comparison and result of the energy evaluation of a health clinic in cold region provided from Revit database is given below. The first step in energy analysis is to obtain third-dimensional modeling in the Revit database and to determine the energy goal. The energy settings are entered in the second step. When using building components, the most important fundamental input parameters are the ground plane, operation schedule, location, and building type. Following that, the energy simulation must be run. The app will ask if it wants to utilize the current analytical modeling or build a new one. It is better to build a novel analytical modelling if any improvements have been made. Following the completion of the analytical modeling, a dialogue box will appear, allowing the user to define the operate energy analysis. After the analysis is completed, the energy simulation output is displayed with the variables below.

A health center project in Kayseri with a gross area of 210 m^2 was designed. In the project, there are 3 examination rooms, 1 intervention room, 1 vaccination-dressing room, 1 staff room, women's—men's and disabled WCs and a tea shop. In the type 1 of the health center project, which was modeled in the Revit environment, the walls were formed as sandwich walls. 25 cm Kayseri Andesite Stone, 5 cm XPS wall insulation, 25 cm Kayseri Andesite Stone were used as sandwich wall layers respectively. In addition to the type 1, the type 2 model was created by adding green wall modules to the facade of the building. Then, the energy models were created in the Revit environment of the model and the annual total energy amount was calculated in the Green Building Studio environment.

8.5.1 Monthly Energy Consumption

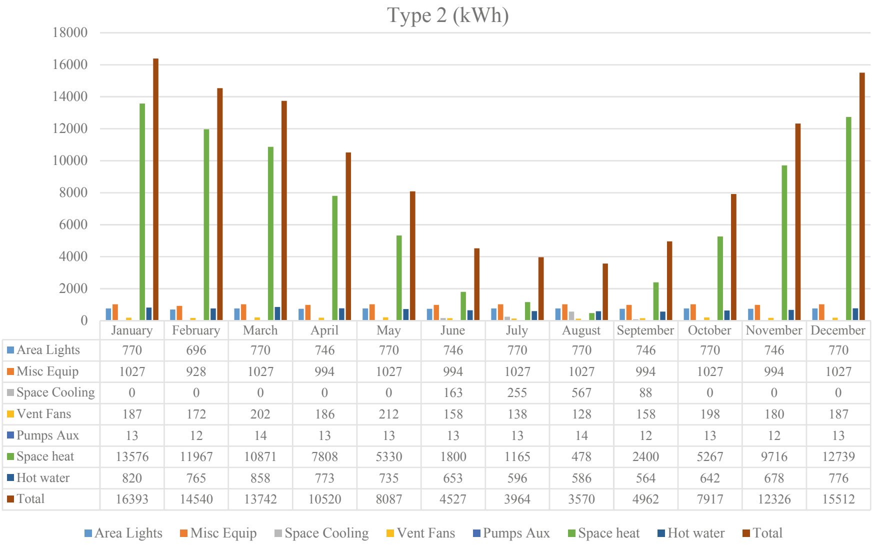
The study of monthly electricity consumption is used The monthly energy consumption assessments can be shown in Figs. 8.4 and 8.5. This shows us that the month of December has the highest electricity use, while the month of July has the lowest. This can be shown in Figs. 8.4 and 8.5. Surprisingly, natural gas usage is at its lowest in the summer. This is due to the fact that during these months, space heating, which is a major consumer of the resource, is not necessary. Natural gas usage peaks in January, as expected, due to the increased demand for space heating and the harsh cold, as shown in Figs. 8.4 and 8.5.

Over the course of a year, the maximum and minimum monthly energy consumptions are observed in January as 15,548 kWh–16,393 kWh and in August as 3616 kWh–3570 kWh with Type 1-Type 2, respectively. Among energy-consuming elements of the health clinic building, the highest energy-consumings determined in space heating were 76,809 kWh (Type 1) and 83,117 kWh (Type 2) in the total consumption. The lowest energy-consumings were found with pumps aux [148 kWh (Type 1) and 155 kWh (Type 2)].



	January	February	March	April	May	June	July	August	September	October	November	December
Area Lights	798	721	798	772	798	772	798	798	772	798	772	798
Misc Equip	1064	961	1064	1030	1064	1030	1064	1064	1030	1064	1030	1064
Space Cooling	0	0	0	0	0	171	265	559	101	8	0	0
Vent Fans	194	179	209	194	218	161	141	135	60	199	186	194
Pumps Aux	12	11	13	12	13	13	12	13	12	13	12	12
Space heat	12638	11139	10111	7270	4899	1652	1052	444	2138	4729	8915	11822
Hot water	842	786	883	795	756	673	613	603	580	660	696	796
Total	15548	13797	13078	10073	7748	4472	3945	3616	4693	7471	11611	14686

Fig. 8.4 Monthly electricity consumption of designed health clinic without green wall

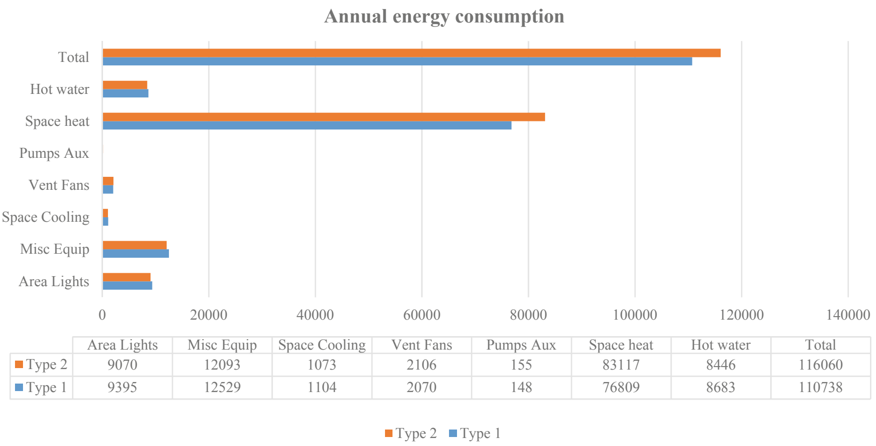


	January	February	March	April	May	June	July	August	September	October	November	December
Area Lights	770	696	770	746	770	746	770	770	746	770	746	770
Misc Equip	1027	928	1027	994	1027	994	1027	1027	994	1027	994	1027
Space Cooling	0	0	0	0	0	163	255	567	88	0	0	0
Vent Fans	187	172	202	186	212	158	138	128	158	198	180	187
Pumps Aux	13	12	14	13	13	13	13	14	12	13	12	13
Space heat	13576	11967	10871	7808	5330	1800	1165	478	2400	5267	9716	12739
Hot water	820	765	858	773	735	653	596	586	564	642	678	776
Total	16393	14540	13742	10520	8087	4527	3964	3570	4962	7917	12326	15512

Fig. 8.5 Monthly electricity consumption of designed health clinic with green wall

8.5.2 *Annual Energy Consumption*

The distribution of energy consumption was investigated. Natural gas is used as energy source. Space heat consumes the most energy in Types 1 and 2, accounting



	Area Lights	Misc Equip	Space Cooling	Vent Fans	Pumps Aux	Space heat	Hot water	Total
■ Type 2	9070	12093	1073	2106	155	83117	8446	116060
■ Type 1	9395	12529	1104	2070	148	76809	8683	110738

Fig. 8.6 The amounts of annual energy consumed throughout the entire system

for 71.61%–69.36%, followed by field miscellaneous equipment, accounting for 10.41%–11.31%, and pumps auxiliary accounting for 0.13%–0.09%, respectively. This is made possible by the extremely efficient ground source heat pumps and air to air energy recovery units installed in each zone. Figure 8.6 displayed the amounts of annual energy consumed throughout the entire system. Only 7.81–8.48% of the electricity consumed by the health clinic's entire energy system is used for area lighting in Types 1 and 2.

8.6 Conclusions

Residential structures consume the most energy in the world, accounting for approximately 24% of total energy consumption. In the structure industry, energy-efficient structures are the best way to reduce energy consumption. The energy-efficient structures can be accomplished by integrating renewable energy systems or passive features or both. The goal of this research is to convert a reinforcement analysis of a health clinic in a cold region into an energy efficient structure. Revt simulation is used to apply the energy analysis. The structure modeling is improved using the Revit simulation, construction data is loaded, and energy evaluations are performed. The energy efficiency of the current structure is predicted using data from the health clinic. The energy usage values of the two types of health clinics designed without and with green walls are analyzed using the sandwich structure. After comparing the two types, we can see that the one with the green wall outperforms the one without the green wall in terms of energy use. Overall, the energy consumption of Type 1 is found to be more than 4.5% higher than Type 1. The highest energy user component is defined as space heat.

