

Review

# Towards Efficient and Clean Process Integration: Utilisation of Renewable Resources and Energy-Saving Technologies

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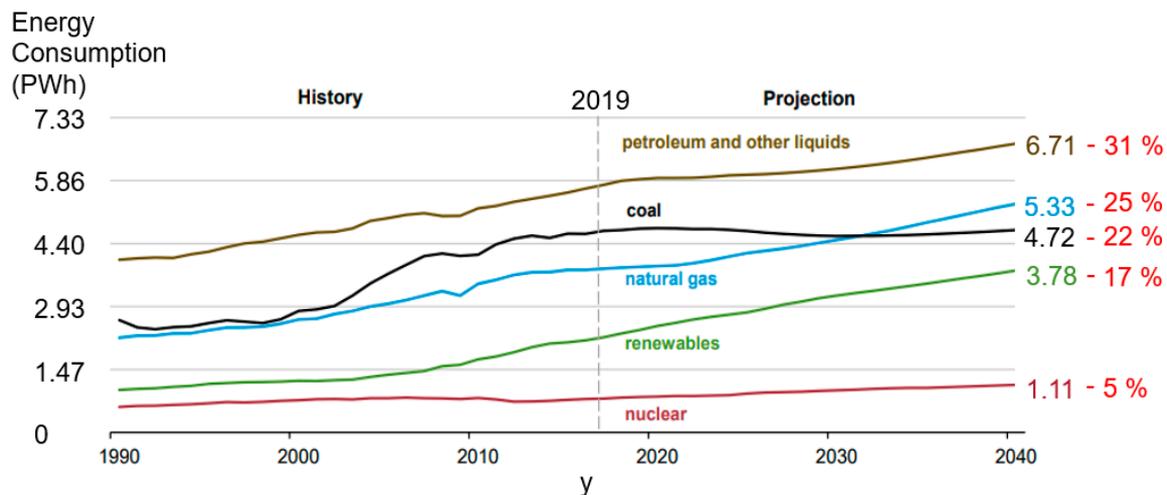
**Abstract:** The strong demand for sustainable energy supplies had escalated the discovery, and intensive research into cleaner energy sources, as well as efficient energy management practices. In the context of the circular economy, the efforts target not only the optimisation of resource utilisation at various stages, but the products' eco-design is also emphasized to extend their life spans. Based on the concept of comprehensive circular integration, this review discusses the roles of Process Integration approaches, renewable energy sources utilisation and design modifications in addressing the process of energy and exergy efficiency improvement. The primary focus is to enhance the economic and environmental performance through process analysis, modelling and optimisation. The paper is categorised into sections to show the contribution of each aspect clearly, namely: (a) Design and numerical study for innovative energy-efficient technologies; (b) Process Integration—heat and power; (c) Process energy efficiency or emissions analysis; (d) Optimisation of renewable energy resources supply chain. Each section is assessed based on the latest contribution of this journal's Special Issue from the 21st conference on Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction (PRES 2018). The key results are highlighted and summarised within the broader context of the state of the art development.

**Keywords:** process integration; renewable energy sources; energy-saving technologies

## 1. An Overview and Introduction

Wang et al. [1] have stated that the economic growth of countries features a strong correlation to their energy consumption, especially for rapidly developing countries. The reliance on energy will only continue to surge as long as the resources are available, and governments are capable of providing them. As the economies continue growing by the utilisation of natural resources, society has started to take their abundance for granted and created an excessive amount of waste that could otherwise be reusable. Fossil fuels, natural gas and coal have been serving humanity as the primary sources of power generation for decades. Inadequate management of the used resources has led to numerous environmental issues, of which climate change (global warming) is one of the manifestations. Melorose et al. [2] have predicted that the Earth's population is expected to grow by more than  $1 \times 10^9$  inhabitants by 2035. The rapid rise of the global population results in almost one-third of the expected increase in energy consumption—see Figure 1. The global oil and natural gas reserves are expected to be exhausted within 60 years if they are exploited at the current rate as predicted by British Petroleum Company (BP) [3], which raises the issues of energy security. As reported by Mah et al. [4], since the

Paris Agreement of 2015, 195 countries are committed to investing efforts to reduce the global average temperature rise to below 2 °C and limit the warming threshold to 1.5 °C. Greenhouse gas (GHG) emissions in a business-as-usual scenario are expected to cause the planet to heat up by 4 °C, creating imbalanced disruptions to the ecological systems. Considering the severe environmental impacts and quick diminishing of natural resources due to exploitation, a cleaner and more sustainable energy resource alternative is needed.



