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REVIEW PAPER

# A review on clean energy solutions for better sustainability

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## SUMMARY

This paper focuses on clean energy solutions in order to achieve better sustainability, and hence discusses opportunities and challenges from various dimensions, including social, economic, energetic and environmental aspects. It also evaluates the current and potential states and applications of possible clean-energy systems. In the first part of this study, renewable and nuclear energy sources are comparatively assessed and ranked based on their outputs. By ranking energy sources based on technical, economic, and environmental performance criteria, it is aimed to identify the improvement potential for each option considered. The results show that in power generation, nuclear has the highest (7.06/10) and solar photovoltaic (PV) has the lowest (2.30/10). When nonair pollution criteria, such as land use, water contamination, and waste issues are considered, the power generation ranking changes, and geothermal has the best (7.23/10) and biomass has the lowest performance (3.72/10). When heating and cooling modes are considered as useful outputs, geothermal and biomass have approximately the same technical, environmental, and cost performances (as 4.9/10), and solar has the lowest ranking (2/10). Among hydrogen production energy sources, nuclear gives the highest (6.5/10) and biomass provides the lowest (3.6/10) in ranking. In the second part of the present study, multigeneration systems are introduced, and their potential benefits are discussed along with the recent studies in the literature. It is shown that numerous advantages are offered by renewable energy-based integrated systems with multiple outputs, especially in reducing overall energy demand, system cost and emissions while significantly improving overall efficiencies and hence output generation rates. Copyright © 2015 John Wiley & Sons, Ltd.

**KEY WORDS**

clean energy; system integration; multigeneration; renewables; sustainability

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## 1. INTRODUCTION

One of the biggest challenges in the world is to meet the growing energy demands in an environmentally-benign and sustainable manner, especially in rapidly developing countries with their rising populations and standards of living. The key prerequisite is, in this regard, to provide clean energy solutions.

The International Energy Agency (IEA) states that in 2012, global total primary energy supply (TPES) was 13,371 Mtoe, electricity generation was 22,668 TW h, and final consumption was 8979 Mtoe [1]. These numbers are expected to escalate dramatically with continuing consumption and population increase trends. Figure 1 demonstrates world's fuel shares of TPES, electricity generation, total final consumption, and resulting $CO_2$ emissions in 2012. From Figure 1, it can be seen that 81.7% of the global TPES, 67.9% of global electricity generation, and 78.29% of global total final consumption were met by fossil fuels in 2012. However, fossil fuels have limited nature; they are not expected to keep up with the increase in energy demand. Also, they are not distributed uniformly, which makes some countries 'energy dependent' on others. Another issue is fossil fuel reserves are getting less accessible as the easily accessible ones are consumed, and the prices of fossil fuels are expected to increase because of accessibility loss and political uncertainties of the countries holding worlds' fossil fuel supplies. In addition to economic and technical issues, greenhouse gasses (GHG; mainly $CO_2$) emissions as a result of fossil fuel utilization and their negative impact on the environment and human health have been raising serious concerns. Figure 1 also shows that 99.5% of global GHG emissions were caused by fossil fuels. Therefore, switching to a

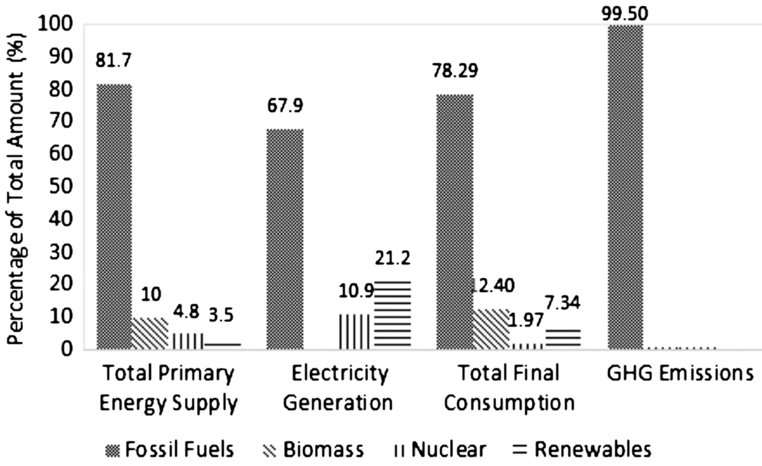


**Figure 1.** Fuel shares of global total primary energy supply, electricity generation, total final consumption, and greenhouse gasses (GHG) emissions (Data from [1]).

nonfossil fuel energy source could greatly reduce the related emissions and their adverse effects.

Supplying the world's drastically increasing demands without environmental detriment and fossil fuel dependence can only be achieved by implementing clean energy systems which can offer considerable social, energetic, environmental and economic benefits. To be truly sustainable, an energy system must meet the following criteria: (i) minimal or no negative environmental or social impact; (ii) no natural resource depletion; (iii) being able to supply the current and future population's energy demand; (iv) equitable and efficient manner; (v) air, land, and water protection; (vi) little or no net carbon or other GHG emissions; and (vii) safety today without burdening future generations.

Clean energy systems have the potential to the following: (i) reduce emissions by taking advantage of renewable and cleaner sources; (ii) lower energy input requirements; (iii) increase system efficiencies by expanding useful outputs (i.e., multigeneration); and (iv) reduce emissions and waste by recovering energy. Dincer [2] makes a pragmatic approach and defines six key pillars, such as better efficiency, better cost effectiveness, better resources use, better design and analysis, better energy security, and better environment in order to achieve better sustainable development.

In this study, it is aimed to review and assess the current state, potential, and applications of clean energy systems. First, renewable energy sources are studied and evaluated based on their types of output. After comparatively assessing renewable energy sources with respect to types of outputs, multigeneration and energy recovery systems are investigated. Ultimately, the objective of this assessment is to identify promising pathways to sustainable solutions for current and future energy systems

## 2. CLEAN ENERGY SOLUTIONS

Clean energy systems are expected to address global energy issues without negatively affecting the environment, economy, and the resources of the future generations as well as sustainability. Clean energy solutions aim to achieve the following critical targets for *better sustainability*:

- better efficiency,
- better resources use,
- better cost effectiveness,
- better environment,
- better energy security, and
- better design and analysis.

These are also directly related to a *3S concept* (so called source-system-service). In this concept, we should have certain tasks achieved in these 3S categories to make truly clean coverage, as illustrated in Figure 2. As we start developing a clean solution, it is important to select a clean energy source. There are of course several criteria to consider, such as abundance, local availability, cost effectiveness, reliability, safety, and environmental friendliness. Most promising sources appear to be renewables. When it comes to specific systems, it is necessary to investigate irreversibilities, energy and exergy efficiencies in addition to the earlier listed main goals. Furthermore, one can study system by considering the following critical steps.

- Process improvement: minimizing consumption while maximizing the amount of desired output.
- Efficiency increase: identifying and improving units/components/streams causing inefficiencies.
- System integration: more reliable operation and higher output rates.
- Multigeneration: increasing the number of desired outputs by using the same input.

When it comes to the service step, which can be considered as the application step, it is equally important to minimize losses, irreversibilities, wastes, and so on, and recovering useful commodities, such as heat to materials.

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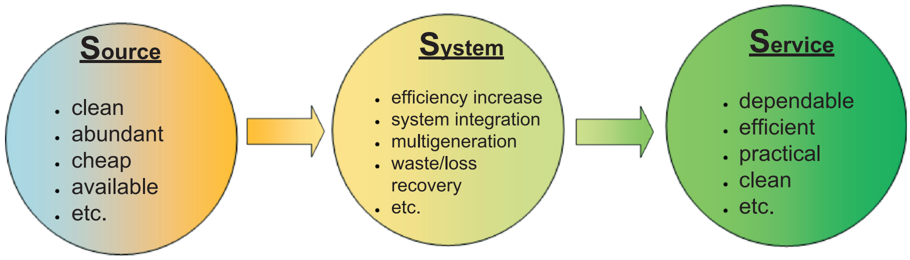


**Figure 2.** 3S (source-system-service) route to sustainability.

In the literature, there is great attention on technology research, development, and implementation of clean energy systems. Figure 3 illustrates possible clean energy system alternatives along with traditional fossil fuel-based ones. Delwulf and Van Langenhove [3] performed a technical assessment by incorporating industrial ecology principles into a set of environmental sustainability indicators. In their study, sustainability of various technology options is evaluated in a quantitative way. By using second law of thermodynamics, they defined sustainability indicators as follows: (i) renewability of resources; (ii) toxicity of generated emissions; (iii) input of used materials; (iv) recoverability of the products at the end of their use; and (v) technological efficiency. However, there is still a lack of single standard or common consensus on sustainability indicators.

There have been tremendous efforts in industry, academia, and social organizations in order to designate tools and manuals to evaluate sustainability in a commonly accepted and quantifiable way. In 2005, the International Atomic Energy Agency [4] published 30 energy indicators for sustainable development. These indicators cover social (equity and safety), economic, and environmental aspects of sustainability. In 2007, the United Nations Commission for Sustainable Development [5] introduced a core set of 50 indicators for sustainable development. In 2012, Singh *et al.* [6] published a review of these sustainability assessment methodologies and compiled the information related to sustainability indices formulation including strategy, scaling, normalization, weighing, and aggregation procedures. One of the recent works of Mainali and Silveira [7] examined different sustainability analysis approaches and presented a method for evaluating the sustainability performance of energy technologies.