To prevent climate change and provide a sustainable built environment in common health buildings, this study advises that low-energy design solutions be integrated with efficient green wall materials. The green materşal option utilized as the building envelope material has a positive impact on the consumption of primary energy and energy prices of the alternatives investigated, according to our findings. With this in mind, BIM-based modeling could be a useful tool for determining the direct effects of wall materials on performance.

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Chapter 9
Study on Thermal Comfort in Elderly Care Centres

Lina Seduikyte, Indrė Gražulevičiūtė-Vileniškė, Heidi Salonen, João Paulo Teixeira, Joana Madureira, and Ugnė Didžiariekytė

Abstract Although consensus exists among researchers that the quality of the indoor environment can adversely impact human health, few studies have evaluated indoor air quality, thermal comfort and health among elderly individuals. With the demographic shift on the population aging worldwide, investigation in this topic will help to develop effective interventions to create healthy and comfortable indoor environments for the elderly in order to attenuate adverse health outcomes. The aim of this study was (i) to analyse patterns and trends of the scientific research related to elderly, thermal comfort, and IAQ and (ii) to determine the maximum thermal comfort for the elderly care centre room ventilated by a mechanical ventilation system and heated by underfloor heating by using different CFD cases simulations. Information gathered from WoS, and Scopus databases on "elderly" showed that published scientific papers on this topic start from 1849. The majority of scientific publications is in medical journals. However, the engineering research field shows

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an increase in the numbers of scientific papers published on this topic. The authors conducted a field study in the elderly care centre in Kaunas, Lithuania, and continued research by preparing several CFD scenarios for ventilation and heating of the rooms to determine the maximum thermal comfort conditions for elderly people. The best thermal conditions were achieved when mechanical ventilation and underfloor heating systems were used. In this scenario, a minimum temperature gradient was 0.3 °C/m.

9.1 Introduction

People spend the majority of their time indoors (>80%) [1]; thus, indoor environmental quality (IEQ) is a key health determinant. This is particularly true for elderly people [2], which are susceptible to indoor air pollutants even at low concentrations [3]. Regarding thermal comfort conditions, elderly people are also more vulnerable than the general population [4] and may perceive the combined effects of indoor climate differently from younger people since regulating body temperature and physiologically adapting to the heat decreases with age [5].

The ASHARE 55 standard [6] describes thermal comfort as a condition of the mind that expresses satisfaction with a thermal environment. Although thermal comfort is not always the cause of health problems, it significantly impacts people's well-being and efficiency [7]. Also, compared to other parameters of living space quality (air quality, acoustic, visual comfort), thermal comfort has a more significant impact on the overall human satisfaction with the quality of indoor space [8].

Thermal comfort depends on the objective climatic parameters in the room and the subjective parameters—the people's behavior in the room, the ability to adapt to the existing climatic conditions [9]. Objective climatic parameters include the following parameters: air temperature, the temperature of the human bodies in the room, air movement, and relative humidity [10]. Thermal comfort is also affected by the vertical temperature gradient—the temperature difference between a person's feet and head [11]. All listed factors are highly dependent on external factors such as room orientation, time of the day, heat source, season, and climate.

To assess the room temperature, reference can be made to the ASHARE 55 standard [6], stating that the person feels comfortable when the room temperature is between 20 and 24 °C. Lithuanian hygiene standard HN 42:2009 "Microclimate of residential and public buildings" [12] does not contradict mentioned standard and states that acceptable room temperature limits in the cold season are 20–24 °C, and in the warm season, the temperature can vary from 23 to 25 °C.

The study presented by Choi et al. [13] suggests a displacement ventilation system to solve odour problems appearing in hospitals and analyses the possibility of using vertical radiant panels as additional heating or cooling system.

Industrialized countries are currently undergoing a remarkable demographic shift. According to the United Nations, the world's population aged 65 and over is growing at a rate of about 3%/year faster than other age groups, accounting for 14%

of the global population by 2040. This trend explains the increasing demand for long-term care services [14], such as elderly care centres (ECC) or nursing centres that provide an alternative residence place.

Over the recent decades, research on IEQ has so far focused on schools [15–19], households [20–22], office buildings [23–25], and sports halls [26–28]. Other authors are investigating different ventilation types and air cleaning as strategic approaches for IEQ management [29]. The World Health Organization (WHO) has suggested that the adverse health effects associated with indoor exposure to biological and chemical agents may include respiratory symptoms, allergies, and asthma [2, 30]. Only a few published works have evaluated the IEQ of multiple indoor air pollutants in ECC [31–35] or at elderly homes [35, 36]; either have investigated the thermal comfort requirements of the elderly [32, 33, 37]. These previous studies indicated a range of major contaminants, such as volatile organic compounds derived from the excessive use of disinfectants and cleaning products in ECC; and suggested that high temperature and humidity levels can also increase indoor pollutant levels, as well as inadequate ventilation by not bringing enough or clean outdoor air to dilute emissions from internal sources.

Therefore, considering the actual major challenge of the population aging requiring increasing efforts in research and policy-making, there is a growing interest in understanding the role of thermal comfort to which the elderly are exposed. This is also important in terms of sustainability, as between sustainable development goals (SDG) we can also see the need to ensure healthy lives and promote well-being for all at all ages (SDG 3), as well as the need to make cities and human settlements inclusive, safe, resilient and sustainable (SDG 11) [38].

This study aims (i) to analyse patterns and trends of the scientific research related to the elderly, thermal comfort, and IEQ and (ii) to determine the maximum thermal comfort for the elderly care centre room ventilated by the mechanical ventilation system and heated by underfloor heating by using different CFD cases simulations.

9.2 Materials and Methods

(i) To analyse patterns and trends of the scientific research related to elderly, thermal comfort, and IEQ publications, including original manuscripts, refereed conference proceedings, and reports, were identified and analysed using the Web of Science (WoS) and Scopus databases. Visualizations were prepared using information from Scopus database and CiteSpace open-access program developed by Chen [39]. A timeframe between 1849 and 2020 was considered.

(ii) Authors have conducted a field study in the winter and summer season in an elderly care centre located in Kaunas, Lithuania. Information about the object, measurement technics and field study results (T, RH, and CO_2 concertation) are presented in Dobravalskis el al. [40] study.

Additionally, for the field study results, the authors calculated PMV values for the summer and winter seasons. A specially developed Microsoft Excel tool was used for calculations of PMV value as a thermal comfort indicator. This tool was developed according to ISO Standard 7730 recommendations. PMV is a value expressed through the vote of comfort on a scale ranging from −3 (very cold) to +3 (very hot).

The input data:

- field measurements data for summer and winter seasons from the sensors at 0.6 m above floor level was used;
- the relative air velocity was set to 0.15 m/s;
- the metabolic rate was considered to be 0.9 met (this metabolic rate represents a relaxed person laying (not sleeping) in his bed);
- Clothing insulation for winter was set to be 1.3 clo;
- Clothing insulation for summer was set to be 1.0 clo;
- Other input data needed like mean radiant temperature and water vapor partial pressure was set using online resources.

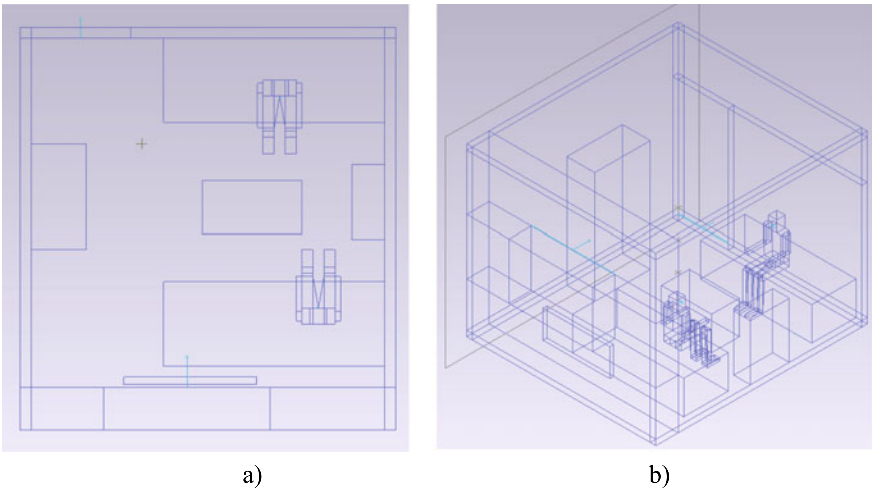
For this study, different computational fluid dynamic (CFD) cases were prepared and analyzed to determine the maximum thermal comfort for the elderly care centre room ventilated by a mechanical ventilation system and heated by underfloor heating.