**Figure 1.** Global energy consumption for different fuels adapted from Capuano [5].

Some renewable energies resources (e.g., nuclear energy and virtually carbon-free energy sources) have emerged as promising solutions for ecological degradation and energy security problems. Many countries have started investing in nuclear and renewable energies to reduce over-dependency on the crude oil trade, stemming from the desires for sustainable energy [6]. Based on the data from Figure 1, conventional energy sources (petroleum and liquids, coal and natural gas) are still forecast to account for about 78% of the global energy consumption in 2040. There might be several reasons for the continuous reliance on non-renewable sources. The scalability of renewable technology to the industrial application is the primary challenge. Most of the successful energy harvesting from renewable sources, such as thin-film solar based on Dharmadasa [7], algae-based biofuel according to Vo et al. [8] and cellulosic ethanol in Zabed et al. [9] are developed at a small scale due to the nature of the resource supply—distribution over the harvesting area [10].

Power generation technologies, including renewable energy technologies and innovative low carbon emissions technologies, take a lot of time and efforts for full commercialisation. Gross et al. [11] mentioned that it could take from 20 to almost 70 years for a full technology and product to emerge from the invention, diffuse into market and reach widespread commercial deployment. According to their study, electricity generation technologies, such as combined cycle gas turbine (CCGT), nuclear power, wind electricity and solar photovoltaic (PV), can take approximately 43 years from invention to widespread commercialisation. No clear reasoning has been provided, but it can be deduced that the asset lifespans of electricity generation technologies are usually very long—several decades in the case of power stations. Longer time duration is often necessary to completely replace the existing facilities. Mature technologies often require years of development and inventions so that they can be stable enough to replace existing technologies. In the case of nuclear power, social acceptance is one of the most significant obstacles to achieving the goal of cleaner energy production.

The requirement of large land space is another obstacle to the implementation of renewable energy technology. At present, the world requires a continuous and consistent energy supply, which is the second critical hurdle for solar and wind technology, because the resources for these energy options are available at rates that vary in time. The need for extensive integration with the grid or installation of battery storage to become the chief power generating sources generates a penalty cost of the large

land footprint. Brook and Bradshaw [12] estimated that around 50% of the total energy demand in the United States could be satisfied with renewable energy technologies, but it would require at least 17% of the land. This is evident from the data in Table 1, which shows the land use for renewables is significantly larger than for conventional sources.

These clean energy sources are claimed to mitigate climate change or improve air quality. Pablo-Romero et al. [13] conducted a Life Cycle Analysis (LCA) on various renewable technologies for electricity generation. They showed that the carbon emission intensities of renewable technologies (including solar power, geothermal power, hydropower, nuclear energy and wind energy) are negligible as compared to fossil fuels and coal. Mathiesen et al. [14] conducted a scenario study on health costs estimation based on the case of Denmark, in the year 2050 when 100% renewable energy systems are used. The health costs are estimated based on the basis of various emissions: SO<sub>2</sub>, CO<sub>2</sub>, NO<sub>x</sub>, PM<sub>2.5</sub>, mercury and lead, and the results show significant health savings can be achieved. Likewise, Patridge and Gamkhar [15] quantified the health benefits of replacing coal-fired generation with 100% wind or small hydro in China. The scenario analysis shows a significant reduction number of hospital stays due to reductions in SO<sub>2</sub>, NO<sub>x</sub> and particulate emissions. Heat generation from renewables might not be the ideal case for air pollutant reduction. For example, the gasification of biomass can produce various ultrafine particles that are detrimental to human health. Poláčik et al. [16] conducted the analysis and concluded that the oxygen contents in the atmosphere could result in higher particulate matter production from biomass combustion. This requires post-treatment for biomass conversion before discharging the flue gas into the atmosphere. To compare between energy supply options, Table 1 shows the economic-environmental impact indicators for the power generating options, adopted from Brook and Bradshaw [12].

