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Smart energy systems for a sustainable future

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HIGHLIGHTS

- Smart energy systems are investigated to address major energy issues in a sustainable manner.
- Evaluation criteria are efficiencies, environmental performance, and energy and material sources.
- Energy sources are fossil fuels, renewables, biomass, and nuclear.

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ABSTRACT

In this study, smart energy systems are investigated and comparatively assessed to solve major global energy-related issues in a sustainable manner. In order to be considered as smart and sustainable, the energy systems should use technologies and resources that are adequate, affordable, clean, and reliable. Therefore, selected smart energy systems are evaluated based on their efficiencies, environmental performance, and energy and material sources. Our results show that increasing the number of products from the same energy source decreases emissions per unit product and increases efficiencies. Also, among the identified sources, geothermal has the most potential in terms of using cleaner technologies with energy conservation, renewability and the possibility of multiple desired products from the same source. Solar, hydro, and biomass are also beneficial. Even with carbon capture technologies, fossil fuels are not very desirable in smart energy systems because of their emissions and non-renewability.

1. Introduction

Energy is the key to tackling the most important issues of today and tomorrow such as climate change, sustainable development, health and environment, global energy and food security, and environmental protection. Nevertheless, traditional energy systems fail to accomplish meeting the multidimensional and multidisciplinary requirements of the 21st century.

During the transition from traditional to smart energy systems, it is primarily expected to design, analyze, develop and utilize transitional solutions to enhance their energetic, exergetic and environmental performance for better sustainability. In this regard, there is a strong need to greenize them in the best possible way by considering various criteria, such as environmental impact, resource utilization, efficiency, and cost effectiveness which will help achieve better sustainability ultimately.

For that reason, a substantial change in energy systems is needed to meet the increasing global energy demand in a sustainable fashion without hurting the environment, society, economy, and the well-being of the forthcoming populations. This study demonstrates that transition to smart energy systems is the most suitable approach to meet this need. Smart energy systems can possibly be beneficial when resolving many of the aforementioned requirements all together and provide multiple advantages at the same time. The successful functioning of smart energy systems necessitates strongminded, continuous, and direct action. There are substantial benefits of smart energy systems. However, in order to be considered as smart, an energy system should meet many expectations simultaneously. These expectations ultimately address the global energy challenges from various dimensions, including efficiency, effectiveness, cost, environment, resource use, sustainability, integrability, commercial viability, etc. The key expectations from smart energy systems are illustrated in Fig. 1 and described below:

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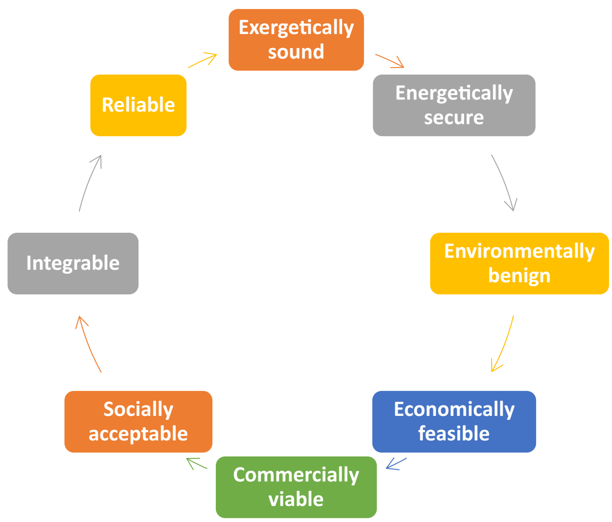

Fig. 1. Major expectations from smart energy systems.

- *Exergetically sound:* Exergy is a critical indicator of the quality of energy. For a system to be considered as smart, it should be exergetically sound. This means the system should have minimum exergy destructions and maximum exergy efficiency possible. In that case, a system could not only conserve the quantity, but also the quality of its energy content.
- *Energetically secure:* This is basically about energy security. A smart energy system should be designed and implemented in a way by taking advantage of affordable, reliable, locally available, abundant and replenished sources. Such smart energy systems then become self-sufficient, safe, efficient and hence secure. With smart energy systems, end users have access to dependable, practical, safe, and efficient energy supply which eventually provides energy security.
- *Environmentally benign:* smart energy systems are clean at every stage from source to their end use with less emissions and efficient resource utilization. Smart energy systems also include waste and loss recovery for both energy and materials. Less waste and loss means more efficient systems, lower emissions, and better environment for future.
- *Economically feasible:* Smart energy systems are expected to use affordable, reliable, available, and abundant resources. In addition, smart energy systems minimize losses and waste and maximize system efficiencies and desired outputs. Together with dependable, affordable, and practical end use options, smart energy systems have significant economic benefits.
- *Commercially viable:* From their sources to end use, smart energy systems essentially take local and marked conditions into account. A smart energy system uses what already available or easily accessible resources and provides the goods and services that are desired and considered as commercially viable. This way they will have ability to compete effectively and economically to be profitable. For example, smart energy systems using renewables increase their commercial viability with the support of the government. Furthermore, multigeneration is an example of how a smart energy system could increase the number of outputs in order to provide more commercial products.
- *Socially acceptable:* A smart energy system are expected to be socially acceptable to the local and global communities as such systems can satisfy the social needs and harmonize the options. This is especially true when considering the end use aspect of smart energy systems. In order for a smart energy system to succeed, it should be accepted by the society so that it could become a part of their daily lives and replace the traditional systems.
- *Integrable:* Smart energy systems are expected to have the integrability feature which will have help achieve system integration for multigeneration purposes. It is also important to engineer energy systems in integrated fashion to be smart or even smarter. The literature has many examples of novel energy systems that require substantial change in existing energy systems. A smarter approach would be developing energy systems that can be integrated to the existing energy infrastructure. The process of Integration is defined as an ultimate operation where energy systems and sources are combined in a synergetic form to achieve better efficiency, cost effectiveness, resources use, and environment. The less modifications an energy system require, the more likely it would be accepted by the society and the industry.
- *Reliable:* The term energy system covers everything from the production, processing, and end use of energy. In every step, smart energy systems should be reliable such as using reliable and available/easily accessible resources, reliable energy processing/conversion systems, and providing reliable service for end use. Reliability also increases the possibility for social acceptability.