CFD is widely used in the design of ventilation and heating systems to predict air movement, indoor temperature distribution, and verify the ventilation system's efficiency. To recreate the air movement and temperature distribution in elderly care centre room as realistic as possible, the CFD program FloVENT (Mentor Graphics, United States) was chosen. Calculations were performed using LVEL k-ε turbulence model as it is the most advanced and widely applicable.

The primary numerical model was developed based on the dimensions and thermal parameters of an actual room nr. 224 (3.2 × 2.6 × 3.3 m) located in the elderly care centre in Kaunas, Lithuania. The geometry, quantity, and arrangement of the furniture and people in the room were recreated (Fig. 9.1). The grid density was 122,094. Three walls in the room were internal, and their temperature in the model was 19 °C, the temperature of the external wall was 16 °C. The temperature of the floor and ceiling were also 19 °C. The CFD simulation heat source in the room was either radiator (40 °C) or a heated floor (23 °C), two people radiating 35 W of heat and exhaling 35 °C air.

Different heating and ventilation systems scenarios were created and examined:

- 1st scenario was designed to recreate the real situation in the room with natural ventilation and radiator heating. The radiator was modelled under the window, reproducing its actual dimensions and locations. The radiant temperature of the radiator was selected as 40 °C. Outdoor air enters the room through an air vent (1.5 m × 0.01 m) above the window. It was assumed that the outdoor air temperature entering the room was the same as the outdoor air temperature


a)

b)

Fig. 9.1 Geometric model of the room (plan (**a**) and an isometric view (**b**))

during the measurement day (2 °C). The outlet was the gap under the door (0.015 m).

- For the 2nd scenario, conditions were the same as in the 1st one, and only radiator was replaced with underfloor heating (the temperature of the heated floor was selected as 23 °C).
- For the 3rd scenario, natural ventilation was replaced by mechanical mixing ventilation. The inlet of supply air (supply air diffuser) was designed in the cleanest place of the room—at the window. The temperature of the supplied air was selected as 18 °C. Air was removed through an air diffuser located at the door. Heating-radiators.
- In the 4th scenario, ventilation was mechanical mixing (air temperature 18 °C) and underfloor heating (the heated floor's temperature was 23 °C).

Three possible cases of human body positions were selected in each scenario:

- both people in a sitting position,
- one person in a sitting position, the other in a lying position,
- both people in a lying position.

9.3 Patterns and Trends of the Scientific Research Related to Elderly, Thermal Comfort and IAQ

For the visualizations of research on "elderly" CiteSpace open access program developed by Chen [29] was used. A timeframe between 1849 and 2020 was considered.

Firstly the search in the Scopus database was performed using the keyword “elderly”. In the first search round 686 020 documents were identified in the time span from 1849 to 2020. The majority of the identified research was published in medical journals (566 072). Solely in 2020, 15 994 documents were identified; this demonstrates the growing number of scientific publications focused on the elderly population. In addition, detailed analyses were performed based on journal articles published in English in the field of engineering in the last two years (until 2020). In this regard, 1994 research publications were identified and analyzed using CiteSpace software for keyword nodes by frequency (Fig. 9.2). The top five authors for these analyses were: Wang Y., Wang J., Li Y., Zhang Y., and Wang Z.

For the published studies on “elderly” and “thermal comfort” the results from Scopus database identified 209 publications between 1969 and 2020. The majority of the research was published from 2013 onwards. 86 documents were published in the engineering field and 69 in the field of environmental sciences. 195 English sources out of 209 were identified and further analyzed. Keywords by frequency, the threshold for the keywords nods is 12. The search was performed on the 195 sources from 1969 to 2020 (Fig. 9.3). As it could be predicted for the top five authors at the first place is Fanger P.O., then follows Schellen L., Van Hoof J., Hwang R.L., and Mendes A.

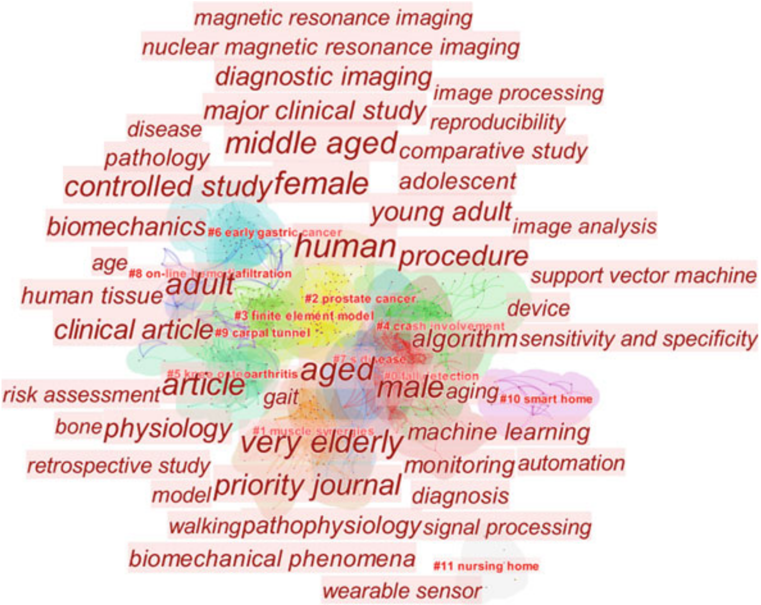


Fig. 9.2 Keywords by frequency for “elderly” in the engineering field (2018–2020). The top 10 dominant keywords were: human, aged, male, female, very elderly, article, adult, middle-aged, priority journal, controlled study. The general keywords are predominant, and this was determined by the general character of the search keyword

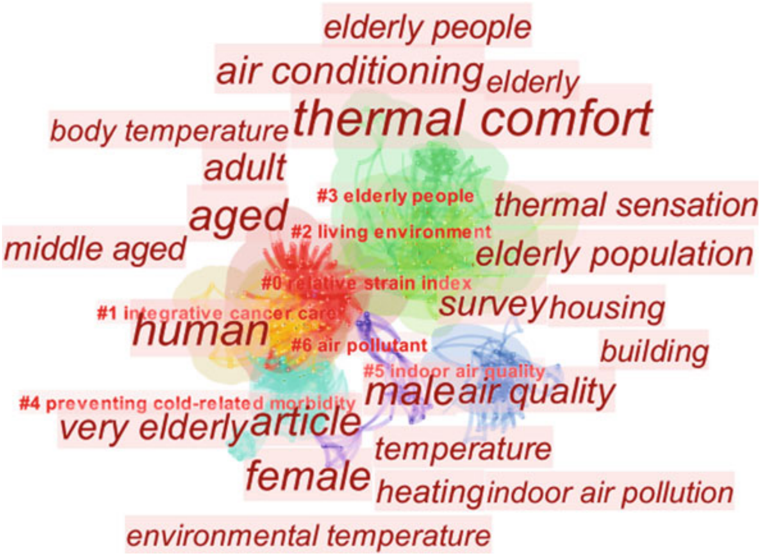


Fig. 9.3 Keywords by frequency for “elderly and thermal comfort” in the engineering field (1969–19 06 2020). The top 10 dominant keywords were: thermal comfort, human, aged, male, female, article, air conditioning, adult, survey, very elderly

For the published studies on “elderly” and “indoor air quality”, in the first search round, a total of 185 documents were identified in the period from 1977 to 2020. The majority of the research was published starting from the year 2013. 57 documents were published in the engineering field, while 104 in the field of environmental sciences. 172 English sources from 185 were identified and further analyzed. Keywords by frequency, the threshold for the keywords nods is 15. The search was performed on the 172 sources from 1977 to 2020 (Fig. 9.4). The top five authors for these analyses were: Klepeis N.E., Bentayeb M., Almeida-Silva M., Simoni M., Bell M.L.

Authors looked for the studies with keywords “elderly”, “thermal comfort” and “indoor air quality” for the period from 2015 to 2020 (as increase of publications was noticed from 2015). Table 9.1 shows data, which indoor air parameters were investigated in each analysed study. Thermal parameters were the most reported environmental factors among all the publications; temperature levels were measured in 82% of the studies, and relative humidity was analysed in about 3/4 of the included studies. CO_2 levels, a proxy of ventilation rates, were also often considered; 47% of studies had this environmental factor. Other chemical contaminants (CO and formaldehyde), physical characteristics (air velocity), biological agents (bacteria, virus, and mould), and radiation (radon) were found as the main indoor air contaminants [41, 42].