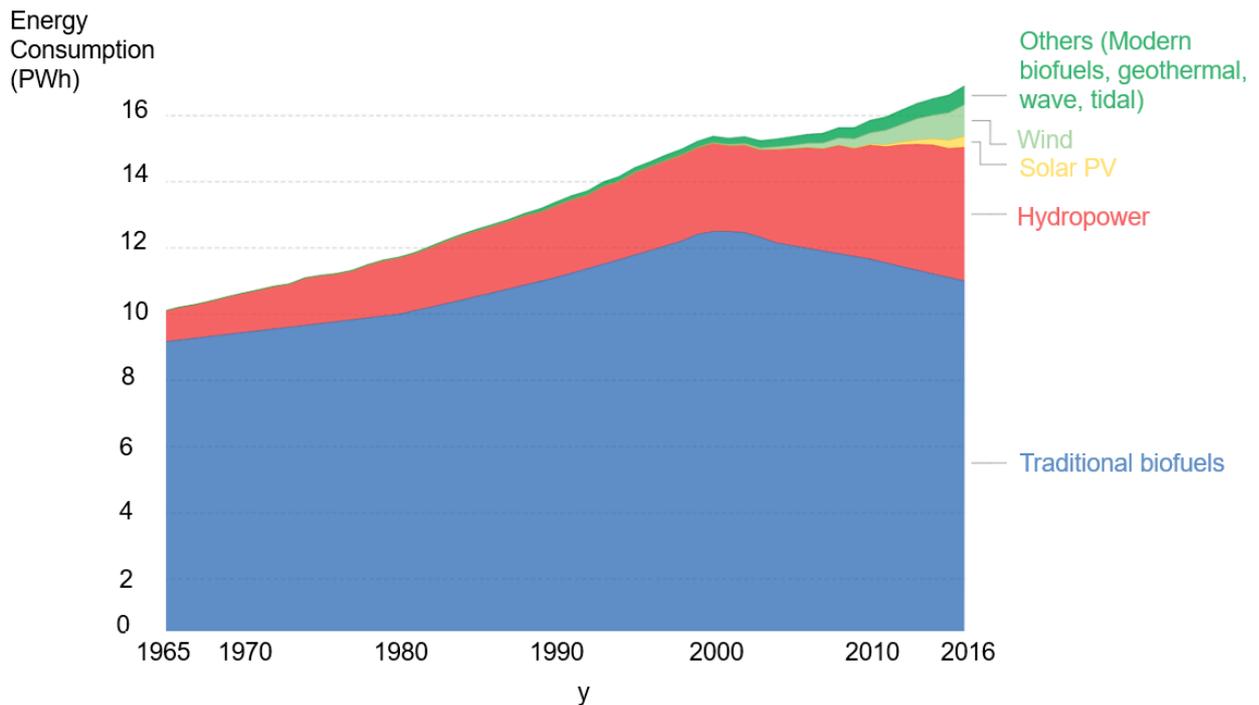
**Table 1.** Relative ranking of the power generation options, data adapted from Brook and Bradshaw [12]. The values in brackets are the relative ranking between energy options.

Indicator Category	GHG Emissions (kt CO <sub>2</sub> /TWh)	Electricity Cost (\$/TWh)	Land Use (km <sup>2</sup> /TWh)	Safety (Fatality/TWh)	Solid Waste (kt/TWh)	Capacity Factors* (%)	Toxic Waste Amount
Coal	1,001 (7)	100.1 (4)	2.1 (3)	161 (7)	58.6 (7)	70–90 (2)	Mid (6)
Natural gas	469 (6)	65.6 (1)	1.1 (2)	4 (5)	NA (1)	60–90 (3)	Low (3)
Nuclear	16 (3)	108.4 (5)	0.1 (1)	0.04 (1)	NA (1)	60–100 (1)	High (7)
Biomass	18 (4)	111 (6)	95 (7)	12 (6)	9.17 (6)	50–60 (4)	Low (3)
Hydro	4 (1)	90.3 (3)	50 (6)	1.4 (4)	NA (1)	30–80 (5)	Trace (1)
Wind (onshore)	12 (2)	86.6 (2)	46 (5)	0.15 (2)	NA (1)	30–50 (6)	Trace (1)
Solar PV	46 (5)	144.3 (7)	5.7 (4)	0.44 (3)	NA (1)	12–19 (7)	Trace (1)

\* The capacity factors represent the percentage of time that the power generation plant operates at full rated capacity. Data adapted from IRENA [17].