Dincer and Rosen [8] investigated several environmental issues such as acid precipitation, stratospheric ozone

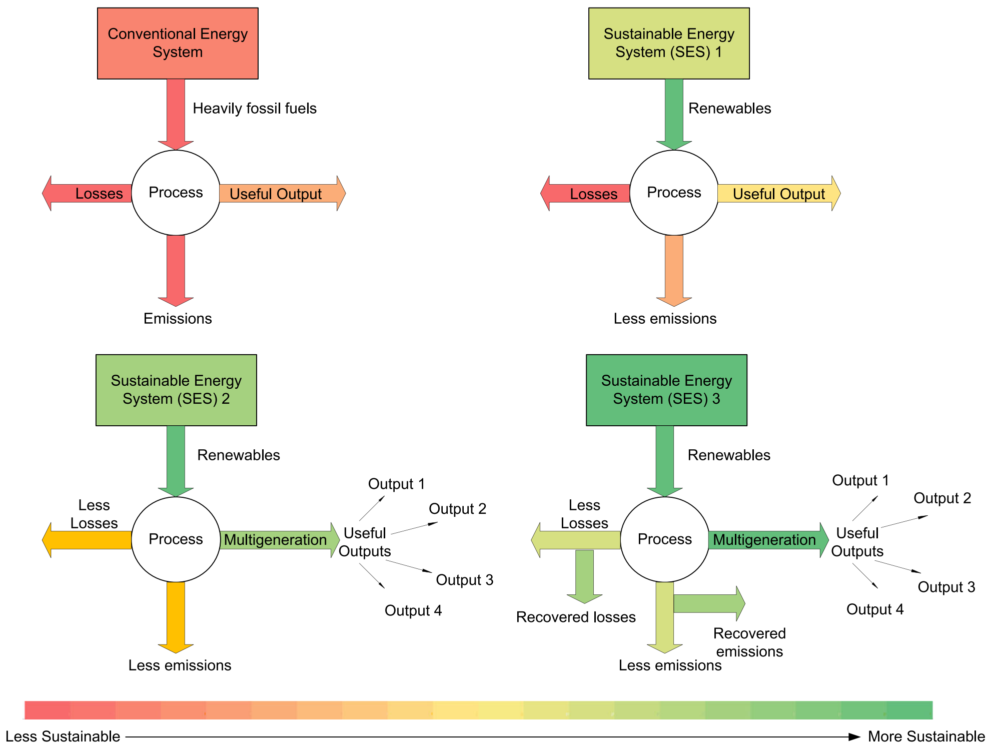


**Figure 3.** Possible sustainable energy system options (Adapted from [12]).

depletion, and GHG effect to relate energy, environment, and sustainable development. Later, Dincer [9] examined the link between renewable energies and sustainable development. In their study, public awareness, information, environmental education and training, innovative energy strategies, promoting renewable energy resources, financing, and monitoring and evaluation tools are listed as essential factors for sustainable development. Principles of exergy are used to study environmental impact of clean energy systems by Dincer and Rosen [10]. In their study, increased utilization of renewable energies is linked to increased sustainability by using technical, economic, commercialization, and social and environmental impact assessments. Midilli *et al.* [11] developed sustainable development parameters and investigated seven different possible green energy strategies based on these parameters. Their parameters are sectoral impact ratio, technological impact ratio, practical application impact ratio, green-energy impact ratio, and green energy-based sustainability ratio. Dincer and Zamfirescu [12] concluded that cogeneration and trigeneration options are promising clean energy system candidates as their efficiencies are higher and hence GHG emissions are lower compared to conventional single-output energy systems.

## 3. RENEWABLE ENERGY SOURCES

Renewable energy sources can reduce, and ultimately eliminate, GHG emissions related to fossil-fuel combustion. Therefore, they are considered to have the key role to mitigate climate change. Proper and efficient utilization of renewable energy sources could potentially lead to social and economic development with secure and sustainable supply and access and reduction of negative impacts of energy sector on the environment.

Energy derived from natural processes using continually replenished sources is described to be renewable energy by the IEA [1]. These energy sources can be directly or indirectly derived from the sun (i.e., solar, hydro, wind, wave, and biomass) or they can be nonsolar (i.e., geothermal, tidal, and ocean). Types of renewable energies along with their output types are shown in Figure 4.

In Figure 5, dispatchability, geographical diversity potential, predictability, and active power control of renewable energy systems are compared based on the data provided by the Intergovernmental Panel on Climate Change [13]. In dispatchability category, a degree of resource dispatchability is compared. Generation units are considered to be fully dispatchable (ranked as 10) when they can be loaded from zero to full capacity without significant delay. Geographical diversity potential shows degree to which siting of the technology may mitigate variability and improve predictability, without substantial need for additional network. Rank 10 in geographical diversity is assigned to the technology with 100% mitigation potential. Predictability indicates the accuracy to which plant output can be predicted at relevant time scales. Control shows technology possibilities enabling plant to participate in active control and frequency response during normal situations (steady state, dynamic) and during network fault situations. In ideal case, the system is assumed to be fully dispatchable (rank 10) with high geographical diversity potential (rank 10), high prediction accuracy (rank 10), and full control possibilities (rank 10). The center of the figure is assigned to have the poorest performance, meaning lowest dispatchability (rank 0), geographical diversity potential (rank 0), predictability (rank 0), and control possibilities (rank 0). In terms of dispatchability, biomass and geothermal have the highest performance, while ocean and wind have the lowest dispatchability. Wind has the highest geographical diversity; on the other hand, it has very low predictability. In terms of control, biomass, geothermal, and hydropower provide better performance. Overall, biomass and geothermal are closest to ideal case, and wind shows the poorest performance. The dispatchability, geographical diversity, predictability, and control rankings of renewable energy sources are summarized in Table I. A summary of

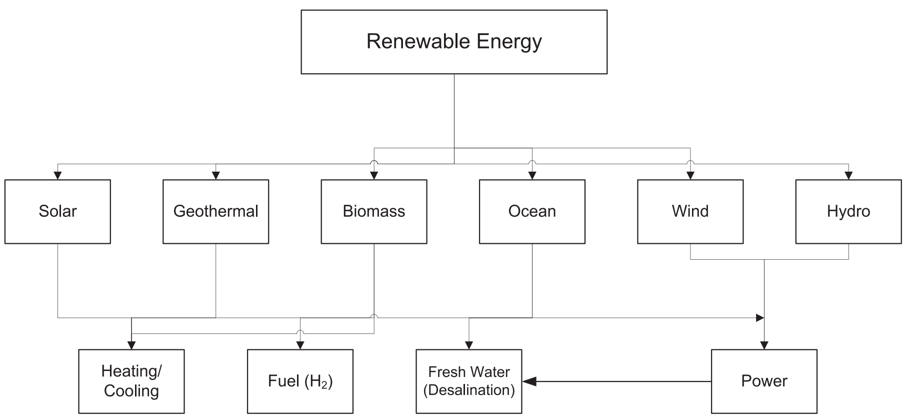


**Figure 4.** Types of renewable energy sources along with their associated outputs.


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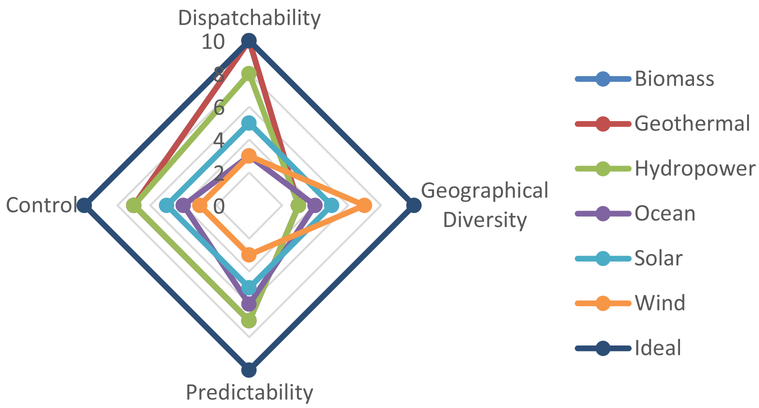


**Figure 5.** Comparison of integration characteristics for a selection of renewable energy systems (Data from [13]).

**Table I.** Summary of dispatchability, geographical diversity, predictability, and control rankings of renewable energy sources.

| Source of energy | Dispatchability | Geographical diversity | Predictability | Control | Average |
|---|---|---|---|---|---|
| Biomass | 10 | 3 | 7 | 7 | 6.75 |
| Geothermal | 10 | 3 | 7 | 7 | 6.75 |
| Hydropower | 8 | 3 | 7 | 7 | 6.25 |
| Ocean | 3 | 4 | 6 | 4 | 4.25 |
| Solar | 5 | 5 | 5 | 5 | 5 |
| Wind | 3 | 7 | 3 | 3 | 4 |
| Ideal | 10 | 10 | 10 | 10 | 10 |

benefits and drawbacks of renewable energy sources is presented in Table II.

### 3.1. Power (electricity)

Before the development of innovative power generation technologies, electricity was produced either by hydroelectric dams in remote locations or by fossil fuel combustion in central areas. Fossil-fuel combustion distributed electricity and waste heat (considered as by-product) to surrounding buildings and rural areas that had no electricity supply. As cities got more populated, fossil fuel (mainly coal)-fired power plants were driven to outside of urban areas because of their heavy emissions affecting human health and the environment. However, 10–15% of the electricity got lost while transmitting electricity to final users, and it was not practical to transmit waste heat over extended distances [14]. With the development of grid systems, electricity could be delivered to cities and rural areas more efficiently. By then, general consensus agreed that central generation was more efficient than decentralized production.

In today's world, there is significant interest in producing electricity in a cleaner, cost effective, and more efficient way for both centralized and decentralized power generation systems. Table III summarizes current annual power generations, capacity factors, mitigation potentials, energy requirements, $CO_2$ emissions, and electricity generation costs of available technologies. Here, capacity factor indicates the ratio of the actual output over a period of time (typically a year) to the theoretical output that would be produced if the unit were operating uninterruptedly. Mitigation potential shows the amount of $CO_2$ emissions reduced by not using fossil fuels. Energy requirements show the amount of thermal energy provided to produce 1 kW h of electricity. Last, all costs are US$-based.

Table III shows that coal, oil, and gas have very high annual generation and capacity factor and low production costs compared with nuclear and renewable options because of fossil fuels' already developed and mature electricity generation technologies. However, fossil fuels have the highest $CO_2$ emissions and energy requirements (kW h thermal energy input to generate 1-kW h electricity). In order to investigate nuclear and renewable energy sources, the data in Table III are normalized excluding fossil fuels (coal, oil, and gas). Normalization is performed based on whether it is desired to minimize or maximize data. By doing normalization, selected electricity production options are ranked based on a zero to 10 scale where zero shows the poorest performance with lowest annual generation,

**Table II.** Summary of benefits and drawbacks of renewable energy sources (Modified from [75]).

| Source of energy | Benefits | Drawbacks |
|---|---|---|
| Biomass | Abundant with a wide variety of feed stocks and conversion technologies | May not be $CO_2$ natural<br>May release greenhouse gasses (e.g., methane) during biofuel production<br>Landscape change and deterioration of soil productivity |
| | Indigenous fuel production and conversion technology in developing countries | High fertilizer and water need<br>Difficulty of maintaining constant supply of resource<br>High sensitivity to local climatic/weather effects |
| Geothermal | Abundant and clean | Expensive start-up and maintenance because of corrosion<br>Risk of hydrogen sulfide emissions<br>Subsidence, landscape change, polluting waterways |
| Hydropower | Abundant, clean, and safe<br>Relatively robust technology<br>Easily stored in reservoirs<br>Relatively inexpensive<br>Accessibility in developing countries | May cause flooding of surrounding communities and landscapes<br>Impact on local ecosystems—risk of droughts, dry seasons, and changes in local water and land |
| | Fairly constant production rate<br>Lower overall and maintenance costs | Site specific<br>High capital/investment costs |
| Ocean | Ideal for remote islands | Construction costs<br>Potential negative impact on ocean wildlife<br>Space and transportation issues<br>Reduction in water motion or circulation |
| Solar | Abundant supply<br>Less environmental damage compared to other renewable options | Cost effectiveness<br>Storage and backup issues<br>Not a constant supply—intermittent and fluctuating nature |
| Wind | Relatively simple and robust technology | Site specific<br>Variable power production<br>High capital/initial investment costs |
| | Low maintenance requirements | Access problems in remote areas<br>Noise pollution<br>Negative impact on the ecosystem |