Based on latest research investigating thermal comfort and IAQ among elderly people, a substantial effort needs to be done by improving the heating and

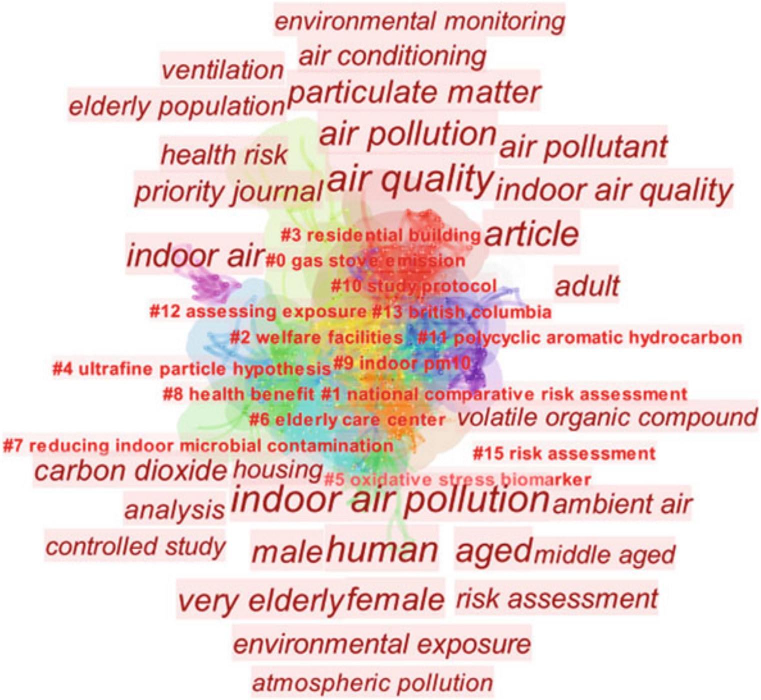


Fig. 9.4 Keywords by frequency for "elderly and indoor air quality" in the engineering field (1977–2020). The top 10 dominant keywords were: air quality, indoor air pollution, human, article, air pollution, aged, indoor air, particulate matter, female, male

ventilation systems to provide appropriate thermal and health-based indoor air conditions. It is also important to note that these interventions should not neglect other source control strategies as the first priority for proper IAQ management.

9.4 Results of CFD Simulations

9.4.1 Field Study

As was referred above, field study results from elderly care centre in Kaunas, Lithuania, were already discussed in the article presented by authors [40]. Table 9.2 gives information on average temperatures and RH measured in summer and winter.

A comparison between field measurements results and National Lithuanian norms showed that results are within national reference levels in all cases. However, in the specific rooms and specific heights there were few points with values that

Table 9.1 Published studies on “elderly”, “thermal comfort” and “indoor air quality” with investigated parameters (2009–2020)

Reference	Investigated parameter																	
	T	RH	CO_2	CO	$PM_{2.5}$	PM_{10}	VOC	TVOC	SVOCs	NOX	Formaldehyde	Bacteria	Fungi	Radon	Asbestos fibers	PMV	PPD	Questionnaire survey/Interview
Dobravalskis et al. [40]	+	+	+															
Panraluk and Sreshthaputra [43]	+	+																+
Chen et al. [35]	+	+	+	+	+		+		+	+								+
Cho et al. [44]	+	+	+	+	+		+			+	+	+		+	+			
Huges et al. [45]	+															+	+	
Pinto et al. [46]	+	+	+					+			+							
Soebarto et al. [47]																		+
Xiong et al. [48]	+	+																+
Fang et al. [49]	+	+	+	+	+		+		+	+	+		+					
Pekkonen et al. [50]																		+
Mendes et al. [33]	+	+														+	+	+
Yang et al. [51]	+	+																+
Bentayeb et al. [52]	+	+	+			+				+	+							+
Fink et al. [53]	+	+	+															
Mavrogianni et al. [54]	+	+																
Mendes et al. [37]	+	+	+	+	+	+		+			+	+	+			+	+	
Tweed et al. [55]																		+

Table 9.2 Average temperature and RH during summer and winter [40]

$T_{0,1}$ (°C)	$T_{0,6}$ (°C)	$T_{1,1}$ (°C)	$RH_{0,1}$ (%)	$RH_{0,6}$ (%)	$RH_{1,1}$ (%)
Summer—August, 2019					
24.02	24.14	24.25	52.57	56.87	56.67
Winter—February, 2019					
19.47	20.10	20.93	36.55	39.67	35.14

were outside of these limits. There are no specialized norms for elderly people, and the gaps between minimum and maximum allowed values are relatively high.

9.4.2 PMV Value

During the summer, PMV value was −0.73. During winter, this value was −0.74. This confirms that elderly people prefer warmer temperatures due to low metabolic rates. This PMV value can be described as being slightly cool that can cause minor discomfort for the occupants. These values were calculated using the average parameters of all the rooms. So PMV value can differ depending on the room. Each person can also change the results significantly depending on their age and clothing.

9.4.3 Evaluation of Reliability of a Numerical Model

When creating a reliable numerical model, it is important to consider its grid parameters. Ideally, all CFD results should be independent of the grid, which means that the results obtained should not change when changing grid parameters. However, it's almost impossible to create a grid-independent model because of computers and time limitations, so it was assumed that the results obtained are grid-dependent and may vary slightly when changing grid parameters. In this work, the density of the grid was increased by increasing the number of cells. The temperature changes were observed in the selected points to reach the point when changes are not significant. The temperature change depending on the number of cells in the grid is presented in Fig. 9.5.

According to Fig. 9.5, the results changed slightly when the number of cells was from 122,094 to 189,312. For this model, accurate results could be obtained with a grid of 122,094 cells. A comparison of the temperature of CFD model and field study is presented in Table 9.3.

The mean relative error between the field study and CFD model was 0.72%, so the model can be considered as reliable.

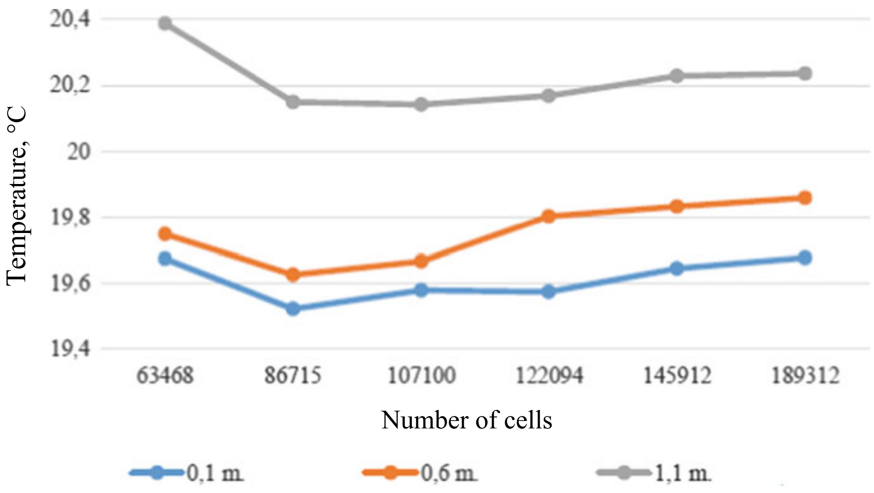


Fig. 9.5 Dependence of the results on the number of grid cells

Table 9.3 A comparison of the temperature of CFD model and field study

The height of the point	Temperature in the field study (°C)	Temperature in CFD study (°C)	Difference (%)
0.1 m	20.1	20.6	1.52
0.6 m	20.6	20.6	0.64
1.1 m	21.33	21.33	0

9.4.4 Temperature Distribution in Different CFD Scerios

As it was mentioned in the Methods section, four different heating and ventilation systems scenarios were created and examined (Table 9.4). CFD simulation temperature distribution results for the 1st scenario is presented in Fig. 9.6, the 2nd—Fig. 9.7, the 3rd—Fig. 9.8, the 4th—Fig. 9.9.

Table 9.5 presents the values obtained at the monitoring points for each case scenario and the calculated temperature gradient and average room temperature.