There are numerous studies present in the literature, focusing on many characteristics of smart energy systems. Dincer and Zamfirescu [1] have discussed smart energy systems in terms of enhancing the amount of useful products from the same renewable energy source. Getting a variety of desired products from the same energy source is definitely a promising way to increase energy conservation. Together with clean energy sources, such as renewables, multigeneration systems offer distinct advantages, such as reduced losses/wastes (and hence reduced environmental impact), increased system efficiencies (and hence increased cost effectiveness), and producing multi outputs simultaneously (e.g., power, heat, cooling, fuels, chemicals) in contrast to the traditional single generation systems (see further details elsewhere [2]).

In the literature, there are several approaches to evaluating the sustainability of traditional and novel energy systems. Several of these studies estimate the sustainability of a given energy system from a thermodynamic [1–3] or an environmental [4–7] point of view. Some of these studies use more thorough methodologies which take into account other characteristics of sustainability. These studies, in general, use ranking indicators with or without normalization by taking the quantitative and qualitative targets of sustainability into account. These studies are more appropriate for the comparative evaluation of traditional and novel energy systems. In addition, some other studies utilize quantitative sustainability evaluation means that tackle the technical, economic, social, and environmental requirements of sustainability [5].

Dincer and Zamfirescu [6] have introduced innovative prospective opportunities to greenize energy processing and end use. The authors' idea is based on the approach introduced by Dincer [7] as six core components to greenize energy systems. These components are better efficiency, better cost effectiveness, better resources use, better design and analysis, better energy security, and better environment. Dincer and Zamfirescu [6] have also proposed a novel greenization factor and demonstrated its use to evaluate the greenization capability of selected traditional and novel energy systems is for different case studies. Singh et al. [8] have conducted a review of sustainability assessment approaches and gathered the information about the sustainability indices formulation together with strategy, scaling, normalization, weighing, and aggregation procedures. Mainali and Silveira [9] have inspected various sustainability examination methodologies and demonstrated a method for assessing the sustainability of smart energy systems.

In the literature, renewable energies are considered as clean and abundant and key to a transition to smart energy systems for a sustainable future. Srirangan et al. [10] have reviewed the state of the art and prospect challenges in the latest progress of biomass based technologies and suggested some novel biomass based energy processing methods for clean energy systems. Chu and Majumdar [11] have explored the strengths, weaknesses, opportunities, and threats of energy systems for a sustainable future. Hadian and Madani [12] have proposed a framework to determine the environmental impact of energy resource options in regard to various sustainability and performance criteria. They have used four sustainability criteria, which are carbon footprint, water footprint, land footprint, and cost of energy production.

In this study, smart energy systems are investigated and comparatively assessed to meet major global energy-related issues in a sustainable manner. In order to be considered as smart and sustainable, the energy systems should use technologies and resources that are adequate, affordable, clean, and reliable. Smart energy systems have many advantages and they are more likely to address the global energy challenges compared to traditional energy systems. Here, selected smart energy systems are evaluated based on their efficiencies, environmental impact, end products, and energy sources.

2. Issues with energy

Energy security is important for the advancement and improvement of all societies. It is also very well known that energy demand is increasing significantly due to global population escalation and rising living standards of people from all over the world. The increasing issues related to energetic and environmental dimensions have motivated many researchers, scientists, engineers, technologists, etc. to develop smart energy systems in an integrated fashion for sustainable future.

At present, industrialization process is highly energy-dependent and industrialization also necessitates significant amounts of material resources. Processing, transporting, and utilizing these material resources for different industries require high amounts of energy as well. In addition to the industry, residential and transportation sectors' energy needs are increasing as well. This is primarily because of the increasing demands for private transportation (especially air travel), heating, cooling, and the introduction of technologically advanced appliances, electronics, etc. [13].

The requirements of environmental sustainability, economic growth, and the society's wellbeing should be simultaneously addressed, with no compromise on any aspects of energy source-system-service chain. These criteria can be listed as convenience, cost, readiness, safety, health, climate, and environmental security. Smart energy systems concentrates on many aspects of the energy chain to provide multiple benefits without compromising from the environmental protection, financial constraints, or societal wellbeing [14].

Some of the major issues with energy use are presented in Fig. 2. Here, environmental limitations for eight criteria: climate change, ocean acidification, ozone depletion, nitrogen cycle, phosphorus cycle, freshwater use, land use, and biodiversity loss. Together, these criteria characterize a secure operational area for the societies (which is shown as the green area). In the interior of this green area societal growth and development has a higher chance of continuing with no significant detrimental impact. The studies in the literature show that in most cases these safety limits are being reached or transgressed. It is well known that the energy

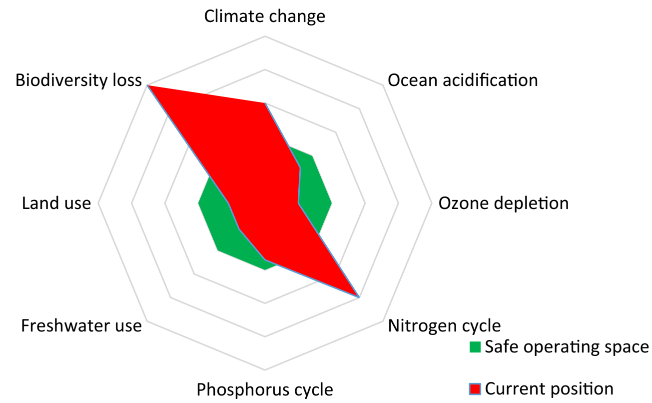

Fig. 2. Current global state of the world for the eight proposed planetary boundaries. The green area denotes a "safe operating space" for human development, and red indicates the current position for each boundary process (Data from [16]). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

systems, or the supply and demand of the energy chain, have tremendous impact on the societies' damage on the environment and reaching to these safety limits. Some examples are climate change, aerosol emissions, ocean acidification, biodiversity reduction, land, water, and air pollution, land use change, the nitrogen cycle, and fresh water utilization [15]. The environmental dimensions and the potential issues related to energy production, conversion and utilization show that greenization studies appear to be more crucial than before.