**Table III.** Summary of current states of electricity generation from fossil fuels, nuclear, and renewable sources.

| Source of energy | Annual generation (TWh/y) | Capacity factor (%) | Mitigation potential ($GtCO_2$) | Energy requirements ($kW h^{th}/kW h^{el}$) | $CO_2$ emissions (g/kW h) | Production cost (US¢/kW h) |
|---|---|---|---|---|---|---|
| Coal | 7755 | 70–90 | N/A | 2.6–3.5 | 900–1200 | 3–6 |
| Oil | 1096 | 60–90 | N/A | 2.6–3.5 | 700–1200 | 3–6 |
| Gas | 3807 | 55–65 | N/A | 2–3 | 450–900 | 4–6 |
| Nuclear fusion | 2793 | 86 | >180 | 0.12 | 65–200 | 3–7 |
| Biomass | 240 | 60 | 100 | 2.3–4.2 | 35–85 | 3–9 |
| Geothermal | 60 | 70–90 | 25–500 | N/A | 20–140 | 6–8 |
| Hydro (large scale) | 3121 | 41 | 200–300 | 0.1 | 45–200 | 4–10 |
| Hydro (small scale) | 250 | 50 | 150 | N/A | 45 | 4–20 |
| Ocean | 5 | 20–30 | 300 | 0.2 | 150 | 15–25 |
| Solar (PV) | 12 | 15 | 25–200 | 0.4–1 | 40–200 | 10–20 |
| Solar (CSP) | 1 | 20–40 | 25–200 | 0.3 | 50–90 | 15–25 |
| Wind | 260 | 24.5 | 450–500 | 0.05 | 65–80 | 3–7 |

Source: [76,15].
PV: photovoltaic; CSP: concentrated solar power.

capacity factor, and mitigation potential and highest energy requirements, $CO_2$ emissions, and production cost. Ten is assigned to the ideal performance with highest annual generation, capacity factor, and mitigation potential and lowest energy requirements, $CO_2$ emissions, and production cost. The results are presented in Figure 6, and a normalization study is performed based on the following equations.

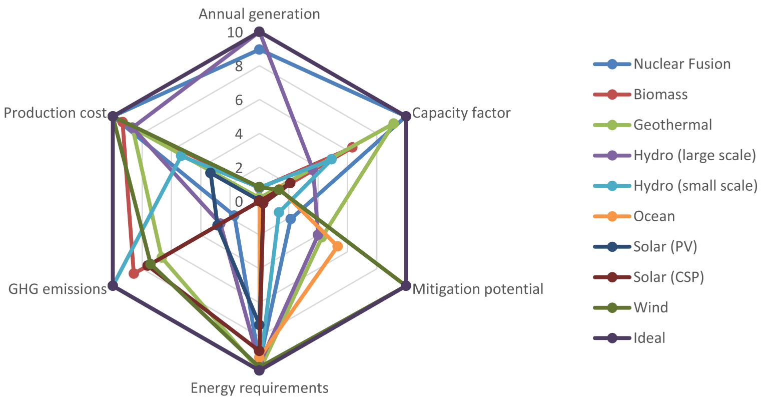


**Figure 6.** Normalized rankings of nuclear and renewable electricity production options. GHGs: greenhouse gasses; PV: photovoltaic; CSP: concentrated solar power.

- For data desired to be maximized (annual generation, capacity factor, and mitigation potential):

$$\text{Rank}_i = \frac{\text{data}_i - \text{minimum}}{\text{maximum} - \text{minimum}} \times 10 \quad (1)$$

- For data desired to be minimized (energy requirements, $CO_2$ emissions, and production cost):

$$\text{Rank}_i = \frac{\text{maximum} - \text{data}_i}{\text{maximum} - \text{minimum}} \times 10 \quad (2)$$

Figure 6 shows that large-scale hydro and nuclear options have the highest annual generation, and solar concentrated solar power (CSP) has the lowest. In terms of capacity factor, nuclear and geothermal give the closest to ideal case results, while solar PV has the poorest performance. Mitigation potentials show that wind gives the ideal results, and biomass has the least among the selected options. Geothermal and hydro have the ideal energy requirements, and biomass has the poorest performance. Hydro has the lowest emissions, while solar technologies have the highest. When it comes to production costs, nuclear, wind, and biomass have the best performance, while ocean and solar technologies have the highest production costs per kW h electricity.

The average normalized rankings of the technologies from highest to lowest are determined as nuclear (7.06/10), wind (6.57/10), geothermal (6.49/10), large-scale hydro (6.44/10), small-scale hydro (5.40/10), biomass (4.17/10), solar CSP (3.14/10), ocean (2.66/10), and solar PV (2.30/10). Nuclear has the highest ranking compared with renewables because it is already seen as a mature technology. In 2012, nuclear contributed 10.9% of the total global electricity generation, while this number is 21.2% for all renewables combined [1]. Nuclear also has a capacity factor of 86% (it mat even go beyond 90%) which is among the highest of all technologies and a competitive-levelized cost between 4 and 7 US¢/kW h. Expected advancements in nuclear-based electricity generation can be listed as increasing the efficiency of reactor fuel utilization, enhanced resistance, and reduction of nuclear wastes [7]. Wind is the second strongest option with an annual growth rate around 34% [15]. Wind technology is simple, and it is mature in developed countries. Although wind energy is a small industry, it is competitive [7]. The poor performances of solar PV and solar CSP can be explained by their high electricity generating costs due to low efficiency (leading low capacity factors) and high investment cost of these technologies. Solar and wind have intermittent and fluctuating natures, therefore requiring some kind of backup systems. Harnessing electricity from renewables depends on the cost and efficiency of the technology, which is constantly improving for all of the options listed here, thus reducing costs per kW h. According to US Energy Information Administration International Energy Outlook report [16], in 2035, the contribution of wind energy to total renewable electricity generation will increase by 12.2% compared with 2007. This is the highest increase percentage compared with hydropower, solar, geothermal, and ocean. Hydropower contribution percentage to overall renewable electricity generation is expected to decrease by 18.7% as geothermal, solar, wind, biomass, and ocean electricity generation technologies evolve (Figure 7).

Table IV shows the cost performance results of selected current renewable electricity generation technologies. Typical sizes (MW) represent the current or most recent sizes. For instance, the range for solar CSP is typical for projects being built or proposed today. However, proposed single site–multiple CSP plants have sizes exceeding 1 GW. The main parameter that influences the size of a solar system is the actual annual solar irradiation in kW h/m$^2$ year at a given location and the type of system. Hydropower projects are site-specific; therefore, they can be very small (around a few kW) and have sizes up to several thousand MWs. The three Gorges project in China is expected to reach 22,400 MW when completed [13]. Also, ocean energy size data are based on a very small size of installations. Wind energy uses a modular technology; a wide range of plants sizes is common, which is selected based on market and geographic conditions, although much larger plant sizes

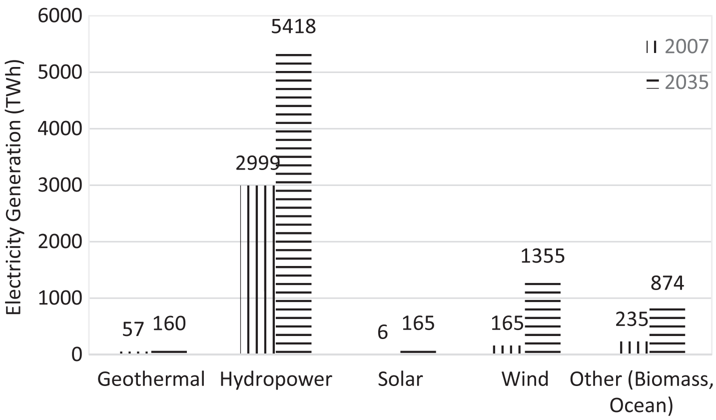


**Figure 7.** Global renewable electricity generation by energy source, 2007 and 2035 (Data from [16]).

**Table IV.** Cost performances of selected current renewable electricity generation technologies.

| | | | | O&M cost | | Feedstock | | |
|---|---|---|---|---|---|---|---|---|
| Resource | Technology | Typical size (MW) | Investment cost (MW) | Fixed (US$/kW) | Variable (US¢/kW h) | Cost (US$/GJ) | Conversion efficiency (%) | Design lifetime (years) |
| Bioenergy | Cofiring | 20–100 | 430–500 | 12 | 0.18 | 1.25–5 | 70–80 | 20 |
| Geothermal | Flash plants | 10–100 | 1800–3600 | 150–190 | | N/A | N/A | 25–30 |
| Hydropower | | >20,000 | 1000–3000 | 25–75 | | N/A | N/A | 40–80 |
| Ocean | Tidal | >250 | 4500–5000 | 100 | | N/A | N/A | 40 |
| Solar | Residential PV | 0.004–0.010 | 3700–6800 | 19–110 | | N/A | N/A | 20–30 |
| | Commercial PV | 0.020–0.500 | 3500–6600 | 18–100 | | N/A | N/A | 20–30 |
| | CSP | 50–250 | 6000–7300 | 60–82 | | N/A | N/A | 20–30 |
| Wind | Onshore | 5–300 | 1200–2100 | | 1.20–2.30 | N/A | N/A | 20 |
| | Offshore | 20–120 | 3200–5000 | | 2–4 | N/A | N/A | 20 |

Source: [13,77].
O&M: operation and maintenance; PV: photovoltaic; CSP: concentrated solar power.

are expected in the future. Feedstock costs are calculated per GJ of feed higher heating value. Regarding lifetimes, hydropower plants in general have very long physical lifetimes. There are many examples of hydropower plants that have been in operation for more than 100 years, with regular upgrading of electrical and mechanical systems but no major upgrades of the most expensive civil structures (dams, tunnels, etc.). The IEA reports that many plants built 50 to 100 years ago are still operating today [1]. For large hydropower plants, the lifetime can, hence, safely be set to at least 40 years, and an 80-year lifetime is used as upper bound. For small-scale hydropower plants, the typical lifetime can be set to 40 years; in some cases, even less. The economic design lifetime may differ from actual physical plant lifetimes and will depend strongly on how hydropower plants are owned and financed.