Table 9.4 Heating and ventilation systems for four scenarios

Scenario	Heating system	Ventilation system
1st	Radiators	Natural
2nd	Underfloor	Natural
3rd	Radiators	Mechanical mixing
4th	Underfloor	Mechanical mixing

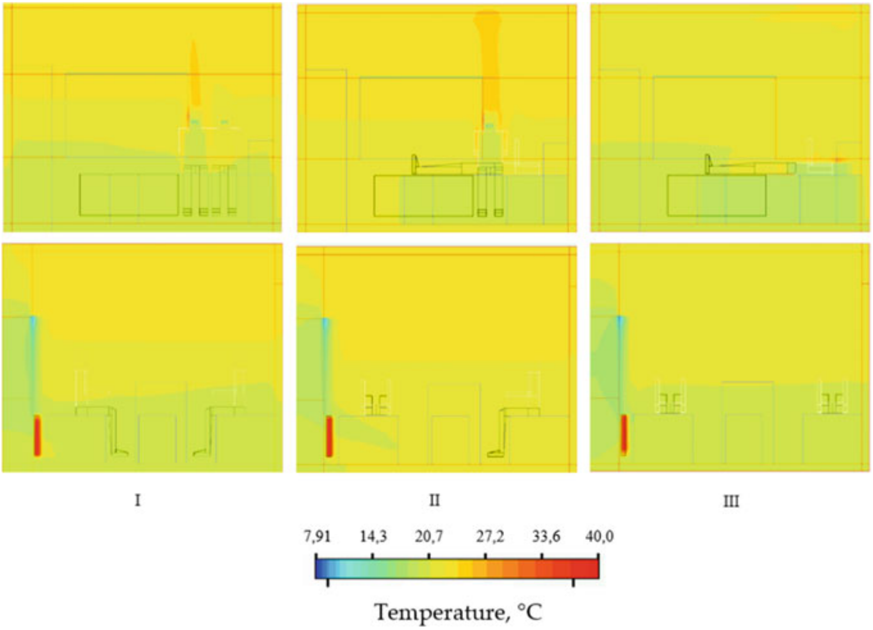


Fig. 9.6 Temperature distribution for the 1st scenario: I—two people sitting, II—one person in a sitting position, te other in a lying position, III—both people in a lying position

CFD results showed that the lowest average temperature in the room was obtained in the model with natural ventilation. In this case, the temperature was in the range of 19.6–21.4 °C. In the scenarios with mechanical ventilation, the average temperature was in the range of 23.6–24.6 °C.

From the results presented in Figs. 9.5–9.8, it could be observed that the best temperature distribution was in the scenario with underfloor heating. This is confirmed by the calculated temperature gradient, which was from 0.3 till 0.9 °C/m for natural ventilation and from 0.3 till 0.6 °C/m for mechanical ventilation.

It was observed that the temperature gradient also depends on the position of the human body in the room. The highest temperature gradient was obtained when both people were in the lying position (for different cases, it was from 0.6 till 1.5 °C/m). The smallest temperature gradient (from 0.4 till 0.7 °C/m) was obtained when both people were sitting.

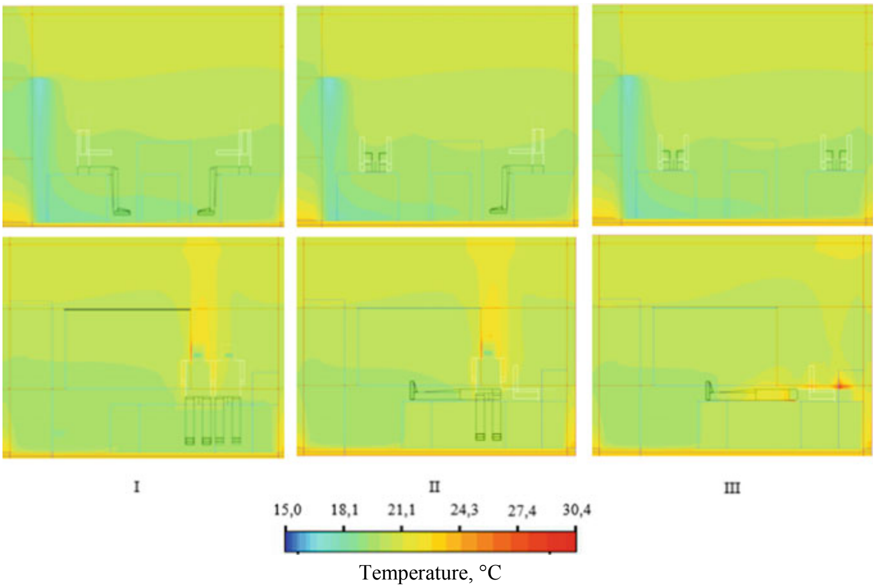


Fig. 9.7 Temperature distribution for the 2nd scenario: I—two people sitting, II—one person in a sitting position, the other in a lying position, III—both people in a lying position

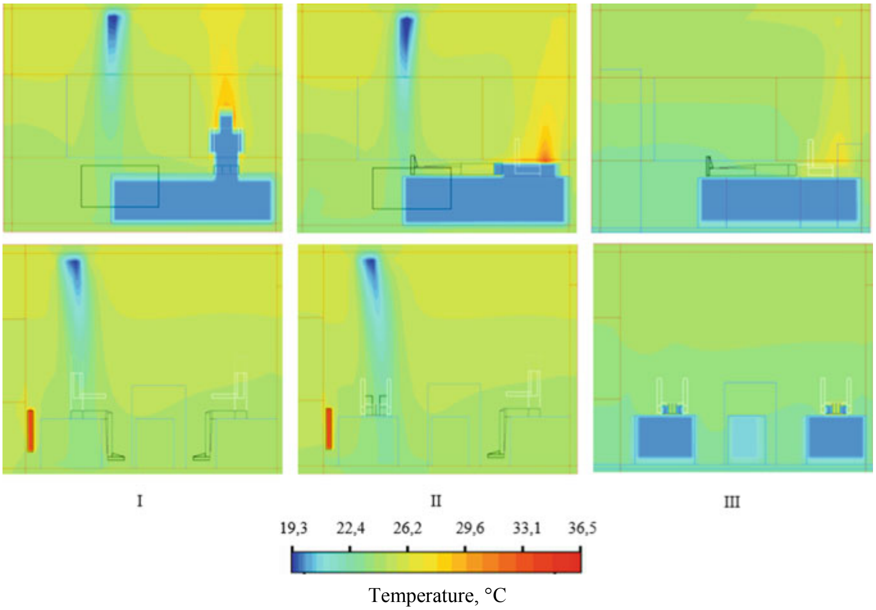


Fig. 9.8 Temperature distribution for the 3rd scenario: I—two people sitting, II—one person in a sitting position, the other in a lying position, III—both people in a lying position

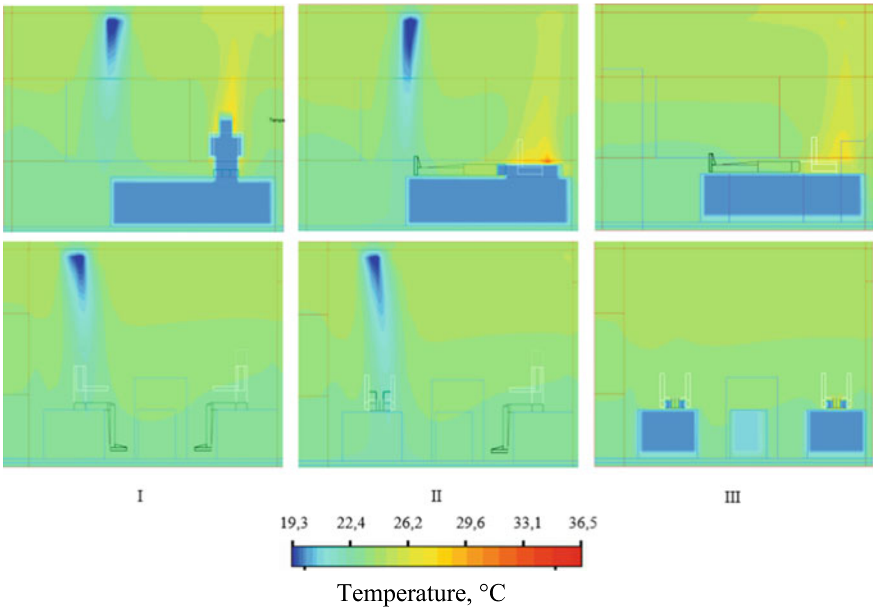


Fig. 9.9 Temperature distribution for the 4th scenario: I—two people sitting, II—one person in a sitting position, the other in a lying position, III—both people in a lying position

9.5 Discussion and Conclusions

During the last decades, thermal comfort and IEQ studies in elderly houses or care centres have arisen as industrialized countries are facing a remarkable demographic shift. One highlight of the current review is the lack of information about the contribution built environment and respective occupants and activities. New study [41] analysed the thermal comfort of elderly people living in nursing homes showed, that residents and non-residents have different thermal sensation and preferences in winter. The building and its occupants have been considered as a key factors of thermal comfort and related indoor air exposure studies [56, 57].

