# Chapter 3
# Energy Sustainability

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**Abstract** Energy sustainability is an important component of sustainability, especially for urban regions due to their relatively large energy use. The importance of energy sustainability is due to the notable environmental impacts of energy processes and the importance of energy in economic development, lifestyles, and living standards, in combination with the pervasiveness of energy use. Many factors need to be addressed appropriately for energy sustainability, including appropriate energy sources, energy carriers, efficiency enhancement, holistic environmental stewardship, and satisfying various other sustainability factors like economics, equity, land use, lifestyle, socio-political actions, and population. In this chapter, energy sustainability definitions are reviewed and the requirements of energy sustainability are discussed, focusing on its technical, environmental, economic, social, and other dimensions. Then energy sustainability is examined, along with means for enhancing it, and energy sustainability evaluation is discussed. An illustrative urban energy system is presented.

**Keywords** Energy · Energy use · Sustainability · Environment · Economy · Society · Equity · Resources · Renewable energy · Fossil fuels

## 3.1 Introduction

Energy sustainability is more holistic than simply sustainable energy sources, involving the sustainable use of energy in overall energy systems. Such systems include the harvesting of energy sources, their conversion to useful energy forms, energy transport and storage, and the utilization of energy to provide energy

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services. Sustainability is often considered to have environmental, economic, and social dimensions, and energy is indirectly linked to each. Energy resources are obtained from the environment, and wastes from energy processes are emitted to the environment. Energy resources drive much of the world's economic activity. Energy services support good standards of living, social and cultural development, and social stability.

Significant social and environmental challenges are linked to development, including high energy consumption, high greenhouse gas emissions, a large ecological footprint, and rapid resource consumption, including food and water. People are continually moving from rural areas to cities due to study and work opportunities, increasing the energy needs of citizens, including for communications. From the United Nations Climate Change Conferences, messages are conveyed to populations to reduce energy use and environmental impacts through actions such as reducing unnecessary use of lights in offices and homes. Most countries are increasingly aspiring to achieve sustainability and sustainable development.

In most countries, urban energy use is significant and often accounts for the majority of energy use. Given that the world's population and economy are becoming increasingly urbanized, the sustainability of urban energy use is a key factor in the quest for energy sustainability.

In this chapter, energy is described, and energy sustainability definitions are examined. The requirements of energy sustainability are discussed, focusing on technical, environmental, economic, social, and other factors. Then energy sustainability is examined, and means for enhancing energy sustainability are discussed. An interesting urban energy system is presented.

## 3.2 Energy

Energy exists in various forms, e.g., fossil fuels and fossil fuel-based products like gasoline, uranium, electricity, work, heat, and electromagnetic radiation (including light). Energy can be converted from form to form with energy-conversion technologies. We use energy carriers (often simply referred to as energy), produced from energy sources, in all aspects of living. Energy sources, or primary energy forms, are found in the natural environment. Many are listed in Table 3.1, where it is seen that some like fossil fuels are finite (non-renewable) while others like solar energy are renewable. Fossil fuels are the basis for most industrialized countries. Energy carriers are the energy forms that we transport and use (see Table 3.2), e.g., secondary chemical fuels and non-conventional chemical fuels like hydrogen and methanol. Many energy carriers do not exist naturally, including such energy forms as work, electricity, and non-ambient thermal energy.

**Table 3.1** Energy sources, broken down by non-renewable and renewable types

| Non-renewable | Renewable |
|---|---|
| Fossil fuels (mainly oil, natural gas, coal) | Solar radiation |
| Non-fossil fuels | Solar-related |
| Biomass (use rate > replenishment rate) | Hydraulic (very large to micro) |
| Uranium | Wind |
| Fusion material (e.g., deuterium) | Wave |
| Wastes (direct use or indirect via conversion) | Ocean thermal (temperature difference of deep and surface water) |
| | Biomass (use rate < replenishment rate) |
| | Non-solar-related |
| | Geothermal (internal earth heat and ground-source) |
| | Tidal (moon/sun gravitation and earth rotation) |

**Table 3.2** Energy carriers, broken down by chemical and non-chemical types

| Chemical | Non-chemical |
|---|---|
| Fossil fuels | Electricity |
| Secondary chemical fuels | Work |
| Oil products (e.g., gasoline, diesel fuel, naphtha) | Thermal energy |
| Synthetic gaseous fuels (e.g., from coal gasification) | Heat (or heated medium) |
| Coal products (e.g., coke) | Cold (or cooled medium) |
| Non-conventional (hydrogen, methanol, ammonia) | |

## 3.3 Energy Sustainability Definitions

Energy sustainability can be developed by extending the general definitions of sustainability to energy, but it is more complex. Energy is the basis of ecosystems, civilizations, and life, and is used in almost all facets of living. The standards of living achieved in countries are often a function of energy-related factors.