In Tables III and IV, technical (i.e., capacity, energy requirements, and lifetime) and economic (i.e., investment, operation and maintenance, feedstock, and production costs) aspects as well as related $CO_2$ emissions of renewable electricity generation are discussed. In addition to air pollutants, potential nonair environmental impacts of selected fossil fuels, nuclear and renewable-based electricity generation are listed in Table V. The environmental impact categories are listed as land use, solid waste and ground contamination, biodiversity, water consumption, and quality of discharge. When compared with the other options presented in the table, solar (PV and thermoelectric) has the lowest nonair impact. However, the water quality/discharge issue should be addressed. Coal has the highest environmental impact, which is expected. In regard to the nuclear power, radioactive waste and contamination appear to be major concerns as they need careful treatment and handling. Another concern may be high water consumption in nuclear power plants. Land use of hydropower and adverse impact of biomass on biodiversity should also be addressed in order to make them more sustainable.

In order to combine the nonair environmental impacts with ranked performance results presented in Figure 6, the following ranks are assigned to the values in Table V: zero (10), low (3.3), medium (6.6), and high (0). Because '0' is assigned to the highest environmental impact, high

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**Table V.** Potential nonair environmental impacts and normalized rankings of potential nonair environmental impacts of fossil fuels, nuclear, and renewable-based electricity production.

| Source of energy | Land use | Water consumption | Water quality of discharge | Solid waste and ground contamination | Biodiversity | Average ranking |
|---|---|---|---|---|---|---|
| Coal | High (0) | High (0) | Moderate to high (1.6) | Low to high (3.3) | High (0) | 0.98 |
| Gas | Moderate (3.3) | Low (6.6) | Zero to high (5) | Low (6.6) | Low (6.6) | 5.62 |
| Nuclear | Moderate (3.3) | High (0) | High (0) | High (0) | Moderate to high (1.6) | 0.98 |
| Biomass | Low to high (3.3) | Moderate (3.3) | Moderate (3.3) | Low (6.6) | High (0) | 3.30 |
| Geothermal | Low (6.6) | Zero (10) | Low (6.6) | Zero (10) | Low (6.6) | 7.96 |
| Hydro (with storage) | High (0) | Moderate (3.3) | Moderate (3.3) | Moderate (3.3) | Moderate (3.3) | 2.64 |
| Hydro (run of river) | Low (6.6) | Low (6.6) | Zero (10) | Zero (10) | Low (6.6) | 7.96 |
| Ocean | Low (6.6) | Zero (10) | Zero (10) | Zero (10) | Low (6.6) | 8.64 |
| Solar (PV) | Low to high (3.3) | Zero to low (8.3) | Low to high (3.3) | Zero (10) | Zero (10) | 6.98 |
| Wind | Moderate (3.3) | Zero (10) | Zero (10) | Low (6.6) | Low (6.6) | 7.3 |
| Ideal | 10 | 10 | 10 | 10 | 10 | 10 |

Source: [78,79].
PV: photovoltaic.

impact is assigned zero. Similarly, zero impact is considered as ideal case and assigned to be '10'. The results listed in Table V show that ocean-based electricity generation has the least nonair environmental impact followed by geothermal and hydropower (run of river). On the other hand, nuclear has the highest adverse effects in terms of nonair environmental impact followed by hydropower with storage and biomass. When the arithmetic mean of technical and environmental average rankings are taken, the electricity generation technologies rankings become (from highest to lowest): geothermal (7.23/10), wind (6.93/10), hydro (run of river, 6.68/10), ocean (5.65/10), solar (4.85/10), hydro (4.54/10), nuclear (4.02/10), biomass (3.72/10). Based on these results, it can be said that although it has high rankings based on annual generation, capacity factor, mitigation potential, energy requirements, GHG emissions, and production costs, nuclear shows a poor performance once nonair environmental impact is taken into account. It is also possible to see the adverse effect of biodiversity on biomass performance because overall ranking of biomass (3.72/10) is lower than the technical ranking (4.17/10).

## 3.2. Heating and cooling

Heating and cooling demands are a significant contributor to increasing global energy demand. Heating requirements are especially high in regions with long, cold winters, and cooling-load need is increasing worldwide because of growing use of heating, ventilation, and air conditioning (HVAC) and refrigeration applications. Renewable energy systems have a large potential to provide more sustainable heating and cooling alternatives to fossil fuel-based ones. An efficient conversion of renewable energies can slow down the growth in global energy demand, which would potentially reduce negative environmental impacts while increasing energy security. Another example of efficient energy utilization is the use of residual heat from industry (or electricity generation) as heating and cooling supplies. Renewable energy sources take advantage of decentralized generation to avoid distribution and energy conversion losses and yield significant reductions of primary energy utilization.

Currently, renewable energy heating and cooling (REHC) systems use solar, geothermal, and biomass as direct sources. However, ocean energy can potentially offer sustainable heating and cooling as well. Solar heat can be harnessed by directly producing hot water by using collectors, ponds, and so on. Additionally, solar thermal and passive solar energy can provide space heating and cooling. Solid biomass (wood chips, forestry and wood processing residues, energy crops, animal and agricultural crop residues, etc.), municipal solid waste and industrial waste, biogas, and biofuels can be used to provide heating and cooling. Geothermal energy can provide heat by conduction or in hot water/steam form, depending on the location. Heat pumps, district heating, bathing/swimming, pond heating, drying, refrigeration, HVAC, and industrial heat requirements are some of the current methods of heating/cooling use. The cooling can also be produced by renewable energy-based absorption cooling. With respect to fossil fuel dependency, cost, and $CO_2$ emissions, solar water heating, biomass for industrial/domestic heating, and geothermal heat pumps give the lowest results. Compared with conventional systems, these systems also provide net savings in terms of life-cycle costs in most cases

[17]. Typical sizes, investment and operation and maintenance costs, feedstock costs and conversion efficiencies, capacity factors, and design lifetimes of various REHC systems are presented in Table VI.

Typical size ranges listed in Table VI are characteristics for a low-energy single-family house (5 kW) or an apartment building (100 kW). Because of the difference in the nature of the feedstock, it is not possible to compare operation and maintenance costs, feedstock costs and conversion efficiencies of biomass, solar, and geothermal. However, among the listed biomass options, anaerobic digestion has the highest fixed operating and maintenance cost range while steam turbine combined heat and power (CHP) has the lowest. Again, among biogas options, domestic heating has the highest feedstock cost. However, this option has the highest feedstock conversion efficiency, and steam turbine CHP has the lowest. The remaining criteria (typical size, investment cost, capacity factor, and design lifetime) are averaged and normalized for ranking purposes. The normalization is performed based on Equation 1 (for typical size, capacity factor, and design lifetime) and Equation 2 (for investment cost). By normalization, maximum typical size, capacity factor, and design lifetime, and minimum investment cost are assigned '10'. On the contrary, lowest typical size, capacity factor, and design lifetime, and highest investment cost are assigned '0'. Normalized ranking results are presented in Table VII which shows geothermal district heating to be closest to ideal case and solar-based domestic hot water to be closest to 'least desired' case.

Next, the average rankings of each option for each criterion are calculated in order to compare biomass, solar, and geothermal. The results are presented in Figure 8 from which it can be seen that biomass has the highest capacity factor; solar has the lowest investment cost but also lowest size, capacity factor, and lifetime; and geothermal has the highest size and design lifetime. Solar heating/cooling performance can be improved by development of cheap and efficient low temperature collectors and introduction of compact and high-density heat-storage mediums. For biomass, advances in agricultural and forest practices and biomass supply logistics could potentially make this option more efficient and better for the environment. With development of cost-efficient, high-quality, and high-energy content fuel production from biomass, heating and cooling efficiencies can be increased while reducing emissions. Geothermal heating/cooling is suitable for large integrated district heating and cooling and its performance can further be enhanced by cogeneration through CHP.

### 3.2.1. Thermal energy storage

When we deal with renewables, there is a critical issue to address, such as a mismatch between demand and supply, due to their fluctuating nature. Thermal energy storage appears to be a crucial solution to offset the mismatch between demand and supply.

Solar, biomass, and geothermal resources can be shared, stored, or combined by hybrid systems, heat pumps, thermal energy storage (TES), cool TES (CTES), and district heating and cooling systems. Hybrid systems can meet the required capacities, reliabilities, and temperatures when one renewable source is not sufficient enough. Heat pumps are used when source and demand temperatures do not match. TES and CTES provide uninterrupted supply when supply-and-demand peak times are different. District heating and cooling systems are advantageous when there are smaller units of demand (e.g., buildings) and source requires large capacity installation. In the literature, there are various studies indicating the advantages of these technologies in clean, efficient, and feasible heating/cooling systems. Suleman *et al.* [18] integrated solar and heat pump-based system for industrial heating is one of them. In their system, a heat-pump cycle is used to supply process heating, and solar energy is utilized to provide heat to textile industry for various processes such as dyeing, cleaning, and ironing/pressing. Their

**Table VI.** Technical and economic comparison of various renewable energy heating and cooling systems.

| | | | | O&M cost (US$) | | Feedstock | | | |
|---|---|---|---|---|---|---|---|---|---|
| Resource | Technology | Typical size (MW) | Investment cost (kW) | Fixed (per kW) | Variable (per GJ) | Cost (US$/GJ) | Conversion efficiency (%) | Capacity factor (%) | Lifetime (years) |
| Biomass | Domestic heating | 0.005–0.1 | 310–1200 | 13–43 | | 10–20 | 86–95 | 13–29 | 10–20 |
| | MSW (CHP) | 1–10 | 370–3000 | 15–130 | | 0–3 | 20–40 | 80–91 | 10–20 |
| | Steam turbine (CHP) | 12–14 | 370–1000 | 1.5–2.5 | | 3.7–6.2 | 10–40 | 63–74 | 10–20 |
| | Anaerobic digestion (CHP) | 0.5–5 | 170–1000 | 37–140 | | 2.5–3.7 | 20–30 | 68–91 | 15–25 |
| Solar | Domestic hot water | 0.0017–0.01 | 120–540 | 1.5–10 | | N/A | 20–80 | 4.1–13 | 10–15 |
| Geothermal | Building heating | 0.1–1 | 1600–3900 | | 8.3–11 | N/A | N/A | 25–30 | 20 |
| | District heating | 3.8–35 | 600–1600 | | 8.3–11 | N/A | N/A | 25–30 | 25 |
| | Greenhouse heating | 2–5.5 | 500–1000 | | 5.6–8.3 | N/A | N/A | 50 | 20 |
| | Ponds | 5–14 | 50–100 | | 8.3–11 | N/A | N/A | 60 | 20 |
| | Heat pumps | 0.01–0.35 | 900–3800 | | 7.8–8.9 | N/A | N/A | 25–30 | 20 |

Source: [13,17].
O&M: operation and maintenance; MSW: municipal solid waste; CHP: combined heat and power.