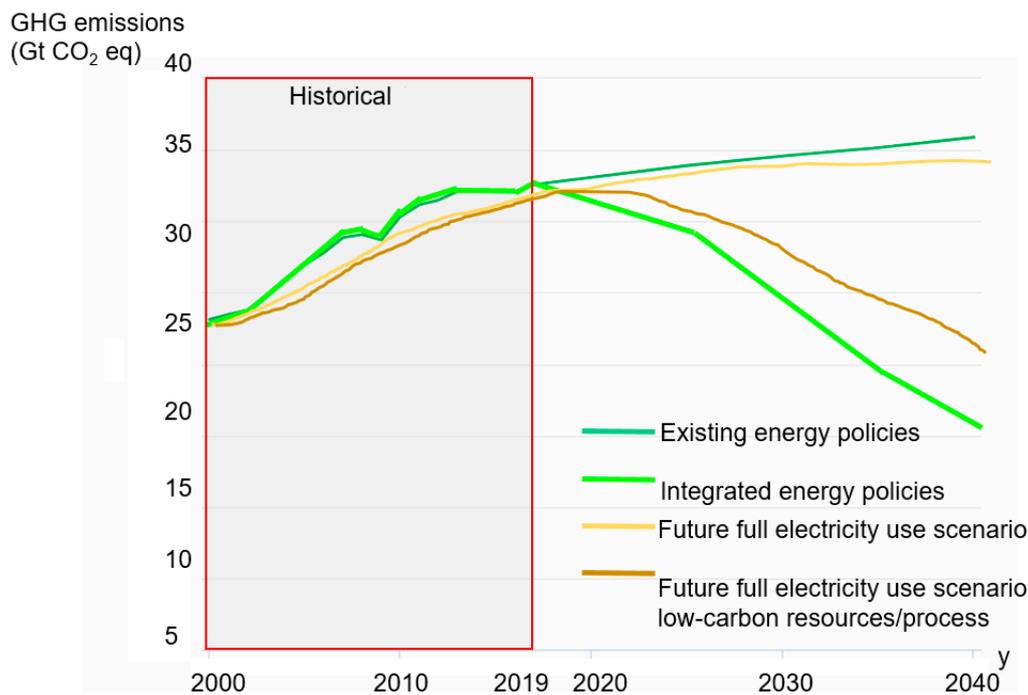
Brook and Bradshaw [12] ranked the preferences of different energy options with various criteria. The readers are referred to them for more information. Table 1 shows that the emissions for coal are the highest among all options. From the estimations in Figure 1, the utilisation of coal is expected to increase in the next few years and around 2030, the natural gas is expected to exceed the consumption of coal. This might be due to the fact that emissions and waste produced from coal usage are higher compared to natural gas. Rapid progress in strengthening of project financing by government policies is enabling more cost-effective installation of dynamic renewable technologies like solar photovoltaics, solar-thermal plants, hydrothermal plants and onshore wind worldwide [18]. The surges in renewable energy consumptions estimated from Figure 1 show the global acceptance and evolution of renewable technologies. Although nuclear power generation is virtually carbon-free and the most efficient option, high amount of radioactive waste produced still creates ethical and ecological issues. The slow expansion rate of the nuclear energy shown in Figure 1 is probably due to its hazardous level, which causes low social acceptance. Figure 2 shows that the traditional biofuel use is preferred by consumers compared to other renewable options. The reason behind is probably because of the capacity factor

for biofuel is also comparatively consistent than the non-nuclear renewable options, as shown in Table 1. Biomass-related fuel requires several stages of energy-intensive pre- and post-treatment. This might be the cause of large land requirements, mainly for biomass upgrading. The electricity cost is relatively higher due to the high operating temperature and heating medium. The generation of an excessive amount of low-quality waste creates a significant obstacle for the green policy. The enforced government policies to reduce environmental emissions and waste decrease the reliance on biofuels slowly, emphasising the use of alternative cleaner renewable options such as hydropower and solar power.



**Figure 2.** Global renewable energy consumption, adapted from Ritchie and Roser [19].

The Renewables 2018 Global Status Report [20] mentioned that the power sector is driving a rapid change towards a renewable energy future, and others are not advancing with the needed rate. The power sector is progressing with positive momentum, but the emissions reductions targets were not being met. In Figure 3, it is clearly shown that the overall carbon emissions are expected to increase, due to the increased dependence on natural gas if compared to other fuels—see also Figure 1. The primary energy demand for natural gas continues to rise in the next 20 years. The World Energy Outlook (WEO) from the International Energy Agency [21] has predicted that the global CO<sub>2</sub> emissions would continue to rise with existing energy policies in the next 20 years. The analysis from WEO also predicted that future electrification in transportation, buildings and industry would lead to a peak oil demand before 2030 and reduce air pollutants. However, the impacts on GHG emissions are negligible after the year 2030. Stronger efforts are needed to increase the utilisation of renewables with low carbon contents so that the predicted CO<sub>2</sub> emissions could decrease (Figure 3). With agreed international objectives, government from all countries could cooperate to tackle the issues of air quality, climate change and universal access to modern energy, ideally results in a significant reduction of global CO<sub>2</sub> emissions. The policies integration around the world is the key to achieve common targets of sustainability, global Circular Economy and the objectives of the Paris Agreement on climate change.