In 2015, energy supply and utilization participated to about 80% of CO_2 and 30% of methane emissions [16]. In addition, the energy supply and utilization contributed to significant emissions of various other pollutants, for instance various types of carbon and aerosols which could potentially change the atmospheric temperature, impacting climate change. In addition, other atmospheric pollutants like nitrogen oxides, sulfur oxides, tropospheric ozone precursors, etc. could cause acidification, eutrophication, and many other risks to human health and the environment. Additionally, many constituents of the energy chain, from supply to demand, require large amounts of land or freshwater supply which are also limited commodities for most of the societies. As a result, one can conclude that future energy systems should be smart to meet the present and future societies' energy needs without compromising from the economy, health, well-being, and the environment [17].

Smart energy systems are essentially expected to support more sustainable consumption and production at global level, not only local level. Presently, the production of internationally traded goods, which are vital to economic growth, account for approximately 30% of global CO_2 emissions [4]. The linkages between materials and energy should also be considered, especially through the life cycles. For example, the mining sector accounts for 7% of the world's energy use, an amount projected to increase with major implications for international policy. The agricultural sector accounts for a staggering 70% of the global freshwater consumption, 38% of the total land use, and 14% of the world's greenhouse gas emissions [4].

The impact of energy supply, service, and end use has severe impact on the environment which is usually referred as climate change. There are many areas that can be affected due to the increasing energy demand of modern societies. Some of these areas are agronomy, biodiversity, land use, fresh water supply, floods, draughts, and rise in sea levels, etc. Furthermore, production, processing, and end use of energy cause land deprivation, biodiversity loss, and freshwater resource deficiency. In order to minimize, and possibly reverse these adverse effects of energy production, service, and utilization, the global consensus is set to decreasing the global warming levels within the ±2 °C limits compared to the beginning of the industrialization era. This anti-global-warming objective is a standard target and it is taken into account in all efforts to develop and maintain a reliable and sustainable future [16]. On the other hand, it is not certain that this 2 °C target could prevent all negative impacts mentioned here so far. Therefore, a more determined objective is needed to minimize and eventually eliminate all of the adverse effects of the energy production, transportation, transformation, conversion, and end utilization and management [18].

In addition to the issues, challenges, and limitations discussed in here so far, there are many social aspects of the energy production, processing, and end use that cannot be easily quantified or monitored. For instance, air, land and water pollution issues cause a drastic reduction in the human and ecological productivities, and it can further cause acidification and eutrophication. Land is influenced due to the disturbance of various ecosystems via land-use change and pollution from the production, processing, and end use of energy. Some of the examples that cause damage to land could be summarized as the mining, drilling, and transportation of fossil fuels. Additionally, risk management systems should be constantly designed, developed, implemented, tested, and improved to prevent any accidents damaging the environment or the society. Nuclear accidents, power plant and mining area explosions, oil tanker spills, and hydroelectric dam floods are some of the examples to be included in any risk management plan of smart energy systems [19].

Some critical targets for environment and development policies that follow from the concept of sustainable development may include the following:

- reviving growth;
- changing the quality of growth;
- meeting essential needs for jobs, food, energy, water, and sanitation;
- ensuring a sustainable level of population;
- conserving and enhancing the resource base:
- reorienting technology and managing risk; and
- merging environment and economics in decision making.

If carefully developed, renewable energies can address the issues with energy and provide numerous advantages, consisting of introduction of new jobs and employment opportunities, increase in energy security, improvement in human and other living organisms' health, less damage to the environment, and reduction of the adverse results of climate change [20]. The major issues related with renewable energies are:

- *High costs*: can be addressed with learning and scale-up
- *Difference with the existing energy structure*: can be addressed by integration into the existing system
- *Low efficiencies*: can be addressed by research and development to ensure technological advances

Traditional energy systems fail to address the issues with energy production, processing, and end use mentioned in here so far. There is a clear need for more action to provide new sources and ways to support the increasing energy demand. Such new methods and sources should be gathered and processed in a way that the priorities can be assessed and determined at a global level for better implementation. To reach the today and future sustainability goals, smart energy systems are needed. Smart energy systems have and substantial short and long term local and global financial, environmental, and societal advantages. Smart energy systems have smart targets that are multidimensional, multidisciplinary, complex, and dynamic. Therefore, in order to reach smart targets of smart energy systems, existing and future resources, technologies, knowledge, and policies should be used in collaboration. Some of the benefits of the smart energy systems can be summarized as better health and environment, better employment, better economies, better productivity, better social welfare (e.g., reduction of poverty), better infrastructure, and better energy security [7].

3. Smart targets

For many of the issues associated with energy, various targets have been formulated by the global scientific, industrial, and political communities, in many situations covering specific measureable and controllable objectives and goals. This section discusses the smart targets in many aspects of the energy systems including production, processing, and end use. A sustainable future necessitates a transition from the present traditional energy systems to those that have significant enhancements in energy and exergy efficiencies in every step of energy production, processing, and end use and larger utilization of renewable and clean energy resources and smart energy systems [21].

Smart targets for smart energy systems for a sustainable future is proposed by Dincer [7] as better efficiency, better cost effectiveness, better resources use, better design and analysis, better energy security, and better environment (Fig. 3).

These smart targets can be achieved via smart solutions, such as smart materials, smart devices, smart technologies, and smart grid. They also offer a detailed problem description and analysis of the causation of energetic, environmental, and economic requirements for future energy systems and hence provide knowledge required for reducing environmental impacts, costs, and enhancing efficiencies. Smart targets show where improvements are necessary, what the crucial changes are required and how much they will contribute to such improvements.