Poor IEQ can lead to health symptoms and may also cause various diseases, such as asthma, allergy, hypersensitivity pneumonitis, and humidifier fever [56].

Information gathered from WoS, and Scopus databases on “elderly” showed that published scientific papers on this topic start from 1849. The majority of scientific publications is in medical journals. However, the engineering research field shows the increase in the number of scientific papers published on this topic.

CiteSpace software analyses showed that Fanger P.O. was at the first place of cited authors for keyword combination “elderly and thermal comfort” and at the third place for keyword combination “elderly and ventilation”. Professional engineers and researchers on human thermal comfort and IAQ over the last five decades will confirm the importance of Fanger’s work [42]. However, more and more

Table 9.5 Results of the CFD simulation at the monitoring points

Scenario-case	The high of the monitoring point (m)	Value (°C)	Temperature gradient (°C/m)	Average temperature (°C)
1-I	0.1	20.6	0.7	20.8
	0.6	20.7		
	1.1	21.3		
1-II	0.1	20.9	1.0	21.4
	0.6	21.1		
	1.1	22.0		
1-III	0.1	20.7	1.2	21.1
	0.6	20.8		
	1.1	21.9		
2-I	0.1	19.5	0.5	19.7
	0.6	19.7		
	1.1	20.0		
2-II	0.1	19.4	0.7	19.8
	0.6	19.7		
	1.1	20.2		
2-III	0.1	19.0	0.9	19.6
	0.6	19.7		
	1.1	20.0		
3-I	0.1	24.0	0.4	24.1
	0.6	24.0		
	1.1	24.4		
3-II	0.1	24.4	0.6	24.6
	0.6	24.4		
	1.1	24.9		
3-III	0.1	23.1	1.5	23.7
	0.6	23.3		
	1.1	24.7		
4-I	0.1	23.4	0.3	23.6
	0.6	23.5		
	1.1	23.7		
4-II	0.1	23.5	0.4	23.6
	0.6	23.6		
	1.1	23.8		
4-III	0.1	23.3	0.6	23.6
	0.6	23.5		
	1.1	23.9		

questions are arising if the thermal comfort parameters, PMV and PPD, which were created with the help of young volunteers, are suitable for elderly people.

Chemical contaminants (CO and formaldehyde), physical factors (temperature and air velocity), biological agents (bacteria, virus, and mould), and radiation (radon) are the main indoor air contaminants) [56, 58]. Accordingly, this review showed that temperature and relative humidity were the most common investigated thermal parameters.

The detailed analyses among published studies from the last five years (2015–2020) on "elderly", "thermal comfort" and "indoor air quality" in open access journals underlined the need to improve heating and ventilation systems in order to have appropriate thermal and IAQ conditions for elderly. Very recently, it was reported that the SARS-CoV-2 virus spreads by air [56, 59]. Several studies pointed out the higher risk in public places with a higher density of occupation and poor ventilation. That might be the case for elderly care centres, especially leisure areas.

The results of the field study, which authors conducted in the elderly care centre in Kaunas, Lithuania [40], showed that in most cases, conditions in elderly care centre were within national reference levels, however they were not optimal for the residents. There is a need for new regulations and standards for susceptible population, as they are at higher risk. After conducting a field study in the elderly care centre in Kaunas, Lithuania, the authors prepared several CFD scenarios for ventilation and heating of the rooms in order to determine the maximum thermal comfort conditions for elderly people. The CFD results showed that the lowest average temperature in the room was obtained with natural ventilation. In this scenario, the temperature was in the range of 19.6 to 21.4 °C and did not meet the recommended temperature range for the elderly people (22–26 °C). With a mechanical ventilation system, the average temperature was in the range of 23.6–24.6 °C.

Some studies show [59] the advantage of using radiator heating in low-energy test facilities with heat recovery ventilation. In our case, the best thermal conditions were achieved when mechanical ventilation and underfloor heating systems were used. In this scenario, a minimum temperature gradient was 0.3 °C/m.

Environmental factors, local characteristics such as demographic and socioeconomic factors, and existing implemented environmental and health policies might differ among countries. Nevertheless, all countries have the same goal—to implement sustainable technologies [60, 61] and ensure comfortable indoor conditions and dignified aging for elderly people.

Therefore, it is crucial to transfer scientific knowledge on the indoor environment conditions which are suitable for the specific needs of the elderly to practice to ensure comfortable and healthy conditions for dignified aging at home or in elderly care centres.

For future research, in order to assess the thermal comfort in the rooms as accurate as possible, it would be useful to evaluate such parameters of thermal comfort as air movement, radiant temperature, PMV and PPD. To improve living spaces for the elderly, it is essential to explore the needs of the elderly by testing and adjusting individual devices: heated beds, personalized ventilation. Elderly people should live in an environment where they do not have to make too much effort to regulate thermal comfort and air quality. The main goal would be to create such an environment where comfort is already taken into account.

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Chapter 10
Evaluating Alternatives in Dental Implant Materials by SWARA and Gray Relational Analysis

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Abstract In an effective communication, teeth are significant parts of our body, which we need while giving confidence to the person with a smile that complements facial expressions. Studies have shown that the healthier they are, the more confident people become during any communication or conversation. However, healthy teeth can sometimes be exposed to deterioration and irreversible damage due to genetic and sometimes external factors. In such a case, dental fillings or root canal treatments for the teeth are no longer a solution for people. Therefore, dental implant, one of the most suitable solutions for teeth, has an important role today. However, the integration of the materials to be used in the dental implant with the teeth in the area where it is applied, as well as being able to cope with difficult situations such as oxidation, rusting and abrasion, should not cause harmful results for the human health. Titanium is one of the most frequently used materials among dental implant materials. In addition, tantalum, cobalt, porcelain, polymer and chrome are also used among dental implant materials. In this study, it was aimed to obtain results about which dental implant material is better. To obtain the results, SWARA and Gray Relational Analysis, which are among the Multi-Criteria Decision Making methods, were used in combination. While SWARA gives numerical results on which criteria are more important when choosing dental implant materials, Gray Relational Analysis method is utilized in the selection of the most suitable dental implant material in line with these results.

Keywords Dental implant materials · SWARA · Gray relational analysis · MCDM

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10.1 Introduction

Tooth loss is one of the most important health problems of our age. Tooth losses can occur for any reason. For this, implants are applied to restore the function and appearance of the teeth. However, the choice of implant materials is also very important. Metals, polymers, ceramics and composites are used as dental implant materials [1]. In addition, the most commonly used metal implant materials can be classified as Ti alloys, 316L stainless steel and Co–Cr alloys [2–4]. In this article, an application was made on the selection of the most suitable metal dental implant material. While choosing the most suitable material, criteria have been determined taking into account its strength properties. For the selection to be made, the most appropriate material was tried to be selected by using SWARA (Step-wise Weight Assessment Ratio Analysis) and Gray Relational Analysis, which are among the Multi-Criteria Decision Making (MCDM) techniques. The weights of the criteria to be considered in material selection were determined with SWARA, and the most suitable one among the alternatives was tried to be determined by using the criterion weights in SWARA with Gray Relational Analysis.

Although studies on MCDM methods on health and especially dental health are limited, Ağaç and Baki have conducted a literature study on the use of MCDM methods in the field of health [5]. Hsu and Pan applied the sorting in tooth quality according to their qualities with AHP (Analytic Hierarchy Process) and Monte Carlo [6]. Taş et al. They performed outpatient clinic evaluations in Ankara using AHP and TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) methods [7]. Gül et al. They studied the fuzzy multi-criteria scenarios of a hospital using fuzzy AHP, Vikor (VIseKriterijumska Optimizacija I Kompromisno Resenje) and Promethee (Preference Ranking Organization Method for Enrichment Evaluations [8]. Jerbi and Kamoun developed a simulation model of the emergency department on the current situation in a university hospital in Tunisia and came up with different alternatives [9]. Eskandari et al. used MCDM methods to reduce the patient waiting of a hospital in Iran, to sort and select the scenarios in the emergency department in order to examine the patient flow efficiently [10]. Turan and Turan used Analytical Hierarchy Method in the selection of nurses, which have an important place among hospital staff [11]. Below are examples of studies where SWARA and Gray Relational analysis are used together. Çakır has made an alternative selection that satisfies all stakeholders by using SWARA and Gray Relational Analysis methods in the rapidly spreading urban transformation process in our cities [12]. Again, Çakır and Akel used SWARA and Gray Relational Analysis in an integrated way to use the service quality of the reservation made through the website of holiday and hotel locations in Turkey, and reached the conclusion of “reliability” as the most important criterion in their survey [13]. They determined the importance of other criteria and tried to choose the best alternative among the alternatives [13]. Amiri et al. conducted a study on finding the optimal combination of supply chain strategies using SWOT analysis, Game theory and Multi Criteria Decision Making Methods, SWARA and ARAS (Additive Ratio