**Figure 3.** Predicted global GHG emissions with different energy policies, adapted from WEO [21].

For better and consistent use of renewable energy, energy storage plays a crucial role. The energy surplus from solar or wind technologies can be stored in a storage unit during their peak seasons and off-peak demand season. The stored energy can then be used to satisfy the energy's demand during peak season, reducing the outsourced electricity from the grid—see Figure 4. As electricity prices are often the highest during peak demand season, the utilisation of energy-efficient storage technologies could aid in electricity saving. This topic is discussed more in Section 2. Main topics in this Special Volume.

One of the typical methods in assessing the energy efficiency of a particular fuel is the so-called Energy Return on Investment (EROI). It measures the quality of fuels by calculating the ratio of energy that can be delivered to the society to the energy invested in the harvesting, based on Murphy and Hall [22]. Hall et al. [23] mentioned that the majority of current EROI analyses tend to focus on the 'energy break-even' point of EROI for different fuels, i.e., whether it is greater than 1:1. The metric is a straightforward analysis. However, the variations of the findings can be wide depending on the selection of study boundaries. The possible boundaries that are often studied are illustrated in Figure 5. EROI analyses are typically categorised into three levels: (a) Standard EROI (EROI<sub>STD</sub>), a conventional analysis that focuses on the energy input for the extraction and the energy needed to generate the desired output; (b) Point of Use EROI (EROI<sub>POU</sub>), the boundary is extended to the additional spent energy to refining and transporting the fuel; (c) Extended EROI (EROI<sub>EXT</sub>), this EROI analysis consider the further the use of that energy in specific applications, for example, to run a boiler. Lambert et al. [24] further emphasised that the EROI boundaries should sum up the entire gains from the fuels and entire energy spent on the fuels. They stress that the vision for a modern energy system should extend to any non-energy cost for setting up the energy system. The temporal boundaries also should cover from the starts of the project until the end of the project. Figure 6 shows the temporal boundaries for determining the comprehensive net energy requirement of thermal technology.

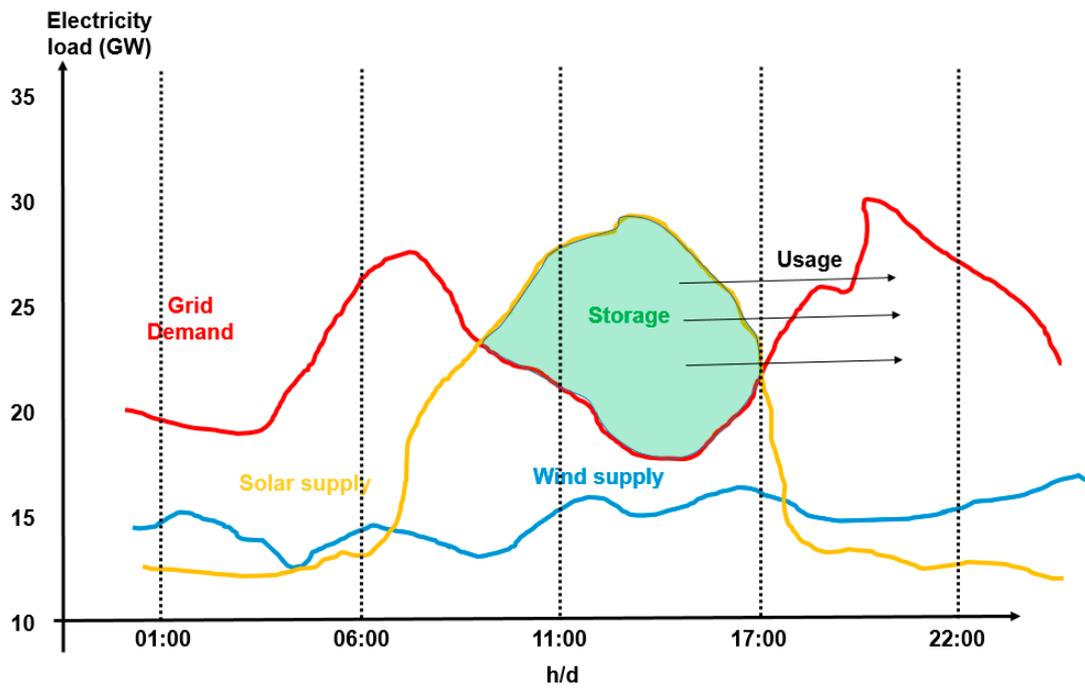


Figure 4. Utilising stored renewable energy surplus to satisfy the energy demand, adapted from Movallen [25].