The present author defines energy sustainability as the provision of energy services, for all people now and in the future, in a sustainable manner. Providing energy services in a sustainable manner implies they are sufficient to provide basic necessities, affordable, not detrimental to the environment, and acceptable to communities and the people living within them. But universal agreement on a definition of energy sustainability has not yet been achieved, and other definitions and descriptions have been presented (Rosen, 2017a).

## 3.4 Energy Sustainability Requirements

There are several factors affecting how energy resources can be used sustainably in society, defining key requirements for energy sustainability, which are described in this section.

### *3.4.1 Capture/Production of Sustainable Energy Sources (Requirement 1)*

Non-fossil fuel energy options reduce or eliminate greenhouse gas emissions, and are renewable, and thus often facilitate sustainable energy options. The main types of renewable energy include solar energy, wind energy, hydraulic energy, geothermal energy (both the internal heat of the earth and the natural temperatures of the ground), biomass energy (provided its rate of use does not exceed its rate of replenishment), wave energy, tidal energy, and ocean thermal energy. Waste materials and energy can be used in waste-to-energy incinerators to generate electricity are also sometimes considered renewable energy. Nuclear energy is not renewable, but it avoids greenhouse gas emissions and thus contributes to avoiding climate change.

### *3.4.2 Conversion of Sustainable Energy Sources to Suitable Energy Carriers (Requirement 2)*

Energy carriers are an important consideration in energy sustainability because conventional and non-fossil fuel energy options are not necessarily readily utilizable in their natural forms. For instance, conversion systems are often needed to make non-fossil energy more conveniently utilizable. Energy carriers include electricity, work, thermal energy, and secondary chemical fuels. An example of a non-conventional energy carrier is hydrogen, which may become an important energy carrier in the future hydrogen economy (Gnanapragasam & Rosen, 2017; Rosen, 2017b; Scott, 2007).

### *3.4.3 Increased Efficiency in Provision of Energy Services (Requirement 3)*

High efficiency allows the greatest benefits to be attained from energy options, including renewable ones, and thus supports efforts to achieve energy sustainability. Increased efficiency elongates the lives of finite energy resources, and reduces the capacities required of energy devices. In a holistic sense, efficiency enhancement measures include technology efficiency improvements, improved energy management, energy conservation, fuel substitution, more efficient utilization of both energy quantity and quality, and better matching of energy supply and demand. Efficiency improvement efforts are often best assessed and developed with exergy analysis, an alternative analysis method often reveals insights not identified with conventional energy analysis (Dincer & Rosen, 2013; Rosen, 2012).

### 3.4.4 Reduced Environmental Impact Over Life Cycle of Energy Processes (Requirement 4)

A wide range of environmental impacts are associated with energy processes. Some notable examples follow:

- Climate change due to emissions of greenhouse gases, particularly carbon dioxide.
- Stratospheric ozone depletion permits the increased ultraviolet radiation to reaching the earth.
- Acidification of water and soil.
- Abiotic depletion of non-renewable raw materials due to their extraction.
- Ecotoxicity exposure and the ensuing health problems.
- Radiological releases that increase rates radiogenic cancer mortality and morbidity.

These energy-related environmental impacts need to be addressed for energy sustainability. For instance, non-fossil fuel energy options are needed to help humanity mitigate climate change (Rosen et al., 2012). To comprehensively assess the environmental impact of an energy activity, its entire life cycle must be considered, from acquisition of energy sources and other resources to their utilization and ultimate disposal. Life cycle assessment (LCA) is such a technique and it creates an inventory of environmental effects like resource depletion, waste generation and energy consumption, and their environmental impacts (Graedel & Allenby, 2010; Jianu, Pandya, Rosen, & Naterer, 2016). Guidelines for LCA have been developed by the International Organization for Standardization.

### 3.4.5 Consideration of Other Facets of Sustainability (Requirement 5)

Many other sustainability issues are related to energy sustainability, and some are now described.

#### 3.4.5.1 Economic Affordability

For sustainability, the energy services required for basic needs must be economically affordable by all societies and people (Rosen, 2011). Sometimes efficiency improvement and environmental mitigation measures can over time save money or be revenue neutral, aiding affordability.