- *Better efficiency:* Smart targets for future energy systems highlight the need for efficiency improvements. Efficiency improvements could be reached by minimizing losses (such as

Fig. 3. Six pillars of sustainability (originally proposed by Dincer [7]).

insulation) and waste (such as waste recovery). Increasing the number of desired products from the same energy source (multigeneration) is also another way of reaching better efficiencies.

- *Better resources use:* means taking advantage of renewable and clean energy sources to escalate the share of locally available energy and material resources in every aspect of the energy chain from extraction to end use. This target aims to lower dependence on resources that are not locally available and affordable. The environmental and economic impacts of energy systems should be assessed and evaluated in detail in order to identify systems and resources that support clean, efficient, and affordable use of resources.
- *Better cost effectiveness:* Enhanced efficiency and better resources use bring another important aspect of sustainability, which is cost effectiveness. By reducing losses and waste, generating multiple products from the same energy source, and using reliable, available, abundant resources; smart energy systems provide better cost effectiveness.
- *Better environment:* aims to at least keep the worldwide average temperature increase to less than 2 °C above the pre-industrial level. In order to reach this smart target, the global CO_2 emissions from the energy sector and the industry should be reduced to 30–70% of 2000 amounts before 2050. After 2050, the goal is to approach zero or almost zero emissions from all aspects of the energy chain. Smart targets also aim to improve the health and environmental conditions by regulating residential and industrial air pollution, ocean acidification, and biodiversity loss. Reducing emissions can be accomplished via smart energy systems such as advanced materials and end-use technologies [22].
- *Better energy security:* means world-wide access to reasonably priced modern-day energy sources, systems, and carriers and end use efficiency. Improved local and global energy security is an additional benefit of smart energy systems for a sustainable future. Lower dependence on energy import/export and energy supply reliability, flexibility, availability, and affordability is a major target for smart energy systems.
- *Better design and analysis:* A smart energy system is sustainable, and the sixth pillar of sustainability is better design and analysis. Smart energy systems are designed to minimize losses/waste and increase efficiency and amount of desired products. Smart energy systems tend to not to "use up" all of their resources as sustainability also requires continuity. Therefore, smart energy systems should have better designs to accommodate all needs at once. An example of better analysis is conducting exergy analysis in addition to energy analysis since exergy analysis provides the information on not only the quantity, but also the quality of energy, which is essential when evaluating the sustainability degree of an energy system.

In addition to the ones listed above, there are many other smart targets aiming to make energy systems smarter by design and operation. For instance, **smart materials** such as nano-based technologies and other novel materials are utilized in smart energy systems. Another smart target is to ideally prevent or contain oil spills, freshwater pollution and excessive use of freshwater, and radioactive waste emissions. Ideally, smart energy systems should not generate waste but in most cases this is not the case. Therefore, waste from smart energy systems must be collected via appropriate (safe, clean, affordable, and environmentally friendly) methods and technologies to minimize any health and environment related adverse impacts [23].

Efficiency enhancement appears to be the most affordable and effective smart target with multiple short and long term benefits. Some of these benefits are minimized damage to the health and environment, energy security and flexibility, and many other financial benefits including cost reduction and waste/loss minimization. The literature suggests that requirements for energy efficiency improvement can be met relatively quickly. There are some ways to enhance the efficiency of energy systems from production to end use such as retrofitting residential units to lower heating and cooling demands, design of residential and industrial units to prevent heat and cooling loss, and identifying the energy sinkholes to reduce the losses and waste [24].

Smart targets could help the societies design, develop, build, and benefit from carbon-free and clean energy systems. Therefore, such attempts have been made to identify the advantages, disadvantages, and challenges during the transition to smart energy systems. These challenging tasks require important transformations in traditional fuel utilization which is achievable with existing methods and technologies:

- Carbon capture and storage (CCS)
- Replacing heavy and carbon-intense fuels with lighter ones such as natural gas
- Retrofitting traditional single generation power plants with multigeneration alternatives

Smart energy systems include all aspects of the energy supply and demand chain. This concept is introduced by Dincer and Acar [25] as "3S concept" (Source-System-Service) as shown in Fig. 4. Smart energy systems should meet all the criteria from its sources to end uses (system). For a smart energy system, it is important to choose the source of energy appropriately. When selecting an appropriate energy source, there multiple important criteria to consider, such as abundance, local availability, affordability, reliability, safety, and environmental friendliness. So far the literature shows that the most suitable sources are renewables. Also, nuclear, biomass, and fossil fuels can be considered relatively clean if they are handled correctly (e.g., with proper waste management, CCS, etc.). When improving an energy system, it is important to find and address irreversibilities and evaluate system efficiencies [26]. An energy system can be improved in many ways some of which are:

- *Process enhancement:* reduced losses and maximized amount of desired output.
- *Efficiency increase:* elimination (ideally) or minimization of irreversibilities.
- *System integration:* enhanced system reliability and increased production rates.
- *Multigeneration:* higher amounts of useful products from the same energy input.

In the service step, which can also be considered as the end use, it is similarly essential to reduce waste, losses, irreversibilities, etc. The use of fossil energy carriers in the service step such as heating, transportation, metal refining, and the production of manufactured goods is of comparable importance, causing the depletion of fossil energy resources, climate change, and a wide range of emissions-related impacts. There are many smart solutions exist in the service step. End users could benefit from reuse and recovery of resources, for instance heat [25]. HVAC, household and industrial appliances, industrial machines, transportation, IT services, lighting, etc. are some of the examples of end use which should be clean, efficient, dependable, affordable, practical, and safe. It should also be noted that energy should be stored in between (i) source and system and (ii) system and service in order to provide continuity, reliability, and availability.