**Table VII.** Normalized technical and economic rankings of various renewable energy heating and cooling systems (based on Table VI).

| Resource | Technology | Typical size (MW) | Investment cost (kW) | Capacity factor (%) | Design lifetime (years) | Average |
|---|---|---|---|---|---|---|
| Biomass | Domestic heating | 0.02 | 7.46 | 2.13 | 2 | 2.90 |
| | MSW (CHP) | 2.83 | 3.98 | 10 | 2 | 4.70 |
| | Steam turbine (CHP) | 6.70 | 7.72 | 7.93 | 2 | 6.09 |
| | Anaerobic digestion (CHP) | 1.41 | 8.09 | 9.27 | 6 | 6.19 |
| Solar | Domestic hot water | 0 | 9.05 | 0 | 0 | 2.26 |
| Geothermal | Building heating | 0.28 | 0 | 2.92 | 6 | 2.30 |
| | District heating | 10 | 6.17 | 2.92 | 10 | 7.27 |
| | Greenhouse heating | 1.98 | 7.48 | 5.67 | 6 | 5.28 |
| | Ponds | 4.90 | 10 | 6.89 | 6 | 6.95 |
| | Heat pumps | 0.09 | 1.50 | 2.92 | 6 | 2.63 |
| Ideal | 10 | 10 | 10 | 10 | 10 | |

MSW: municipal solid waste; CHP: combined heat and power.

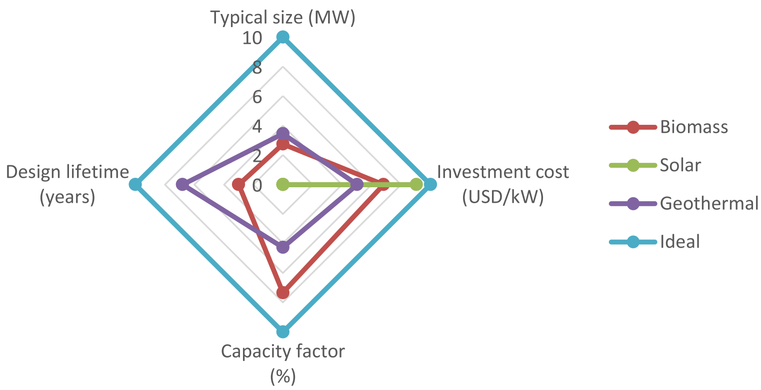


**Figure 8.** Average normalized technical and economic rankings of biomass, solar, and geothermal-based heating.

integrated system is 58% energy and 75% exergy efficient with an energetic coefficient of performance of 3.54. Heat-pump and system-integration studies focus on performance improvement, cost reduction, and environmental performance enhancement. Future studies will likely concentrate on integration of hybrid heating/cooling technologies into smart grids, more efficient compressors and heat exchangers, and cost and size optimization for heat pumps [19].

## 3.3. Hydrogen

Renewable energy sources are considered as sustainable alternatives to fossil fuels, as discussed in earlier sections. However, most of the renewable energy sources have their intermittent and fluctuating nature, which requires development of efficient energy storage mediums to take advantage of their advantages. Renewable energies can be stored in the form of electricity or chemical energy (in this case, hydrogen). Electricity is commonly used as energy storage medium, and it is a part of our daily lives, and hydrogen has been gaining increasing amount of attention because of its promising features as an energy carrier. To ensure sustainable development and address economic and environmental concerns, both of the energy carriers should be generated from clean energy sources in environmentally benign and efficient ways.

As a chemical fuel, hydrogen has certain advantages over electricity such as storage and transportation by using existing infrastructures. As a chemical fuel, hydrogen is more suitable for extended storage periods. Also, existing chemical energy storage and transfer infrastructures are suitable for hydrogen, but they cannot be used for electricity. Another disadvantage of electricity is the transmission losses as a result of the high voltage-related heat production and the electrical resistance of system components. Therefore, hydrogen is an ideal energy carrier because of the following: (i) it has high energy conversion efficiencies; (ii) it can be produced from water with no emissions; (iii) it is abundant; (iv) it can be stored in different forms (e.g., gaseous, liquid, or in together with metal hydrides); (v) it can be transported over long distances; (vi) it can be converted into other forms of energy in more ways than any other fuel; (vii) it has higher heating value and lower heating value (LHV) than most of the conventional fossil fuels; and (vii) if produced from renewable energies and water, its production, storage, transportation, and end use do not harm the environment. On the other hand, most of the hydrogen production methods are not mature, resulting in high production costs and/or low efficiencies. High production cost and low efficiency related issues are expected to be addressed in the future as renewable hydrogen production technologies evolve. Hydrogen is potentially to become the most versatile, efficient, and safe fuel [20]. Factors supporting hydrogen economy can be summarized as global environmental problems, local air quality concerns, energy security, supply, and sustainability issues, and technological innovation. Some of the barriers to hydrogen economy are fuel cell viability/cost and reliability/durability, logistic investments, combustion engine improvements, and fossil fuel dependence [21].

Dincer [22] identified and categorized the principal methods to produce green hydrogen based on process driving energy and material resource. Dincer [22] identified recovered energy (e.g., industrial waste), nuclear energy, and renewables as green energy. Renewables included solar, geothermal, biomass, wind, hydro, and ocean. Material resources from which hydrogen is to be extracted were water, sea water, hydrogen sulfide, biomass, and fossil hydrocarbons. As process driving energies, electrical, thermal, biochemical, and photonic energies, and their combinations were identified. Experimental investigation results of hydrogen production via electrolysis (including high temperature electrolysis), thermochemical Cu–Cl, Mg–Cl, and hybrid sulfur cycles, thermolysis, photoelectrolysis, photocatalysis, photoelectrocatalysis, photoelectrochemical cells, and hybrid photocatalytic Cu–Cl cycles are presented and discussed by Dincer and Naterer [23]. Their overview concluded that thermochemical and solar methods can potentially address hydrogen production challenges and provide distinctive solutions. A brief summary of fossil fuel, nuclear, and renewable-based hydrogen production in terms of current state of energy resources and use and possible future directions is studied by Orhan *et al.* [24]. They also investigated sustainability aspects of fossil fuel, renewable and nuclear-based hydrogen production options and determined that nuclear should be used as backup in renewable hydrogen production.

Because of its advantages, hydrogen, more specifically renewable hydrogen, has become synonymous with sustainability in both energy supply and storage. Granovskii *et al.* [25] presented an economic evaluation of air pollution emissions mitigation by introduction of renewable energies instead of fossil fuels in hydrogen production. Midilli and Dincer [26] showed the relationship between green hydrogen energy system and hydrogen economy-based life and discussed strategies for sustainable hydrogen-energy systems. They listed required strategies for sustainable hydrogen energy systems and global sustainability. Midilli and Dincer [27] introduced some exergetic performance parameters to evaluate global fossil fuel consumption cutback of hydrogen utilization; these parameters are fossil fuel-based global waste exergy factor, hydrogen-based global exergetic efficiency, fossil-fuel-based global irreversibility coefficient, and hydrogen-based global exergetic indicator. They concluded that fossil-fuel-based global waste exergy factor increased between 1990 and 2005, while hydrogen-based global exergetic efficiency increased in the same period of time, and hydrogen-based global exergetic efficiency to be expected to increase in the future. Dincer and Rosen [28] described and discussed sustainability aspects of hydrogen and fuel cell systems by using thermodynamics and life cycle assessment. They used the exergy concept to identify efficiency and sustainability improvement of hydrogen energy systems. A number of potential sustainable hydrogen production methods are classified and examined by Dincer and Zamfirescu [29]. In their study, water, hydrocarbons, biomass, and hydrogen sulfide are identified as natural resources, while biomass residuals, municipal wastes, plastics, sewage water etc. are considered to be anthropogenic wastes; renewables and nuclear are presented as clean-energy sources to drive hydrogen extraction processes from material resources. Dincer and Zamfirescu [29] identified 24 hydrogen production techniques including electrolysis, high temperature electrolysis, pure and hybrid thermochemical cycles, and photochemical/radiochemical methods.

Table VIII presents energy and exergy efficiencies, production costs, social cost of carbon (SCC), global warming potential (GWP), and acidification potential (AP) of hydrogen production from nuclear and renewable energy sources. GWP (kg $CO_2$ eq) is a measure of $CO_2$ emissions. AP (g $SO_2$ eq) indicates $SO_2$ discharge on soil and into water and measures the change in degree of acidity [30]. SCC of selected hydrogen production methods is calculated based on the results published by Parry *et al.* [31]. An average of US$160 per tonne of $CO_2$ emissions is used to estimate the SCC of each hydrogen production method. Efficiency is defined as useful output by consumed input. Energy efficiency of a hydrogen production method can be calculated as

$$\eta = \frac{\dot{m}\mathrm{LHV}_{H_2}}{\dot{E}_{in}} \quad (3)$$

where $\dot{m}$ is the mass flow rate of produced hydrogen, LHV is the lower heating value of hydrogen (121 MJ/kg), and $\dot{E}_{in}$ is the rate of energy input to the process. The following equation is used for exergy efficiency:

$$\psi = \frac{\dot{m}ex^{ch}{}_{H_2}}{\dot{Ex}_{in}} \quad (4)$$

Here, $ex^{ch}{}_{H_2}$ is the chemical exergy of hydrogen, and $\dot{Ex}_{in}$ is the rate of exergy input into the process.