#### 3.4.5.2 Community Involvement and Social Acceptability

For energy sustainability, people and communities must be involved in and supportive of energy-related decisions. Communities support is critical, and almost always requires consultation.

#### 3.4.5.3 Lifestyles

Modifying lifestyles and moderating energy-related desires can support energy sustainability, although this is often challenging because people's aspirations tend to increase. Translating future energy-related threats into immediate priorities will likely remain a difficult challenge for decision and policy makers.

#### 3.4.5.4 Appropriate Land Use

Land uses for energy need to be balanced with uses for such other purposes as agriculture and recreation, e.g., land use for the growth of energy plants needs to be balanced with agricultural needs while land requirements for electricity transmission need to be balanced with the needs of the ecosystems they traverse sensitive areas.

#### 3.4.5.5 Equity

All societies must have access to energy resources, regardless of geographic location, and future generations must also be able to access energy resources. In addition, equity among developed and developing countries must be achieved in terms of energy opportunities.

#### 3.4.5.6 Meeting Increasing Energy Demands

The increasing use of energy resources, especially as developing countries become more urbanized, industrialized, and attain higher living standards, must be satisfied. This issue is exacerbated by populations rise.

#### 3.4.5.7 Aesthetics

The cleanliness of the environment affects the well-being of people and thus pertains to energy sustainability. Even renewable energy technologies can mar the landscape, e.g., large wind turbines farms and rooftop or ground-mount photovoltaic panels.

## 3.5 Urban Energy Sustainability

The energy needs of cities are large and increase with urban growth. In general, urbanization causes major shifts in land-use patterns, and changes the ways societies use energy. Urbanization is accelerating in many developing countries. Increasing urban energy efficiencies can often improve living standards, quality of life, and satisfaction of people. For example, Sweden has a per capita gross domestic product near to that of the USA but uses 40% less energy per capita and outranks the USA on most social indicators. Some contributing factors are lower energy wastes in residential and commercial buildings, and transportation advantages such as better public transit, smaller automobiles, higher gasoline taxes, and compactness of geography.

Energy measures can sometimes be introduced voluntarily and be successful, while at other times governments need to use incentives and enforcement measures. In urban communities, for example, the combination of inexpensive energy and moderate environmental constraints in North America has led to a preference for urban travel by automobile rather than public transportation. Options related to energy issues to improve living standards can be technical and nontechnical (e.g., changing lifestyles and increasing awareness). China and its cities provide a notable recent example of the challenges of urban energy sustainability. Energy use in China rose notably from 2000 to 2005, especially in urban areas, increasing wealth and living standards and fostering trends of greater resource consumption and purchase of consumer goods. This change in behavior can further increase demands for resources, including energy. A reinforcing effect can thus develop, where increased energy use raises living standards, which in turn drives further increases in energy use (Zhang & Wang, 2013).

## 3.6 Improving Energy Sustainability

Numerous methods and technologies can be used to enhance energy sustainability, and often apply strongly in urban contexts. Some of these are described below.

**High-Efficiency Devices and Lighting**
Energy sustainability can be supported by the use of high-efficiency devices, e.g., high-efficiency home appliances, furnaces and air conditioners, and motors and

fans. New lighting systems have significantly higher efficiencies and longer lives than older equipment.

**Energy Storage**
Energy storage can be used to improve system efficiency by storing energy between times when it is available and when it is needed (Dincer & Rosen, 2011), e.g., solar thermal energy collected in the day for space heating at night.

**Energy Loss Prevention and Waste Recovery**
Efficiency can be improved by preventing energy losses and recovering energy wastes, by inspecting periodically to detect and mitigate losses, and using technologies and processes to avoid losses (e.g., insulating).

**Maintenance, Monitoring, and Control**
The efficiency and life span of equipment can be enhanced via maintenance, e.g., regular cleaning of equipment, replacement of consumable items, and lubrication of moving parts, periodic equipment overhauls, and periodic calibration, tuning and testing of equipment.

**Improved Matching of Energy Supplies and Demands**
Instead of supplying energy of a much higher quality than required for a demand, it can be more efficient to supply an energy form of a better matched quality, e.g., supplying furnace combustion gases at 600 °C to space heat a building to 22 °C is a poorer match than heat at 45 °C.