Smart energy systems, overall, should meet the following targets in order to provide a sustainable future: (i) access to

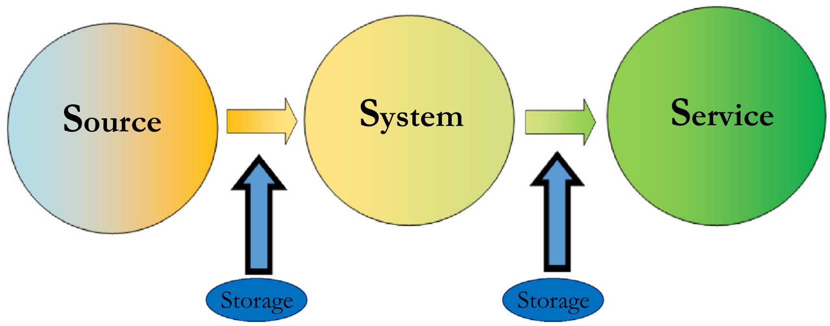

Fig. 4. Smart targets for smart energy systems from 3S (Source-System-Service) approach (modified from [25]).

reasonably-priced contemporary energy storage and carrier options as well as end-use options, (ii) enhanced energy security, (iii) climate change mitigation, and (iv) environmental protection [27]. The smart targets mentioned in this section require significant modifications in existing energy systems. These modifications lead to smart energy systems which is discussed in the upcoming section.

4. Smart energy systems

There is no certain description for smart energy systems since they are dependent on the characteristics of the local conditions such as their regions, state of the economies. Smart energy systems can also be defined differently in rural and urban areas. Therefore, different methodologies are needed in different locations and economies for the transition to smart energy systems for a sustainable future. Smart energy systems which function effectively in a certain location might not operate well in another one. On the other hand, the shared experiences of different locations and economies during the transition to smart energy systems are still useful for the global transition to a more sustainable future. The development of smart energy systems depends on how well the technologies are employed and how well smart energy systems are established to support the changes between traditional and smart energy systems [28].

Sustainable transformation from energy and material resources to different forms of energy and industrial commodities is very important when designing smart energy systems. In addition, effective transfer and delivery of these products for different end-use purposes is very important. Therefore, in the literature, there is special attention on various types of energy carriers for example electricity, hydrogen, heat, etc. All of these energy carriers are essential to transferring energy produced in remote (and mostly rural) production sites to expanding urban population centers with growing populations. In smart energy systems, it is fundamental to provide novel, integrated, and reasonably priced energy storage systems for up-to-date energy carriers. This is conceivably the principal and most perplexing aspect of the smart energy systems for a sustainable [29].

The establishment of transformative change from traditional to smart energy systems might be observed in numerous innovations and small scale experimental studies in the energy sector. The primary goal of these experimental studies is to contribute to a better understanding of how to decouple economic growth from environmental degradation via smart energy systems. These experimental studies primarily consist of:

- technological improvements in production and end-use of energy
- system-level advances which require reconfiguration of the current energy systems
- business model and industrial adjustments based on delivery and end use of energy.

In general, these experiments focus on hybrid and integrated energy systems, where different primary energy sources are combined to concentrate on energy related issues such as resource discontinuity. Experimental studies focusing on end-use of energy cover technological opportunities for the generation of multiple products at once. Experimental studies focusing on system-level advancements consist of improvements in distributed production and storage of energy. These studies also include enhancement of energy efficiency by efficiently monetizing end-use savings. Some of these system level experiments also focus on technological advancements which can change interactions between energy suppliers and consumers. This could also change roles for players in the field of energy systems. For instance, consumers might become energy suppliers by taking advantage of smart energy systems that operate independently from the main grid system.

In order to provide a foundation to inventions leading to smart energy systems, successfully supporting the energy systems which have promising technological characteristic is important. There are many studies in the literature focusing on large-scale, transformative transformation in energy systems. These studies involve a hierarchy of modifications from experimental studies to novel technology ideas, ranging from small to large scale energy systems in both rural and urban areas [30].

Recently, Dincer [17] has categorized smart energy portfolio in eight new options, such as exergization [28], greenization [29], renewabilization, hydrogenization, integration, multigeneration, storagization and intelligization. In this approach, exergization is the utilization exergy analysis and more detailed information on exergization can be found in [28]. Greenization is a way of process improvement or design of novel systems to make them more environmentally benign which is discussed in detail by Dincer [29]. Renewabilization is substituting conventional fuels with renewable energy sources. Hydrogenization is the achievement of a hydrogen-based economy for enhanced sustainability. Integration is the combination and/or hybridization of different energy systems/sources to reach better efficiency, cost effectiveness, resources use, and environment. Multigeneration is reducing losses and waste and increasing system efficiencies by producing multiple outputs from the same energy source. Storagization is employing reliable, affordable, and cleaner energy storage methods. Intelligization is using artificial intelligence tools when modeling, implementing, optimizing, automating and controlling, and managing and metering energy systems.

Smart energy systems also have considerable financial, environmental, and societal advantages. For instance, reducing emissions in a reliable and affordable way while providing the energy requirements of growing societies could possibly improve the health quality and also lower the risks of climate change. Smart energy systems do not only provide local advantages. With smart energy systems, it is possible to receive global economic, social, and environmental benefits which is very appealing. This frequently occurs in smart energy systems. Some examples of smart energy investments are energy efficiency enhancement and switching to renewable energy resources. For that reason, even though various advantages of smart energy systems cannot be straightforwardly monetized, these systems are key to future sustainability in many promising ways.

4.1. Cleaner technologies

One of the targets of the smart energy systems is to reduce emissions of GHGs. Fig. 5 presents normalized rankings of the specific GHG emissions per kW h for different energy generation methods. The data used in this study are extracted from the literature and they are all life-cycle based most important emissions converted to CO_2 equivalent per kW h. These emissions data are taken from [25,31–33].

In Fig. 5, single generation is the electricity production, cogeneration is heat and electricity production (CHP), trigeneration is heat, cooling, and electricity production (CCHP), and quadgeneration is heat, cooling, hydrogen, and electricity production (CCHP-H_2). It should be noted that in cases where wind or hydro is the energy source, it is assumed to have two products only. Therefore, in these cases, cogeneration is electricity and hydrogen and trigeneration and quadgeneration are not considered. The ranking is done based on the following equation:

$$Rank_i = \frac{Maximum - Method_i}{Maximum - Minimum} \quad (1)$$

Here, *Minimum* and *Maximum* are the minimum and maximum emissions and $Method_i$ is the emissions of a selected method. This equation assigns a ranking to each method which is between 0 and 1 where 0 means the highest amount of emissions and 1 means the lowest amount of emissions (cleanest method).