It should be noted that the data in Table VIII are the average values of results presented by Cetinkaya *et al.* [32], Hacatoglu *et al.* [33], Ozbilen *et al.* [30], and Acar and Dincer [34]. Nuclear options include hybrid thermochemical cycles (i.e., Cu–Cl, Mg–C, and S–I); biomass options include gasification, pyrolysis, and reforming; geothermal, hydropower, ocean, and wind options include electrolysis; and solar includes PV electrolysis,

Table VIII. Average technical, cost, and environmental performances of renewable and nuclear hydrogen sources.

| Energy source | Energy efficiency (%) | Exergy efficiency (%) | Cost (US$/kg $H_2$) | SCC (US$/kg $H_2$) | GWP (kg $CO_2$/kg $H_2$) | AP (g $SO_2$/kg $H_2$) |
|---|---|---|---|---|---|---|
| Nuclear | 53 | 48 | 2.6800 | 0.320 | 2 | 3.44 |
| Biomass | 60.5 | 52.5 | 1.8900 | 0.640 | 4 | 31.50 |
| Geothermal | 33 | 15 | 5.1000 | 0.128 | 0.80 | 3 |
| Hydropower | 29 | 26 | 4.500 | 0.080 | 0.50 | 1 |
| Ocean | 22 | 20 | 5.700 | 0.096 | 0.60 | 1 |
| Solar | 10.8 | 9 | 5.9025 | 0.200 | 1.25 | 2.70 |
| Wind | 28 | 25 | 5.8500 | 0.160 | 1 | 2.50 |

Source: [30,32–34].

photolysis, photocatalysis, and photoelectrochemical. Biomass option has high AP because of $SO_2$ discharges during gasification. Solar includes a wide variety of options, some of which are in early research phase, therefore, giving low average efficiency and high cost results. And PV method's negative environmental impact can be seen in the fairly high GWP of solar option. To gain a better understanding on improvement potentials of each source, normalization is performed by multiplying exergy and energy efficiencies of each source by 10 (100% efficiency, as ideal case, would have the ranking 10); other criteria (cost, SCC, AP, and GWP) are desired to be minimized; therefore, the source giving the minimum is assigned to be 10 (with lowest cost and environmental impact), and the maximum ones are assigned to be 0 (with highest cost and environmental impact). The data desired to be minimal are normalized according to Equation 2, and the results are presented in Figure 9.

From Figure 9, it can be seen that none of the sources can reach 100% energy and exergy efficiencies but biomass and nuclear give the highest efficiencies and closer to ideal production costs. However, biomass and nuclear have low environmental impact (GWP, AP, and SCC) rankings because of their considerable high discharges compared with renewable options (solar, wind, ocean, hydropower, and geothermal). Figure 9 indicates the trade-off between efficiency-cost and environmental impact. Novel hydrogen production options give lower environmental impact, but there is cost and efficiency sacrifice. More mature technologies have better efficiencies, and they are more cost competitive, yet they have high environmental impact. In the future, with improvement of renewable energy harnessing technologies, it is expected to have cost competitive and efficient hydrogen production systems with low environmental impacts. When average rankings of energy and exergy efficiencies, GWP, AP, SCC, and production costs are taken, performances of the sources from highest to lowest are: nuclear and hydropower (6.5/10), geothermal and ocean (5.7/10), wind (5.3/10), solar (4.5/10), and biomass (3.6/10).

## 4. MULTIGENERATION SYSTEMS

Multigeneration systems have been recognized for their significant benefits in meeting global energy needs while reducing negative environmental and economic impacts. Fuel and $CO_2$ emissions savings, minimized losses and waste, and increased efficiencies are some of the benefits of multigeneration systems over conventional single-

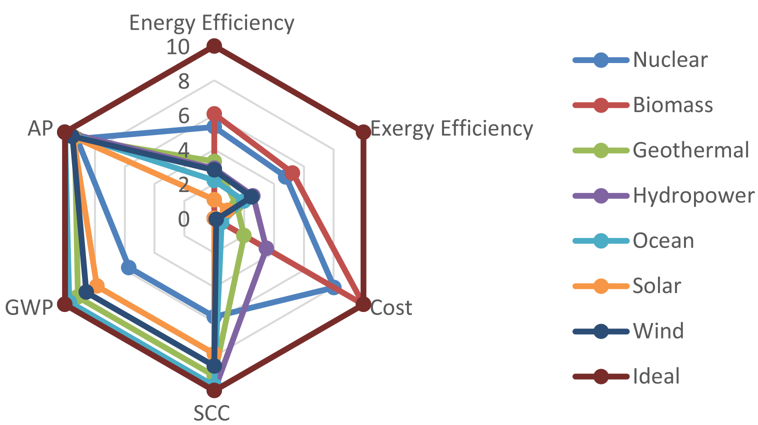


**Figure 9.** Normalized efficiency, cost, and environmental impact rankings of nuclear and renewable-based hydrogen production (based on Table VIII). AP, acidification potential; GWP, warming potential; SCC, social cost of carbon.

generation processes. Figure 10 shows how the overall system efficiency is increased by increasing the number of outputs.

It should be noted that in Figure 10, types of outputs can be selected in any order, efficiency increases with increasing the number of outputs, not by types of outputs. In Figure 11, different types of multigeneration options considered in this study are presented by their number and type of outputs.

All of the systems presented in Figure 11 have significant benefits over conventional energy/heat and cooling/fuel generation processes. These benefits can be listed as follows: reliability, better environmental performance by reduction of GHG and other air pollutants' emissions, economic feasibility, and higher efficiencies.

### 4.1. Cogeneration

Combined heat and power, or cogeneration, offers potential solutions to address global energy, environmental, and economic concerns in a clean, efficient, and cost-effective way. In conventional methods, electricity is bought from the local grid, and heat is generated by burning fuels in a boiler. CHP systems take advantage of the by-product heat which can be as high as 60–80% of total primary energy in combustion-based electricity generation. CHPs combine production of electrical (or mechanical) and useful thermal energy from the same primary energy source in one energy efficient step. With their proven efficiencies, CHPs advantages can be listed as follows: (i) significant reduction of $CO_2$ emissions; (ii) increasing efficiencies; (iii) cost reduction; (iv) creation of potential new jobs; (v) wide variety of geographical applicability; and (vi) energy security.

Combined heat and power plants are capable of recovering a share of the waste heat that is otherwise released by power plants that generate only electricity. The global average efficiency of fossil-fuelled power plants is 37%, whereas the global average efficiency of CHP units is 58% if both power and the recovered heat are taken into account. State-of-the-art CHP plants are able to approach efficiencies over 85% [1]. The usefulness of decentralized cogeneration units is discussed in [35]. Low-temperature heat-driven heat

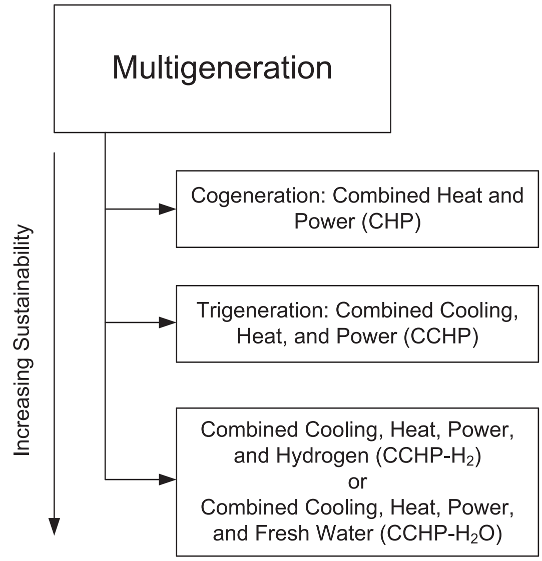


**Figure 11.** Types of multigeneration systems with their associated outputs.

engine proposed by Hogerwaard *et al.* [36] as a cost-effective system for power and heat production for small-scale applications, their system had energy and exergy cogeneration efficiencies of 87% (single generation option gave 17%) and 35% (single generation option gave 5%), respectively. Further emissions reductions from fossil fuel systems are possible through $CO_2$ capture and storage (CCS).

Table IX lists selected performance criteria of diesel and natural gas engines, steam/gas/micro turbines, and fuel cells as potential CHP technologies. Diesel and natural gas engines and gas turbines have the advantages of lower capital costs, quick start-up times, high efficiencies, and reliability. However, they require regular maintenance and their $NO_x$ emissions are high. Steam turbines are flexible with fuel input, but they have lower electric efficiencies and longer start-up times. Micro turbines are flexible with fuel input as well; they also have high rotation speeds, compact sizes, less moving parts,

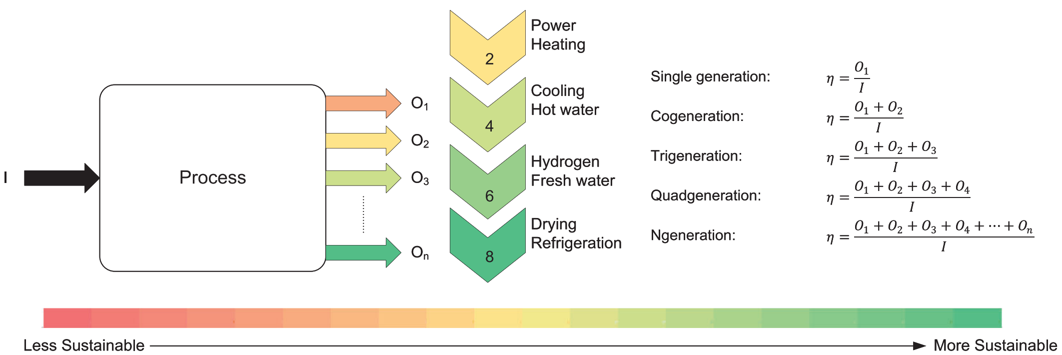


**Figure 10.** Illustration of efficiency increase by increasing number of outputs (multigeneration).


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**Table IX.** Performance summary of prime movers of CHP technologies.

| | Diesel engine | Natural gas engine | Steam turbine | Gas turbine | Micro turbine | Fuel cells |
|---|---|---|---|---|---|---|
| Electric efficiency (LHV, %) | 30–50 | 25–45 | 30–42 | 25–60 | 20–30 | 40–70 |
| Size (MW) | 0.05–5 | 0.05–5 | 0.05–250 | 3–200 | 0.025–0.25 | 0.2–2 |
| Footprint (m$^2$/kW) | 0.02 | 0.02–0.03 | <0.01 | 0.002–0.06 | 0.01–0.14 | 0.02–0.2 |
| Installment cost (US$/kW) | 800–1500 | 800–1500 | 800–1000 | 700–900 | 500–1300 | >3000 |
| Operation and maintenance cost (US¢/kW h) | 0.5–0.8 | 0.7–1.5 | 0.4 | 0.2–0.8 | 0.2–1 | 0.3–1.5 |
| Start-up time | 10 s | 10 s | 1–24 h | 10–60 min | 1 min | 3–48 h |
| Fuel pressure (bar) | 0.3 | 0.1–3 | N/A | 8–35 | 3–7 | 0.1–3 |
| $NO_x$ emissions (kg/MWh) | 1.4–15 | 1–13 | 0.8 | 0.1–1.8 | 0.2–1 | <0.01 |
| CHP output (kJ/kW h) | 3400 | 1000–5000 | N/A | 3400–12,000 | 4000–15,000 | 500–3700 |
| Usable temperature (°C) | 80–500 | 150–260 | N/A | 260–600 | 200–350 | 60–400 |
| Uses for heat recovery | | | | | | |
| Hot water | + | + | | + | + | + |
| Direct heat | | | + | + | | |
| District heating | + | + | + | + | | |
| LP stream | + | + | + | + | + | + |
| HP stream | | | + | + | | + |

Source: [80,81].
LHV: lower heating value; CHP: combined heat and power; LP: low-pressure; HP: high-pressure.

and lower noise. On the other hand, they have high capital costs, low electric efficiencies, and sensitivity to ambient conditions. Micro turbines are beneficial when energy systems are distributed with micro-to-small-scale production needs. Fuel cells operate quietly with high reliability and efficiency and extremely low emissions. Yet, they have high energy consumption, which needs to be lowered [37]. Selecting the most appropriate prime mover for a CHP system depends on current local resources, system size, budget limitation, and GHG emission requirements.