**Building Envelopes**
The energy efficiency of a building can be improved via insulation to reduce heat gains in summer and losses in winter, weather stripping and caulking, to reduce air leakages, high-efficiency windows with multiple glazing and low-emissivity window coatings, and window shades or blinds equipped with sensors that adjust to keep out excessive sunlight.

**Passive Methods and Technologies**
Passive, as opposed to active, methods can be used to enhance energy sustainability, e.g., utilizing daylight harvesting to offset artificial lighting and using solar energy to heat buildings, as well as placing trees, windows, and window shades so as to keep buildings cool during summers.

**District Energy and Integrated Energy Systems**
Thermal energy can be a particularly useful energy carrier for urban energy use. It can be produced in centralized heating or cooling facilities and transported to users over long distances in district heating and/or cooling systems, which are used in many cities and industrial parks (Rosen & Koohi-Fayegh, 2016). Efficiency can also be increased by linking separate systems advantageously to create integrated energy systems, e.g., cogeneration, trigeneration, and multigeneration (Rosen & Koohi-Fayegh, 2016).

**Use of Exergy Analysis and Other Tools**

It has been suggested that thermodynamic performance is best evaluated and improved using exergy analysis in addition to or in place of energy analysis, where exergy is a measure of the usefulness or quality or value of energy (Dincer & Rosen, 2013). Exergy analysis provides more meaningful efficiencies energy analysis, and specifies process inefficiencies (types, causes, and locations) better. Many applications of exergy analysis have been reported, including advanced optimization methods (Dincer, Rosen, & Ahmadi, 2017).

## 3.7 Illustrative Example: Net-Zero Energy Buildings and Communities

Buildings are responsible for a significant portion of the energy use and environmental impacts in many countries. The design and operation of buildings and communities can be transformed to reduce energy use and emissions, by allowing buildings to act as a net energy generator. Thus, net-zero energy buildings can contribute to energy sustainability, especially in urban areas (Rosen, 2015). A net-zero energy building is defined as one that, in an average year, produces as much electrical plus thermal energy from renewable energy sources as it consumes. A net-zero energy community is similar, but applicable to communities. Smart net-zero energy buildings and communities can reduce environmental impacts, localized generation strategies, manage loads, reduce utility electrical demands, and transportation energy savings via electric or hybrid cars that use electricity from renewable building-integrated energy systems (Garmsiri, Kouhi-Fayegh, Rosen, & Smith, 2016).

Work on net-zero energy buildings has been reported. The Smart Net-zero Energy Buildings Strategic Research Network was launched in Canada in 2011 (http://www.solarbuildings.ca), and the International Energy Agency has an annex entitled "Towards Net-zero Energy Solar Building." Design, optimization, and modeling issues have been investigated (Berggren, Hall, & Wall, 2013; Bucking, Athienitis, & Zmeureanu, 2013; Cellura, Guarino, Longo, & Mistretta, 2014; Mohamed, Hasan, & Sirén, 2014), as has the relation between net energy use and the urban density of solar buildings. The integration of net-zero energy buildings into the electrical grid has been examined (Gaiser & Stroeve, 2014). Work on net-zero energy buildings was extended in recent years to net-zero energy communities, e.g., the design of solar-optimized neighborhoods, infrastructure interactions in the design of sustainable neighborhoods, and benefits of seasonal storage of solar energy for space heating in the Drake Landing Solar Community in Canada (Rad, Fung, & Rosen, 2017).

Net-zero energy buildings and communities can make significant contributions to energy sustainability:

- **Sustainable energy sources**. The main benefit of net-zero energy buildings and communities, averaged over the year, is that they typically utilize renewable energy sources like solar and geothermal (Rosen & Koohi-Fayegh, 2017).
- **Sustainable energy carriers**. Thermal energy (heat) is used, which facilitates the use of renewable energy sources like solar and geothermal.
- **Increased efficiency**. The efficiency of net-zero energy buildings and communities is typically high.
- **Reduced environmental impact**. Net-zero energy buildings and communities have little environmental emissions associated with their operation, even after accounting for the full life cycles of the buildings and communities.
- **Fulfillment of other aspects of sustainability**. Net-zero energy buildings and communities are anticipated to contribute to economic affordability of energy, alleviate resource demands on societies, and be acceptable, noting that net-zero energy buildings and communities are likely to be implemented only where they are viewed as socially acceptable.