From Fig. 5, it can be seen that coal has the highest emissions (lowest rankings), followed by natural gas. Hydro and wind have the lowest emissions (highest rankings), followed by solar, biomass, and geothermal. Nuclear energy has less emissions compared to fossil fuel based methods. This is the case even with the fossil fuel based systems with CCS. Also, regardless of the energy source type, increasing the number of products reduces emissions per unit of energy content of the products.

Fossil fuels processing with CCS technology lowers harmful emissions considerably. However, even these technologies have significantly higher emissions than the systems with renewable energies and nuclear. Joint utilization of fossil fuel and biomass with CCS could provide electricity, heat, hydrogen, and industrial commodities with zero or minimal emissions. Quantifying emissions for electricity that is multi-generated is complex since it is not clear how to allocate emissions to different products. The methodology used in this study is to allot a fraction discount (or surge) in emissions equivalent to the emission for the overall multigeneration system divided by the emissions of a reference state (base system) containing separate traditional fossil fuel based systems with no CCS that separately generate the equal amount of products. It should be noted that even though CCS lowers the emissions related to fossil fuel utilization, it does not address the issue related to limited supply and possible adverse impacts of increasing rates of fossil fuel extraction.

The objective of this study is to examine the major paths of impacts through which these selected energy conversion methods influence the numerous objects of smart energy systems, along with to recognize further benefits. Nevertheless, whether an item is an advantage or issue is subject to the reference point and local conditions: for instance, liquid petroleum gas (LPG) has many negative environmental influences yet it still offers important benefits in numerous locations by replacing conventional biomass combustion. In summary, Fig. 5 shows that in addition to using cleaner sources, an energy system can be greenized and become smarter via multigeneration as increasing the number of outputs from a single source decrease the amount of emissions per unit product.

4.2. Energy conservation

Technological advancements and scientific improvements in increasing energy efficiency and energy conversion rates are fundamental for smart energy systems. Rapid improvement of energy efficiency requires innovations in existing systems based on energy conservation in each step of the 3S approach (Source-System-Service) introduced by Dincer and Acar [25].

The enhancement of conversion efficiency in energy systems has many advantages including many environmental, social, and economic benefits. Some examples of these benefits are: reduced energy demand, lower emissions, improved social welfare, lower production costs; lower emissions, and improved health conditions via significant reduction of indoor and outdoor air pollution, etc. These benefits mostly bring creditable productivity improvements as well. Productivity improvements and overall improvements in energy conservation translate into improved competitiveness. There are some other benefits of increasing energy efficiency which cannot be quantified or accounted easily. Some of these benefits are enhanced comfort and wellbeing and new business opportunities [34].

Fig. 6 presents normalized rankings of the efficiencies for different technologies. The efficiencies data are the average of the energy and exergy efficiencies for electricity and hydrogen generation from the selected energy sources. And the data are compiled from [16,25,35,36]. Same as Fig. 5, in Fig. 6, single generation is the elec-

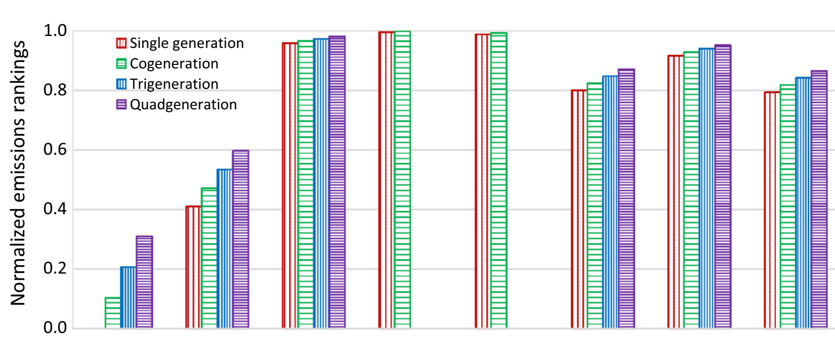

Fig. 5. Normalized emissions rankings from various energy sources in different generation technologies.

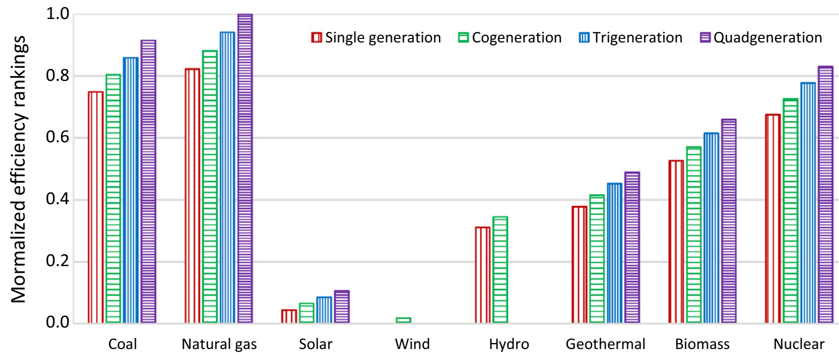

Fig. 6. Normalized efficiency rankings from various energy sources in different generation technologies.

tricity production, cogeneration is heat and electricity production (CHP), trigeneration is heat, cooling, and electricity production (CCHP), and quadgeneration is heat, cooling, hydrogen, and electricity production (CCHP-H_2). In cases where wind or hydro is the energy source, it is assumed to have two products only. Therefore, in these cases, cogeneration is electricity and hydrogen and trigeneration and quadgeneration are not considered. The normalized ranking is done by taking the average efficiencies as they are, between 0 and 1.

Fig. 6 shows that natural gas have the highest efficiencies (highest rankings), followed by coal and nuclear. Solar and wind have the lowest efficiencies (lowest rankings), followed by hydro, biomass, and geothermal. Also, regardless of the energy source type, increasing the number of products increases efficiencies, therefore increasing the energy conservation.