Operational flexibility of CHP plants may be constrained by heat loads, although thermal storages and complementary heat sources can mitigate this effect [38–41]. Reservoir hydropower can be useful in balancing because of its flexibility. Certain combinations may present further challenges [42]: high shares of variable renewable power, for example, may not be ideally complemented by nuclear, CCS, and CHP plants (without heat storage). Obtaining flexibility from fossil generation has a cost and can affect the overall GHG reduction potential of variable renewable energy sources [35,42]. Demand response and energy storage can potentially offer additional flexibility. Demand response is of increasing interest because of its potentially low cost [43–46], albeit some emphasize its limitation compared with flexible conventional supply technologies [47]. Smart meters and remote controls are key components of the so-called smart grid where information technology is used to improve the operation of power systems, especially with resources located at the distribution level. Development of intelligent district heating and cooling networks in combination with heat storage allows for more flexibility and diversity and facilitates additional opportunities for low-carbon technologies (CHP, waste heat use, heat pumps, and solar heating and cooling). In addition, excess renewable electricity can be converted into heat to replace what otherwise would have been produced by fossil fuels [48].

## 4.2. Trigeneration

Combined cooling, heat, and power (CCHP), sometimes referred as trigeneration or building cooling, heating, and power, is derived from CHP. The technology is proven and reliable, mostly used in large-scale centralized power plants for more than 100 years. In addition to heat and power provided together by CHPs, CCHP systems further exploit electrical (or mechanical) energy to deliver space or process cooling capacity. CCHP systems can be considered as 'seasonal operation' because there is almost zero or minimal cooling load requirement during the winter months. Recent progress in CCHP technologies is linked to demand for distributed/decentralized energy sources as they can be efficiently implemented in small distributed scales to meet multiple energy demands of various end-users. CCHPs can also be used to support large-scale applications.

A major advantage of CCHP systems is the increased fuel energy utilization efficiency of 70–90%, which is around 30–45% for traditional systems. Therefore, they require less input to generate the same amount of electrical/mechanical/thermal energy which reduces costs. CCHP systems also minimize transmission and distribution losses and emissions by consuming less fuel to meet the same demand. Reliability is another major advantage of CCHPs compared with large-scale centralized plants which are more vulnerable in changing environments (i.e., varying customer and market needs) [49]. With distributed energy technologies, CCHPs are likely to resist external risks. They are also grid independent which protects them during electricity blackouts. Alanne and Saari [50] compared the reliability of distributed and centralized energy systems in detail with a special emphasis in Finland and Sweden.

Typical CCHP system components are (i) power generation unit (PGU) and (ii) HVAC components such as absorption chillers, cooling towers, and air handling units. PGU includes a prime mover (Table IX) and electricity generator. Al-Sulaiman *et al.* [51] comparatively assessed different CCHP prime movers by different selection criteria. Heat recovery unit plays a crucial role in CCHPs in collecting the by-product from the prime mover. Absorption chiller is the most commonly used thermally activated technology applied to CHP/CCHP systems. Several characteristics of absorption technologies including operating temperatures, working fluids, cooling capacities, and coefficients of performance are listed in Table X.

There are two types of single-effect cycles listed in Table X. LiBr/water cycles are the simplest among the other options, and they are widely used. However, because water is the working fluid, they cannot provide cooling lower than 0 °C. They also require water-cooled absorber to prevent crystallization at high concentrations. In water/$NH_3$ systems, cooling below freezing temperature of water can be offered. Another advantage of water/$NH_3$ systems is the lack of crystallization problem. They also have wide operating ranges. Double-effect absorption technologies with series flow have high performances, and they are commercially available. Because the steps are in series; one step's output is used as the other one's input to maximize efficiency. Although they are highly efficient, triple-effect cycles are very complex, and they require advanced control systems. Because their operating temperatures are significantly higher than the other options, they require more maintenance because of corrosion. Each technology has different advantages and disadvantages; selection of a heating unit depends on the design of the HVAC components of the CCHP.

In the literature, there are several studies focusing on thermodynamic analyses of CCHP systems in order to minimize losses and maximize efficiencies. Ahmadi *et al.* [52,53] compared an integrated organic Rankine cycle (ORC) CCHP system with simpler alternatives and concluded that exergetic efficiency of a gas turbine–ORC CCHP system is higher than that of a CHP system or gas turbine system alone. By using energy efficiency analysis, Al-Sulaiman *et al.* [54] showed that a CCHP system with parabolic trough solar collectors combined with ORC has very high efficiencies in trigeneration mode. They found maximum efficiency to be 94%, which is superior compared with solar single generation, or cooling/heating cogeneration. Ozcan and Dincer [55] performed a thermodynamic analysis of a CCHP system powered by a solid oxide fuel cell (SOFC), a high-temperature fuel cell system fueled by syngas, integrated with an ORC operating from the heat of the fuel cell stack exhaust gasses, and a Li–Br absorption chiller also driven by SOFC exhaust gasses. The energetic efficiency resulting from this system arrangement was over 50%, significantly higher than that of an SOFC system operating alone. They also note that incorporating solar-assisted heating, cooling, and electricity production can further increase the overall system efficiency. Suleman *et al.* [56] performed comprehensive energy and exergy analyses on a new integrated solar and geothermal-based system. They showed that by integrating CCHP with solar and geothermal sources, efficiencies can go above 80%.

### 4.3. Quadgeneration (CCHP-$H_2$)

Hydrogen production via CHP/CCHP systems further enhances their output spectrum thus reduces losses and potential emissions. Hydrogen is considered as the key component of sustainability. CCHP-$H_2$ systems integrate benefits of both multigeneration and hydrogen in a clean, efficient, and cost-effective way. Thermodynamic analyses of renewable-based integrated systems capable of producing electricity, heat, cooling, and hydrogen together indicate the outstanding advantages of these systems as higher efficiencies, greater sustainability, and environmental impact, and cost reduction [57–60].

Combined cooling, heat, power, and hydrogen systems are relatively new in the literature and can be considered as novel technologies. However, with rising awareness to meet global energy demand in a more sustainable way, there has been an increasing number of studies in the literature; focusing on different aspects of CCHP-$H_2$ systems, such as different renewable energy sources, different system working fluids, and various configurations and operation types. Zhang *et al.* [61] proposed, developed, and experimentally tested a solar-powered $CO_2$ Rankine cycle

**Table X.** Technical characteristics of available absorption cooling systems.

| | Operating temperature (°C) | | | | |
|---|---|---|---|---|---|
| System | Heating | Cooling | Working fluid | Cooling capacity (tonnes) | COP |
| Single-effect cycle | 80–110 | 5–10 | LiBr/water | <1500 | >0.7 |
| | 120–150 | <0 | Water/$NH_3$ | >1000 | 0.5 |
| Double effect (series) | 120–150 | 5–10 | LiBr/water | <1500 | >1.2 |
| Double effect (parallel) | 120–150 | <0 | Water/$NH_3$ | <1000 | 0.8–1.2 |
| Triple effect | 200–230 | 5–10 | LiBr/water | N/A | 1.4–1.5 |

Source: [82].
COP: coefficient of performance.

for hydrogen production under various conditions. AlZahrani *et al.* [62] thermodynamically analyzed an integrated geothermal powered system by combining $CO_2$ Rankine cycle, cascaded by the ORC (R600), an electrolyser, and a heat recovery system for heat, cooling, power, and hydrogen production. Their system produced 245 kg/h hydrogen and about 19 MW power with overall energy and exergy efficiencies of 13.67% and 32.27%, respectively.

An integration of solar thermochemical processes with multigeneration systems to produce hydrogen is another focus in the literature. Sack *et al.* [63] developed and validated a solar-driven thermochemical process simulation for an existing pilot plant and their results showed well agreement with the pilot plant data. Ratlamwala and Dincer [64] found that an integrated solar power tower with Cu–Cl and Kalina cycles have better performance than an integrated solar power tower with Cu–Cl cycle and a water electrolysis system. An integrated solar and Mg–Cl cycle-based hydrogen production plant for 1 kmol/s of hydrogen production has been thermodynamically analyzed by Ozcan and Dincer [65]. They considered a heliostat field with molten salt TES as the main energy input for both hydrogen and power production cycles where the power cycle is designed to provide required electrical work for electrolysis step of the Mg–Cl cycle. They evaluated energy and exergy efficiencies to be 18.8% and 19.9%, respectively. Their results showed that Mg–Cl cycles have feasible reactions throughout the system with less corrosive substances than other hybrid thermochemical (e.g., Cu–Cl and HyS) cycles.

Further emission reductions can be achieved by utilizing chemical looping cycles (CLCs). Wolf and Jan [66] proposed a novel CLC configuration for heat, power, and hydrogen production. A comprehensive thermodynamic analysis of CLC conducted by McGlashan [67] showed that integrated with fuel cells, a CLC plant can reach efficiencies above 40%. A three-stage Rankine cycle with zero emissions is proposed by Chen *et al.* [68], where a CLC and SOFC are combined. Their results showed that the integrated system exploited waste heat to be converted as a useful output which gave a considerable increase in overall system efficiency. Carbon capture and separation is a highly energy-demanding process considered to be the cause of performance reduction in power plants. Integrated systems show promising alternatives in effective carbon capture by recovering possible waste streams into useful products such as heat, cooling, and hydrogen. The chemical looping hydrogen production system developed by Zhang *et al.* [69] succeeded to reach an overall efficiency of 59.8% with zero emissions which is significantly higher than 40% reported by McGlashan [67].

An iron-based chemical looping hydrogen generation system for clean combustion of coal without reacting with air has been studied by Ozcan and Dincer [70]. They integrated an organic bottoming cycle and heating processes to recover waste heat from the system and achieved an overall efficiency higher than 55%, which is superior to conventional plants. Another major advantage of the system is $CO_2$ capturing and utilization. Their proposed multigeneration system enhanced the efficiency by around 6% compared with similar systems studied in the literature.