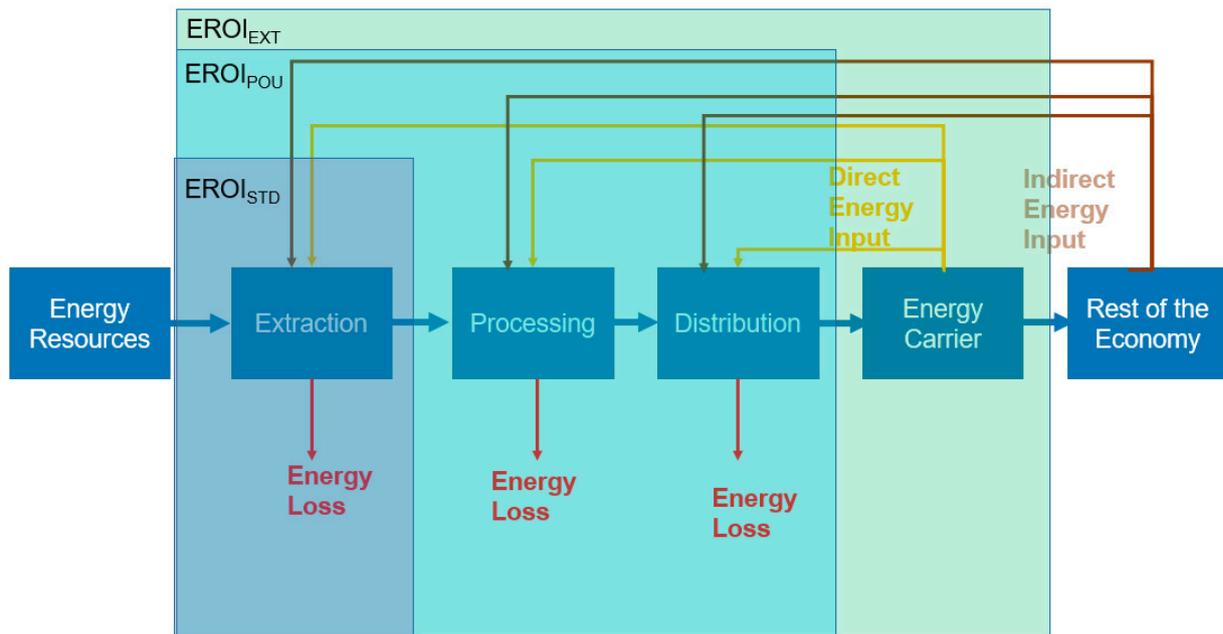


Figure 5. Possible boundaries of a net energy assessment, adapted from Hall et al. [23].

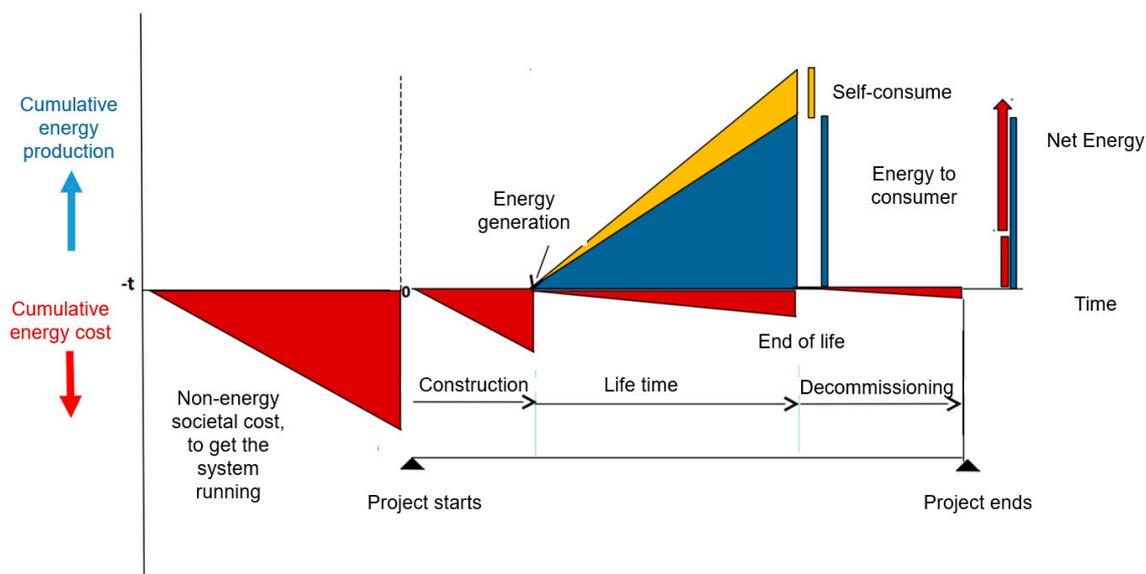


Figure 6. Net energy requirements for technology, adapted from Priesto and Hall [26].