Integrating energy sources and increasing the number of desired products increase efficiencies significantly. Although solar and wind seem to have lower efficiencies compared to the other options, they are expected to become more efficient as the technologies advance. Also, it should be noted that solar and wind based production is mostly small scale, and small scale systems have lower efficiencies compared to large scale systems. Fig. 6 shows that even though renewable and clean energy sources tend to offer lower efficiencies (mainly because most of them are state-of-the-art or in early development phase) multigeneration increases system efficiencies as increasing the number of outputs from a single source also increase the overall efficiencies.

4.3. Renewables

The name "renewable" insinuates that the energy resources do not diminish unlike the case for traditional fossil fuel type energy sources. For instance, fossil fuel based energy resources are expected to deplete due to their limited nature and non-renewability. In the literature, solar, wind, wave, tide, hydro, ocean, and geothermal energy are accepted as renewable energy resources [37]. Dincer [17] has defined renewabilization as the process of switching to renewable energy (including solar, wind, geothermal, hydro, ocean, and biomass) based options from conventional fossil fuels based ones.

Proliferated utilization of renewable energy sources and renewable energy based technologies could potentially tackle a comprehensive range of issues, such as energy security, energy equity problems, energy conversion and use related emissions. Additionally, renewable energy resources successfully address a variety of other sustainability related issues for instance poverty reduction, clean water protection, development of transport, agriculture, infrastructure, and industry, job creation, etc. The potential advantages of renewable energy resources are generally not taken into account when assessing the return on investment, for example enhanced energy security, cleaner, easier, and more reliable access to energy, decreased economic instability, climate change alleviation, and new business and employment prospects [38].

Renewable energy resources are essential in smart energy systems for the reason that they are considered as non-diminishable resources of energy with improved quality and minimum or no detrimental influence on the environment. Therefore, it is very essential to use renewable energy sources in smart energy systems with enhanced energy efficiency. The effectiveness of any energy conversion method is restricted due to system irreversibilities such as heat generation as a result of friction. As a result, in traditional single-generation systems, there is always some sort of a type of lost or wasted energy. There are various examples of energy waste or losses in traditional energy systems, some of them are heat discarded from the heat engines, partial combustion, etc. The primary energy use becomes more efficient and cleaner when lost and/or wasted energies are regained and transformed into desired products [39].

In this study, the renewables rankings are assigned to each energy source as 0 meaning non-renewable (fossil fuels and nuclear) and 1 meaning renewable which includes solar, wind, hydro, and geothermal. Biomass is assigned to be 0.5 since its renewability depends on the rate of consumption. If the rate of consumption of the biomass is lower than the rate of biomass regeneration, it can be taken as fully renewable. However, if the rate of consumption exceeds the rate of resource replenishment, then the source is not renewable. In this case, since the energy sources are being ranked, multigeneration (increasing the number of outputs) do not change the renewability rankings.

4.4. Energy storage and carriers

Affordable, reliable, and cleaner energy carriers is an important requirement for a sustainable future, therefore, smart energy systems need to integrate with a variety of energy carriers such as electricity, heat, cooling, and chemical fuels (e.g., hydrogen) and their storage options. Multigeneration of these energy carriers offers tremendous advantages. As the number of products increase, the emissions and cost per unit amount of product decreases and the energy systems become "smarter" with improved energy conservation and cleaner technologies [40].

A major advantage of smart energy systems is the fact that they offer multiple advantages at once. This is principally correct for energy efficiency, renewable energy use, and the multigeneration of electricity, heating, cooling, chemical fuels such as hydrogen, which bring many benefits such as economic growth, introduction of new jobs, enhanced energy security, better health and environmental conditions, and climate change alleviation [41]. Dincer [17]

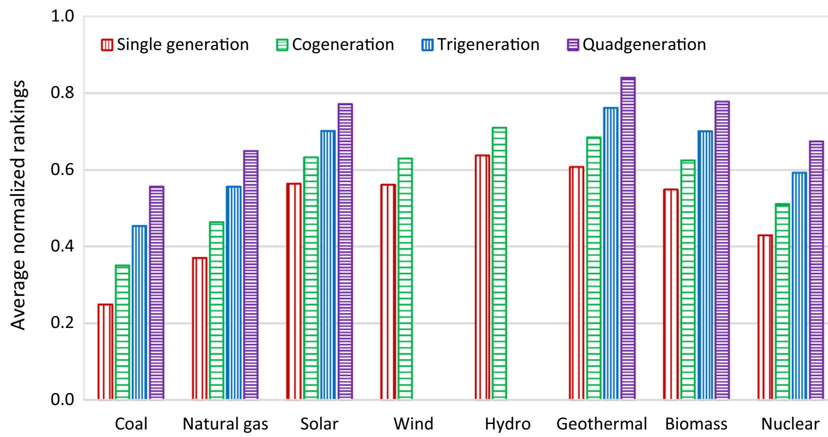

Fig. 7. Average normalized rankings of various energy sources in different generation technologies.

has introduced a concept called "storagization" which is defined as the process of implementing energy storage options to offset the mismatch between demand and supply and to operate the systems in a more efficient, economic, and environmentally sound manner.

The selected options are ranked based on the number of products they generate regardless of the energy source. Single generation is assigned to be 0.25, cogeneration is assigned to be 0.5, trigeneration is assigned to be 0.75, and quadgeneration is assigned to be 1.

4.5. Overall comparison

In this section, averages of the normalized rankings in terms of emissions, efficiencies, renewability, and number of desired products are taken. Fig. 7 presents these average rankings of coal, natural gas, solar, wind, hydro, geothermal, biomass, and nuclear.