### 4.4. Quadgeneration (CCHP-$H_2O$)

Increasing world population, industrialization, and rising standards of living have caused a dramatic growth in both fresh water and energy demands because both of the commodities are essential for sustaining life on earth. Fresh water supply is limited with nonhomogeneous distribution, and it is below global demand level. The United Nations World Water Assessment Programme states that 85% of the world population resides in areas with almost none to very low fresh water supply, considered as 'dry'. As a result, 783 million people live with no clean water access, 2.5 billion people have lack of adequate sanitation, and 6 to 8 million people die annually from the consequences [71].

Desalination technologies provide clean water solution to a wide range of needs. However, they are known to be energy-intensive. Integrating desalination units to multigeneration systems would further recover waste heat from these systems by using it to meet the energy needs of the desalination units. Together with renewable-based multigeneration systems, energy requirements for desalination can be met by developing innovative, low-cost, and low-energy technologies and process hybridizations. Gude *et al.* [72] evaluated existing desalination technologies driven by various renewable energy sources and combinations along with their associated costs. They discussed clean, efficient, cost-effective, and sustainable ways to meet the global energy and water demand and concluded the necessity of combining renewable energy-based systems with waste recovery and utilization.

Ghosh and Dincer [73] used three renewable sources, that is, solar, geothermal, and wind in an integrated system to produce power, heating, cooling, drying, and fresh water. Their system provided about 3500 kW power, 200 kW cooling water, 2300 kW heating, 2.8 kg/s product drying, and 87.3 kg/s fresh water with energy and exergy efficiencies of 37% and 25%, respectively. Their theoretical results showed that integrated system has higher efficiencies compared with single-input systems. However, the authors pointed out the challenge in finding geographical locations where the wind speed, solar energy, and geothermal water are constant or high in energy/exergy content simultaneously. For instance, in absence of solar light and geothermal water, their system produced just one output, that is, fresh water from wind energy with an exergy efficiency of 1.5%.

El-Emam and Dincer [74] comprehensively analyzed a seawater reverse-osmosis plant, of 7586 $m^3$ daily fresh water capacity, with energy recovery using Pelton turbine. Based on the first and second laws of thermodynamics, they performed thermodynamic and thermoeconomic analyses on their proposed system. The effects of the system components irreversibilities on the economics and cost of product water are parametrically studied through the thermoeconomic analysis. For the base case; their system achieves an exergy efficiency of 5.82%. The product cost is estimated to be 2.451 $/m^3$ and 54.2 $/MJ when source water with salinity of 35,000 ppm is fed to the system.

## 5. STRENGTHS, WEAKNESSES, OPPORTUNITIES AND THREATS ANALYSIS

There is a significant increase in the need for better, cleaner, and more efficient energy systems, involving production, distribution, and use of energy. Clean energy systems offer a great potential to meet this need and address the issues related to increasing global energy demand. With clean energy systems, present needs can be met without compromising the ability of future generations to meet their own needs [12]. Social and economic well-being can be achieved with clean energy systems without damaging the environment. However, there are certain challenges that need to be addressed before taking advantage of the opportunities of clean energy systems. Therefore, in Table XI, strengths, weaknesses, opportunities, and threats of clean energy systems are presented.

Clean energy systems take advantage of clean, nonexpensive, vast, and available sources by integrating different energy input types to increase productivity (e.g., by integrating solar and wind, a system can work continuously without having day/night cycles). Therefore, economic potential, use of local sources, flexible energy market, diversification, smart technologies, innovative solutions, reliability, and end-use variability can be listed as strengths of clean energy systems. Also, clean energy systems are designed to minimize losses, increase efficiency and outputs, leading to better design practices compared with traditional dealings. Besides, clean energy systems can be built on different scales to meet different levels of demand. With multigeneration and waste/loss recovery, clean energy systems meet different end-users' needs at different scales. Another strength of clean energy systems is the already available government incentives and encouragements through different funding programs.

Currently, there is lack of cooperation among political authorities, government agencies, industrial sector, and academia on clean energy systems which comes up as an issue. That is why many countries establish task forces and groups to work on this issue and develop partnership programs to address the issue and develop solutions. There is no commonly accepted definition on clean energy systems' framework and no consensus among policy makers which are the weaknesses of clean energy systems. Although clean energy systems bring significant advantages compared with existing conventional options, public acceptance to a significant change usually takes long times. Besides, whether there is a system improvement or infrastructure change, switching from a conventional energy system to a cleaner counterpart requires investment costs. And currently, most of the 'clean' energies and storage technologies are characterized by low energy densities. Because existing infrastructures are built to work with conventional energy systems, clean energy systems require building new infrastructures or improvement on the existing ones which makes them less affordable. High initial investment, installation, and operation, and maintenance costs and high payback times make clean energy systems less affordable. Another threat to clean energy systems is lack of information and training.

A major opportunity of clean energy systems is that unlike conventional ones, clean energy systems take advantage of locally available, abundant, clean, and affordable energy sources which eventually decreases the dependence on fossil fuels coming from certain regions of the world. Clean energy systems require different levels of expertise

**Table XI.** Strengths, weaknesses, opportunities, and threats analysis of clean energy systems.

| Strengths | Weaknesses | Opportunities | Threats |
|---|---|---|---|
| | Lack of cooperation with political authorities and enterprises | | |
| Economic potential | Public perception | Energy independence and security | Global financial crisis |
| Use of local resources | Resistance to changes | Job creation | Scalability and timing |
| Vast resources | Commercial viability | Market enhancement | Commercialization |
| Flexible energy market | Lack of information and training | Overall productivity | Substitutability |
| Diversification options | High initial investment, installation, O&M costs | Supply efficiency | Complexity |
| Better design practices | Lack of affordability | Carbon footprint | Regulatory requirements |
| Smart technologies | Low energy density | Air/water/soil quality | Government regulations and policies |
| Innovative solutions | High payback time | Climate change | Low price of conventional energy sources and systems |
| Reliability | Infrastructural changes | Need for sustainability | |
| Government incentives | Lack of institutional and government consensus and policies | Vitality | |
| End-use variability | | | |

and work and have a potential to create new job areas, potentially leading market enhancement, and a decrease in unemployment. Clean energy systems have higher efficiencies than conventional ones. Minimization of waste and losses and multigeneration eventually increases overall productivity by using supplies more efficiently. Other major opportunities clean energy systems provide are reduced carbon footprint by emitting significantly less $CO_2$ (GHG) emissions, improved air/water/soil quality by not emitting toxic materials to air, water, and soil. With these opportunities, clean energy systems have a great potential to address climate change issues and the need for sustainability.

Clean energy systems require infrastructural changes, which require high investment and initial operation costs. Any type of financial crisis might be a threat to global application of clean energy systems. For the promise of a clean energy system, the energy source must be available in the time frame and volume/amount needed at a reasonable cost. Intermittent and fluctuating nature of clean energy sources can also be listed as threats. Commercialization, substitutability, complexity, government regulations and policies, and regulatory requirements are some of the other threats to clean energy systems. Last, but not least, low prices of existing conventional energy systems poses a threat to clean energy systems.

## 6. CONCLUSIONS

In this study, current and potential states and applications of various clean energy solutions to achieve better sustainable development are discussed and evaluated from various technical and nontechnical dimensions. There are two parts in this study. In first part, possible primary outputs of the energy systems are identified to be power (electricity), heating/cooling, and fuel (hydrogen), and a comparative assessment of these systems is carried out. Some of the findings can be summarized as follows.

- Annual generation, capacity factor, mitigation potential, energy requirements, GHG emissions, and production costs of power generation systems are compared, and the overall performance rankings from highest to lowest are as follows: nuclear (7.06/10), wind (6.57/10), geothermal (6.49/10), large-scale hydro (6.44/10), small-scale hydro (5.40/10), biomass (4.17/10), solar CSP (3.14/10), ocean (2.66/10), and solar PV (2.30/10).
- When nonair pollution environmental impact criteria (land use, water consumption/discharge, solid waste, and biodiversity) are taken into consideration, the previous rankings are changed to be (from highest to lowest) as follows: geothermal (7.23/10), wind (6.93/10), hydro (run of river, 6.68/10), ocean (5.65/10), solar (4.85/10), hydro (4.54/10), nuclear (4.02/10), and biomass (3.72/10).
- Among available heating/cooling energy sources, a performance comparison considering size, investment cost, capacity factor, and design lifetime gave the following rankings: biomass (4.97/10), geothermal (4.89/10), and solar (2/10).
- In regard to hydrogen production, energy sources are ranked based on energy and exergy efficiencies, global warming and APs, production cost, and SCC. Performance rankings of the sources from highest to lowest are found to be as follows: nuclear and hydropower (6.5/10), geothermal and ocean (5.7/10), wind (5.3/10), solar (4.5/10), and biomass (3.6/10).

Furthermore, multigeneration systems are introduced, and their potential benefits are discussed with the findings of recent studies in the literature. Integrated renewable-based systems have found to have significant advantages which make them a key to be considered as ‘sustainable solutions’. These advantages can be listed as reduced overall energy demand, overall system cost and emissions, and enhanced efficiencies with increased useful outputs.

## NOMENCLATURE

| | |
|---|---|
| AP | = acidification potential, g SO2 eq/kg hydrogen produced |
| BCHP | = building cooling, heating, and power |
| CCHP | = combined cooling, heat, and power |
| CCS | = carbon capture and storage |
| CHP | = combined heat and power |
| CLC | = chemical looping cycle |
| COP | = coefficient of performance |
| CSP | = concentrated solar power |
| CTS | = cool thermal energy storage |
| EIA | = US Energy Information Administration |
| GHG | = greenhouse gasses |
| GWP | = global warming potential, g CO2 eq/kg hydrogen produced |
| HHV | = higher heating value |
| HVAC | = heating, ventilating, and air conditioning |
| IAEA | = International Atomic Energy Agency |
| IEA | = International Energy Agency |
| LCA | = life cycle assessment |
| LHV | = lower heating value |
| MSW | = municipal solid waste |
| MTOE | = million tonnes of oil equivalent (also Mtoe) |
| ORC | = organic Rankine cycle |
| PGU | = power generation unit |
| PV | = photovoltaic |
| REHC | = renewable energy heating and cooling |
| SCC | = social cost of carbon, $/kg hydrogen produced |
| SOFC | = solid oxide fuel cell |
| TES | = thermal energy storage |
| TPES | = total primary energy supply |
| UNCSD | = United Nations Commission for Sustainable Development |

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