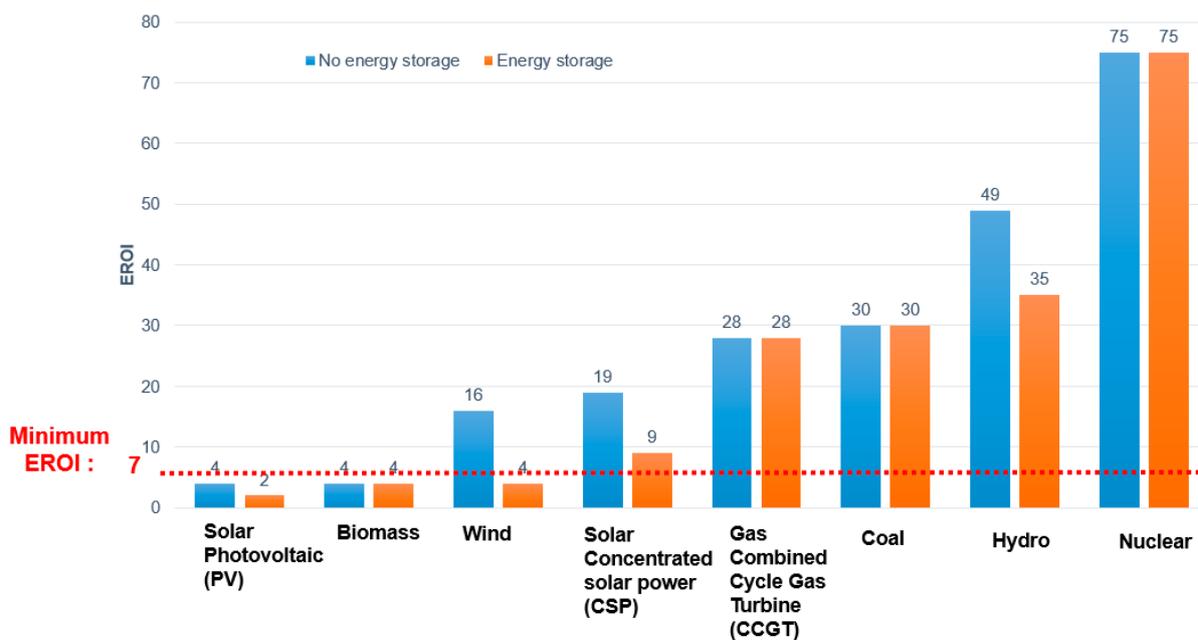


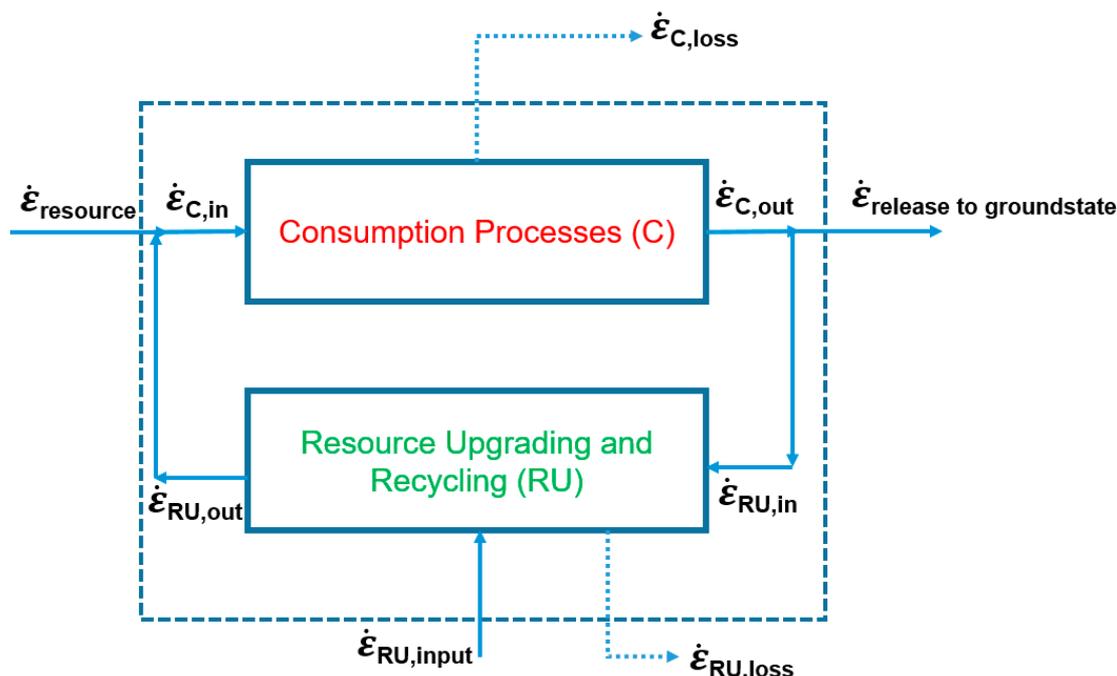
Figure 7. EROI of different fuels, data adapted from Weißbach et al. [27]. The minimum EROI is taken as the average minimum EROI value from Hall et al. [28].