From Fig. 7, it can be seen that average rankings increase with increasing number of products. Smart energy systems are obviously expected use cleanest resources in the most efficient way possible at acceptable price levels. So far, energy sources and systems are comparatively evaluated based on their emissions, efficiencies, renewability, and possible output types and numbers. Each evaluation up to here takes one criteria into account, however, a smart energy system must have better rankings in each category. As a result, when technology cleanness, energy conservation, renewability, and energy storage and carrier options are taken into account, quadgeneration with geothermal has the average rankings (0.84/1.00), followed by biomass based quadgeneration (0.78/1.00) and solar based quadgeneration (0.77/1.00). Following these three technologies, geothermal based trigeneration (0.76/1.00) has good rankings as well. Then the list goes with hydro based cogeneration (0.71/1.00), trigeneration with solar or biomass (0.70/1.00), geothermal based cogeneration (0.68/1.00), nuclear based quadgeneration (0.67/1.00), natural gas based quadgeneration (0.65/1.00), and hydro based single generation (0.64/1.00). On the other hand, coal based single generation has the lowest rankings (0.25/1.00), followed by coal based cogeneration (0.35/1.00) and single generation with natural gas (0.37/1.00). Nuclear based single generation also has low average rankings (0.43/1.00). Detailed investigation on the energy sources are conducted by taking the average rankings of all generation technologies in terms of emissions, efficiencies, renewability, and the number of products. The corresponding results are presented in Fig. 8.

Fig. 8 shows that in terms of emissions, wind has ideal rankings. Hydro (0.99/1.00) and solar (0.97/1.00) have also very high average rankings when emissions are considered. Coal has the highest emissions and therefore lowest rankings (0.16/1.00) followed by natural gas (0.50/1.00). When efficiencies are taken into account, natural gas (0.91/1.00), coal (0.83/1.00), and nuclear (0.75/1.00) are advantageous. Wind (0.01), solar (0.08), and hydro (0.33) have the lowest efficiencies. Together with renewability and number of

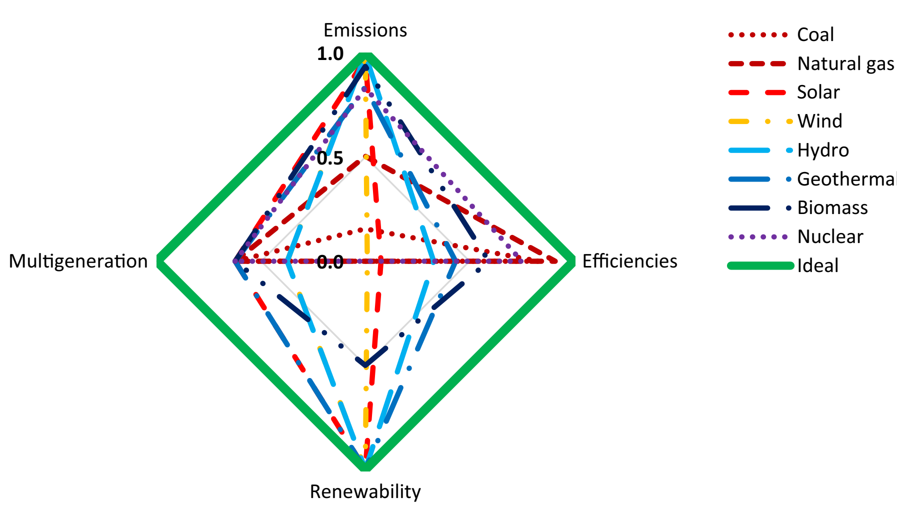

Fig. 8. Average normalized rankings of various energy sources in terms of emissions, efficiencies, renewability, and the number of products.

outputs (the availability of different energy carrier and storage options), on average, geothermal has the closest to ideal rankings (0.72/1.00), followed by solar and hydro (0.67/1.00) and biomass (0.66/1.00). On the other hand, coal has the lowest average rankings (0.40/1.00), followed by natural gas (0.51/1.00) and nuclear (0.55).

It is essential to note that smart energy systems continuously evolves and they are highly dependent on technological advancements. Also, the choice of a smart energy system starts with selecting the most appropriate source for a specific region. The findings listed here are the averages of the data published previously in the literature. For instance, our findings suggest that geothermal would be the most promising option when the following criteria are taken into account: technology cleanness, energy conservation, renewability, and the possibility of having different energy carriers from the same source at the same time. However, if geothermal is not available, reliable or very expensive in one region, this option will no longer be considered as "smart". A smart energy system should be support sustainability in every stage of its life cycle, from cradle to grave, following the 3S (Source-System-Service) flow. Transition to smart energy systems for a sustainable future is currently seen as the key driver of innovation and is an ongoing effort. Novel technology solutions, development in materials science, and introduction of new sources, systems, and services could potentially accelerate replacing the traditional ones with smart energy systems.

5. Conclusions

Energy is an essential factor influencing the challenges of the 21st century. Energy provides a useful opportunity to tackle many of the challenges due to its immediate and direct relations with most important social, economic, security, and development targets of future sustainability. Amongst the numerous other challenges, energy systems are strongly related to worldwide economic activities, to existing freshwater, land, and food resources, to biodiversity and air quality through emissions of particulate matter and precursors of tropospheric ozone, and to climate change.

In this study, the issues with global energy use and the smart energy systems to address these issues and challenges are discussed in detail. Essential requirements for transition to smart energy systems for a sustainable future can be summarized as:

- energy conservation
- enhanced use of renewable energies
- smart grids to support renewable energy utilization
- cleaner technologies
- multigeneration and efficient storage of energy carriers and chemicals

In sum, smart energy systems could attain a sustainable future by tackling challenges and issues related to production, processing, and end use of energy. Our results show that increasing the number of products from the same energy source decreases emissions per unit product and increases efficiencies. Also, among the selected sources, geothermal has the most potential in terms of using cleaner technologies with energy conservation, renewability and the possibility of multiple desired products from the same source. Solar, hydro, and biomass are also beneficial. Even with carbon capture technologies, fossil fuels are not very desirable in smart energy systems because of their emissions and nonrenewability.

This study concludes that substantial new approaches are needed to decarbonise the global economy and that in this regard, a systematic global shift to smart energy systems is urgently needed to avoid the risk of catastrophic climate change or increasing gap between energy supply and demand.

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