Assessment) [14]. Examples of studies in which the SWARA method is applied with other alternative determining methods used in decision making can be given as follows. Vafaeipour et al. In the implementation of solar energy projects in Iran, they used SWARA and WASPAS (Weighted Aggregated Sum Product Assessment), one of the mixed multi-criteria decision-making methods based on 25 cities, in determining the priority of the regions [15]. Keršulienė and Turskis have used SWARA and ARAS, one of the Multi Criteria Decision Making methods, for the selection of architects [16]. Zolfani and Saparauskas have used the SWARA method in prioritizing the sustainability assessment for energy [17]. Alimardani et al. They made a study that allows companies to choose the most suitable supplier for their policies and strategies by using SWARA and VIKOR methods, taking into account flexibility, performance, technology and cost criteria in today's agile supply chain [18]. Ruzgys et al. With the fact that most of the energy consumed in Europe belongs to old residences and external wall insulation studies were carried out, they wanted to list the most suitable alternatives by using the integrated evaluation SWARA and TODIM methods [19]. Karabasevic et al. They conducted a study by using SWARA and MULTIMOORA together in the selection of candidates belonging to the mining industry [20]. The studies in which the Gray Relational Analysis method is applied can be given as follows. Ertuğrul and Budak applied their employment studies for disabled people by using Gray Relational Analysis and MAUT (Multi Attribute Utility Theory), one of the MCDV methods, and investigated in which years the employment of disabled people in Turkey was higher [21]. Gold et al. They evaluated the airports in Europe in terms of their size. While doing this study, they preferred the Entropy method to find the criterion weights. In ordering the alternatives, Gray Relational Analysis and COPRAS (Complex Proportional Assessment) were used and airports were listed. The efficiency of the airports was analyzed with Data Envelopment Analysis. As a result of the study, 10 airports have emerged [22]. Chan and Tong applied the Gray Relational Analysis method in the alternative selection made by considering the economic, technical and environmental factors of the materials used in the manufacturing facility [23]. Elitaş et al. Using the Gray Relational Analysis method, he discussed the evaluation of the insurance companies that are in the ISE and traded in terms of performance [24]. Karaatlı et al. They also made a study about the livability of provinces in Turkey by using MCDV methods. They used Gray Relational Analysis, SAW (Simple Additive Weighting) and TOPSIS methods while doing the study [25]. Kung and Wen analyzed the financial performances of 20 venture capital firms in Taiwan in terms of financial indicators, taking into account the years 2001–2003 and measured them with the Gray Relational Analysis method [26]. Lin and Wu used the Gray Relational Analysis method in the banking sector to research credit risks. They applied Gray Relational Analysis to make a more reliable forecast than other classical methods in order to create a financial crisis warning due to the high risks in banking [27].

In this study, some of the most commonly used dental implant materials in the development of effective implant materials are analyzed by using SWARA and Gray Relational Analysis methods. With the multi-criteria analysis methods, the most performance material for dental implants has been determined.

10.2 Methodology

Although oral and dental health is important, problems may occur if the utmost importance is not shown. Among these, tooth loss is encountered as one of the most important problems. These losses are overcome by applying implants to the tooth. However, the type of material to be selected while applying the implant is also important. This study focuses on the selection of the most ideal metal dental implant materials. While making the selection, Multi Criteria Decision Making methods are applied. Criterion weight and grade were obtained by SWARA method and Gray Relational Analysis will be used in the selection of the most suitable alternative metal dental implant material. While determining the criterion weights, a paired comparison was made and the criterion weights and degrees of importance were taken into consideration [28]. Each column in this method is evaluated separately. Data entry is made for each column with the max and min values of each column. Therefore, the fact that the unit values of the parameters of all columns are different does not change the result.

10.3 SWARA Methodology

SWARA (Step-wise Weight Assessment Ratio Analysis) has been developed by Keršuliene et al. [29]. Its steps are as follows [30]:

Step 1: Criteria are ranked from most important to least important, in line with the opinion of the decision maker.
Step 2: Paired comparison between criteria j measure (j + 1). It is determined how important it is according to the criteria and (j + 1). It is written as the relative importance level in the opposite column of the criterion. However, while doing this, it starts with the second criterion [29].
Step 3: The k_j coefficient is determined by Eq. 10.3.1 (k variable)

$$k_j = \begin{cases} 1 & j = 1 \\ s_j + 1 & j > 1 \end{cases} \tag{10.3.1}$$

Step 4: w_j is determined by Eq. 10.3.2. x_{j-1} shows w_{j-1} (w variable)

$$w_j = \begin{cases} 1 & j = 1 \\ \frac{x_{j-1}}{k_j} & j > 1 \end{cases} \tag{10.3.2}$$

Step 5: Criteria weights $\left(q_j\right)$ are determined by Eq. 10.3.3.

$$q_j = \frac{w_j}{\sum_{k=1}^{n} w_k} \tag{10.3.3}$$

10.4 Grey Relational Analysis Method

Gray relational analysis is actually included in the Gray System Theory and was proposed by Deng in 1982 [31]. Its steps are given below [32].

Step 1: The decision matrix is created with the data set (i = line, j = column, x_i = option, $x_i(j)$ = performance values)

$$x_i = (x_i(1), x_i(2), x_i(3), \ldots, x_i(n)) \tag{10.4.1}$$

$$i = 1, 2, 3, \ldots, m \quad ve\, j = 1, 2, 3, \ldots, n \tag{10.4.2}$$

$$X = \begin{bmatrix} x_1(1) & \cdots & x_1(n) \\ \vdots & \ddots & \vdots \\ x_m(1) & \cdots & x_m(n) \end{bmatrix} \tag{10.4.3}$$

Step 2: Reference series and comparison matrix are created

$$x_0 = (x_0(1), x_0(2), x_0(3), \ldots, x_0(n)) \tag{10.4.4}$$

$$X_{new} = \begin{bmatrix} x_0(1) & \cdots & x_0(n) \\ \vdots & \ddots & \vdots \\ x_m(1) & \cdots & x_m(n) \end{bmatrix} \tag{10.4.5}$$

Step 3: The normalization matrix of the decision matrix is created

$$x_i^* = \frac{x_j^{(0)}(i) - \min x_j^{(0)}(i)}{\max x_j^{(0)}(i) - \min x_j^{(0)}(i)} \tag{10.4.6}$$

$$x_i^* = \frac{\max x_j^{(0)}(i) - x_j^{(0)}(i)}{\max x_j^{(0)}(i) - \min x_j^{(0)}(i)} \tag{10.4.7}$$

$$x_i^* = \frac{x_j^{(0)}(i) - x^0}{\max x_j^{(0)}(i) - x^0} \tag{10.4.8}$$

If the criteria of Eq. 10.4.6 are beneficial, Eq. 10.4.7 is cost oriented, and Eq. 10.4.8 is used in the most appropriate case and normalization process is performed. The values in the normalized table take values between 0 and 1.

Step 4: The absolute value table is created.

Step 5: The gray relationship coefficient matrix is created

$$\gamma(x_{0i}(j)) = \frac{\Delta_{min} + \delta\Delta_{max}}{\Delta_{0i}(j) + \delta\Delta_{max}} \tag{10.4.9}$$

$$i = 1, 2, 3, \ldots, m \; ve \; j = 1, 2, 3, \ldots, n \quad n, m \in N \tag{10.4.10}$$

The parameter δ is referred to as the "differential coefficient" and takes value in the range of [0,1]. The parameter δ regulates the relationship between Δ_{0i} and Δ_{max}, and this coefficient does not affect the overall ranking. Generally, 0.5 is taken [33].

Step 6: Determine gray relationship degrees

$$\Gamma_{0i} = \sum_{j=1}^{n} [w_i \, (j) \gamma_{0i}(j)] \tag{10.4.11}$$

w_i value given in Eq. 10.4.11 is the criterion weight.

10.5 Application

The study was conducted on the selection of the most suitable metal dental implant material. Six alternatives were evaluated according to four criteria, and the most suitable alternative was tried to be determined. Criterion weights were obtained by the SWARA method and the weights found were used in the Gray Relational Analysis method at the stage of sorting the alternatives. The initial decision matrix is given in Table 10.1.