**Closing Remarks**

Energy sustainability is important for overall sustainability. Various factors need to be appropriately addressed to achieve energy sustainability, including appropriate selection of energy resources, proper energy carriers to facilitate sustainable energy resources, enhancement of the efficiency of energy activities, environmental stewardship in energy processes, and consideration of other key sustainability measures, such as economics, lifestyles, living standards, and equity. The material provided in this chapter, which includes energy types, energy sustainability definitions and requirements, energy sustainability, and means for enhancing it, is intended to help in achieving, or at least shifting closer to, energy sustainability by doing so, it is hoped that sustainability can be given a greater focus.

## References

Berggren, B., Hall, M., & Wall, M. (2013). LCE analysis of buildings: Taking the step towards net zero energy buildings. *Energy and Buildings, 62*, 381–391.

Bucking, S., Athienitis, A., & Zmeureanu, R. (2013). An information driven hybrid evolutionary algorithm for optimal design of a net zero energy house. *Solar Energy, 96*, 128–139.

Cellura, M., Guarino, F., Longo, S., & Mistretta, M. (2014). Energy life-cycle approach in net zero energy buildings balance: Operation and embodied energy of an Italian case study. *Energy and Buildings, 72*, 371–381.

Dincer, I., & Rosen, M. A. (2011). *Thermal energy storage: Systems and applications* (2nd ed.). London: Wiley.

Dincer, I., & Rosen, M. A. (2013). *Exergy: Energy, environment and sustainable development* (2d ed.). Oxford: Elsevier.

Dincer, I., Rosen, M. A., & Ahmadi, P. (2017). *Optimization of energy systems*. London: Wiley.

Gaiser, K., & Stroeve, P. (2014). The impact of scheduling appliances and rate structure on bill savings for net-zero energy communities: Application to West Village. *Applied Energy, 113*, 1586–1595.

Garmsiri, S., Kouhi-Fayegh, S., Rosen, M. A., & Smith, G. R. (2016). Integration of transportation energy processes with a net zero energy community using captured waste hydrogen from electrochemical plants. *International Journal of Hydrogen Energy, 41*(19), 8337–8346.

Gnanapragasam, N. V., & Rosen, M. A. (2017). A review of hydrogen production using coal, biomass and other solid fuels. *Biofuels, 8*(6), 725–745.

Graedel, T. E., & Allenby, B. R. (2010). *Industrial ecology and sustainable engineering*. Upper Saddle River, NJ: Prentice Hall.

Jianu, O., Pandya, D., Rosen, M. A., & Naterer, G. (2016). Life cycle assessment for Thermolysis and electrolysis integration in the copper-chlorine cycle of hydrogen production. *WSEAS Transactions on Environment and Development, 12*(Art. #26), 261–267.

Mohamed, A., Hasan, A., & Sirén, K. (2014). Fulfillment of net-zero energy building (NZEB) with four metrics in a single family house with different heating alternatives. *Applied Energy, 114*, 385–399.

Rad, F. M., Fung, A. S., & Rosen, M. A. (2017). An integrated model for designing a solar community heating system with borehole thermal storage. *Energy for Sustainable Development, 36C*, 6–15.

Rosen, M. A. (2011). *Economics and exergy: An enhanced approach to energy economics*. Hauppauge, NY: Nova Science Publishers.

Rosen, M. A. (2012). *Environment, ecology and exergy: Enhanced approaches to environmental and ecological management*. Hauppauge, NY: Nova Science Publishers.

Rosen, M. A. (2015). Net-zero energy buildings and communities: Potential and the role of energy storage. *Journal of Power and Energy Engineering, 3*(4), 470–474.

Rosen, M. A. (2017a). Sustainable development: A vital quest. *European Journal of Sustainable Development Research, 1*(1), 2.

Rosen, M. A. (2017b). Enhancing renewable energy prospects via hydrogen energy systems. *Journal of Fundamentals of Renewable Energy and Applications, 7*(5), 22.

Rosen, M. A., & Koohi-Fayegh, S. (2016). *Cogeneration and district energy systems: Modelling, analysis and optimization*. London: Institution of Engineering and Technology.

Rosen, M. A., & Koohi-Fayegh, S. (2017). *Geothermal energy: Sustainable heating and cooling using the ground*. London: Wiley.

Scott, D. S. (2007). *Smelling land: The hydrogen defense against climate Catastrophe*. Ottawa: Canadian Hydrogen Association.

Zhang, Y., & Wang, Y. (2013). Barriers' and policies' analysis of China's building energy efficiency. *Energy Policy, 62*, 768–773.