Table 10.1 Initial decision matrix

Tissue/ material	Young's modulus (GPa)	Yield strength (MPa)	Compression strength (MPa)	Tensile strength (MPa)
Ti6A14V (casted)	114	820	855	912.5
Ti6A14V (wrought)	114	965	1034	912.5
Stainless steel 316L	193	240	730	770
CoCrMo alloy	240	1000	452	1220
Mg (99.9%, casted)	41	21	40	87
Mg (99.9%, wrought)	41	100	120	180

10.5.1 SWARA Application

While applying SWARA, the importance of the criteria is taken from the study of Uçar and Balo [28]. Criteria were listed in order of importance and a pairwise comparison was made, and how many times it was important (s_j values) was started from the 2nd criterion (the opposite column was left blank because the binary comparison of K3 is not more important than itself) and placed in the column. K3 has been identified as the most important criterion and other criteria are placed in order of importance. Then the values of k_j, q_j and w_j given in Eqs. 10.3.1, 10.3.2 and 10.3.3 were calculated. Criteria weights are given in Table 10.2.

The most important criterion is Compression Strength with 0.74419, while the least important criterion is Tensile Strength with 0.02326. The sum of the criterion weights gives 1.

Table 10.2 Criteria weights

Criteria name	Order of importance	Sorted criteria		s_j	k_j	q_j	w_j
Young's modulus (GPa) (K1)	1	K3	1		1	1	0.744
Yield strength (MPa) (K2)	2	K2	2	3	4	0.25	0.186
Compression strength (MPa) (K3)	3	K1	3	3	4	0.062	0.046
Tensile strength (MPa) (K4)	4	K4	4	1	2	0.031	0.023
Total						1.343	1

10.5.2 Grey Relational Analysis Application

As a first step, the reference series is determined according to the max and min criteria in the initial decision matrix (Table 10.1). However, since there is no minimum direction among the criteria, all of them are determined according to the maximum directions. While determining the reference series, the best value in each column (since it is max directional, the highest value is taken into consideration). This process is done for the other columns as well and the reference series is determined. The determined series is expressed as x_0 = Reference Series {240, 1000, 1034, 1220} and is shown in Table 10.3.

The values in Table 10.3 are the same as the initial decision matrix (Table 10.1). However, the only difference is that the reference series has also been added. Then, by finding the max and min values in the columns (without considering the row with the reference series), they are shown in Table 10.4.

In line with the values in Table 10.4, the normalization process was performed by using Eq. 10.4.6 (since the criteria are in max direction) and shown in Table 10.5.

New values are created by subtracting the normalized values from the Reference Series in absolute value (done separately for each row and column). For example, the values in the K1 column are subtracted from 1 (the reference series value of that column) in the absolute value and new values are found. These values are shown in Table 10.6.

The largest (Δ_{max}) and smallest (Δ_{mib}) in Table 10.6 are found by looking at the whole table. The δ parameter, which is defined as the separating coefficient, is also

Table 10.3 Reference series data set

Tissue/material	Max	Max	Max	Max
	Young's modulus (GPa) (K1)	Yield strength (MPa) (K2)	Compression strength (MPa) (K3)	Tensile strength (MPa) (K4)
Reference series	240	1000	1034	1220
Ti6A14V (casted)	114	820	855	912.5
Ti6A14V (wrought)	114	965	1034	912.5
Stainless steel 316L	193	240	730	770
CoCrMo alloy	240	1000	452	1220
Mg (99.9%, casted)	41	21	40	87
Mg (99.9%, wrought)	41	100	120	180

Table 10.4 Min and max values

Min	41	21	40	87
Max	240	1000	1034	1220

Table 10.5 Normalized matrix

Tissue/ material	Young's modulus (GPa) (K1)	Yield strength (MPa) (K2)	Compression strength (MPa) (K3)	Tensile strength (MPa) (K4)
Reference series	1	1	1	1
Ti6A14V (casted)	0.367	0.816	0.820	0.729
Ti6A14V (wrought)	0.367	0.964	1	0.729
Stainless steel 316L	0.764	0.224	0.694	0.603
CoCrMo alloy	1	1	0.414	1
Mg (99.9%, casted)	0	0	0	0
Mg (99.9%, wrought)	0	0.081	0.080	0.082

Table 10.6 Absolute value matrix

Tissue/ material	Young's modulus (GPa) (K1)	Yield strength (MPa) (K2)	Compression strength (MPa) (K3)	Tensile strength (MPa) (K4)
Ti6A14V (casted)	0.633	0.184	0.180	0.271
Ti6A14V (wrought)	0.633	0.036	0	0.271
Stainless steel 316L	0.236	0.776	0.306	0.397
CoCrMo alloy	0	0	0.586	0
Mg (99.9%, casted)	1	1	1	1
Mg (99.9%, wrought)	1	0.919	0.920	0.918

Table 10.7 $\Delta_{max}, \Delta_{min}$ve differential coefficient

Min	0
Max	1
ζ	0.5

Table 10.8 Grey relational coefficient matrix

Tissue/ material	Young's modulus (GPa) (K1)	Yield strength (MPa) (K2)	Compression strength (MPa) (K3)	Tensile strength (MPa) (K4)
Ti6A14V (casted)	0.441	0.731	0.735	0.648
Ti6A14V (wrought)	0.441	0.933	1	0.648
Stainless steel 316L	0.679	0.392	0.620	0.557
CoCrMo alloy	1	1	0.461	1
Mg (99.9%, casted)	0.333	0.333	0.333	0.333
Mg (99.9%, wrought)	0.333	0.352	0.352	0.353

shown in Table 10.7. This parameter does not affect the ranking in the studies and it is taken as 0.5 in the literature.

Grey Relationship Coefficient Matrix is created by writing these values given in Table 10.7 separately for each row in Eq. 10.4.9. This matrix is shown in Table 10.8.

The last process, the Determination of Gray Relationship Degrees and the Sorting process, was also placed in Eq. 10.4.11, and the best alternative was determined according to the Gray Relational Analysis method. In other words, the value in each column given in Table 10.8 has been multiplied by the criterion weight of the column (Table 10.2). Ranking process, on the other hand, has been collected by summing the row with each alternative and the Γ_{oi} values are obtained and shown in Table 10.9.

According to the Gray Relational Analysis Method, which is made with the criteria taken into consideration when choosing metal dental implant materials, the best metal dental implant material is Ti6A14V (wrought) with 0.953. With 0.719, Ti6A14V (casted) is in second place. CoCrMo Alloy ranked third with 0.599, Stainless Steel 316L fourth with 0.579 and Mg (99.9%, wrought) ranked fifth with 0.333. According to the method, the last one is Mg (99.9%, casted) with 0.351.

Table 10.9 Grades of gray relationships and ranking considering criteria importance

Tissue/ material	Young's modulus (GPa) (K1)	Yield strength (MPa) (K2)	Compression strength (MPa) (K3)	Tensile strength (MPa) (K4)		
W_i	0.047	0.186	0.744	0.023	Γ_{oi}	**Ranking**
Ti6A14V (casted)	0.021	0.136	0.547	0.015	0.719	2
Ti6A14V (wrought)	0.021	0.174	0.744	0.015	0.953	1
Stainless steel 316L	0.032	0.073	0.462	0.013	0.579	4
CoCrMo alloy	0.047	0.186	0.343	0.023	0.599	3
Mg (99.9%, casted)	0.016	0.062	0.248	0.008	0.333	6
Mg (99.9%, wrought)	0.016	0.066	0.262	0.008	0.351	5

10.6 Conclusion

All the developments and changes in the field of health, as in all other sectors, show that the increasing number of alternatives in solving problems and troubles leads people to make choices. Although health and human structure (teeth, eyes, height, etc.) vary from person to person and the problems encountered are tried to be solved by considering these factors, the selection and use of materials in some areas pushes people to choose among alternatives. In case of tooth loss, there are dental implant materials that can replace the main tooth in terms of appearance and function thanks to the advancing technologies. In this study, it has been tried to find which one of these is more appropriate by using Multi Criteria Decision Making methods.

When choosing the best alternative, MCDM methods were used. When choosing the alternatives, the criteria were taken into consideration, which criteria were important and the criterion weights were found, and these values helped to select an alternative. As mentioned at the beginning, the importance and order of importance of the criteria were applied with the SWARA method, taking into account the work of Uçar and Balo [28]. These weights found were also used in the Gray Relational Analysis method when choosing an alternative. According to the results of the method, Ti6A14V was among the best 3 materials, while Mg (99.9% casted) took the last place.

In order for people to be more knowledgeable in the selection of materials, promotions should be made in this area in dentists and social media. In order to use dental implant materials more efficiently, studies should be carried out using the highest technology.

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