To illustrate the EROI values for different energy options, the facilities in Germany, which one of the most advanced economies in the EU, are used as an example. Figure 7 shows the EROI values for different energy options in Germany country presented by Weißbach et al. [27]. The EROI boundary is contained within the project implementation period. It should be noted that pump storage is used as the energy storage option. The requirements of additional energy for storage reduce the EROI values for the fuels which decrease their economic preferences. Solar PV in Germany has an EROI far below the economic limit, even with the most effective roof installation. A study from Hall et al. [28] indicated that the minimum EROI limit is about 5–10 for any energy supply option, which is just enough for civilisation. Wind energy has a preferable EROI, but falls below an economic threshold, even when combined with pump storage. Installation in the German coast to enhance the EROI values is also futile. Biogas-fired plants have the problem of requiring enormous fuel provisioning efforts, which brings

them clearly below the economic limit with no potential for achievable improvements contemplated. Solar CSP has better performance among the new solar/wind technologies. However, pump storage is often not available in regions with high solar irradiation. Less effective storage techniques like molten salt thermal storage and the connection to the European grid probably brings the EROI again below the economic limit. Further information on energy storage is briefly discussed in Section 2.3.

Even though EROI is the most critical parameter to measure the energy effectiveness of power technology, it is neither fixed nor the only parameter for such an assessment. EROI slowly changes with time due to fossil fuels extraction—when they become harder to access, but also when processes are improved as it happened with the steel production and the uranium enrichment [27]. The land consumption, the impact on nature, and the scope of the stockpiles have to be taken into account separately. This is where the term ‘exergy’ comes into play. The central definition of exergy is bounded to a physical process which usually measures the utilisation of energy. It is defined as the maximum attainable work inside a system. The exergy of a heat flow measures theoretically the amount of work that can be generated if it is to be discharged into a reference environment (usually ambient), which mimics the heat engine configuration. Exergy accounts for both the energy in the system and the condition of the system relative to the environment. The high energy efficiency of the system does not necessarily mean that the energy is used to its full potential. Consider two energy storage systems (ESS1 and ESS2) as an example; both ESS1 and ESS2 are charged with the same amount of input energy and produced the same amount of output. The energy efficiency for both systems can be similar, but the exergy efficiency can be different. If ESS1 produces a thermal energy flow with a higher temperature than ESS2, the exergy efficiency of ESS1 would be higher than ESS2. This is due to the output from ESS1 has a higher quality of heat (higher temperature), which theoretically can be used to generate more work. The output from ESS2 has lower quality as exergy is lost in the system, which stems the term ‘exergy efficiency’.

Exergy efficiency is a useful indicator to pinpoint the technical inefficiency of any process. For the example of energy storage systems above, if both have over 90% efficiency, one can actually satisfy with the performance of the system without modifications. However, if there are secondary processes after the primary process that utilised heat from the storage systems, the ‘higher’ quality heat can further be used as a heating source. The lower quality heat has limited usage. The strategies to reduce the exergy destruction for ESS2 can be developed to improve the performance. Exergy can be applicable in any physical transformation process, not limited to only thermodynamic or chemical processes. It can be used for resource accounting by evaluating the resource consumption, depletion and degradation in a spatial and temporal boundary. This concept is also widely used in a few Life-Cycle Analysis (LCA) studies of energy processes. The thermal and electrical energy is converted into equivalent ‘works’ which provide the ‘weighting’ for various forms of energy. The exergy concept can be implemented into EROI calculations to determine the technical limits for each thermal processes, see Figure 8 for the illustration of the potential study boundary. The evaluation should be performed through comprehensive top-down analysis, ranging from raw materials, extraction, consumptions, recycling, energy usage to environmental emissions. The exergy can also be used to represent the degradation of the resources over time, which energy is not able to do so. To pinpoint the technical bottlenecks, the exergy efficiency should be evaluated starting from the resource input exergy until it is used up and released to ground state. The temporal effect can also be incorporated into the analysis to evaluate the overall efficiency affected by resource degradations. The resource upgrading units vary depending on the type of resource, for example, heat pumps for energy resources and desalination for water resources. The upgraded resources can be utilised not only to the original consumption process but can be used in a secondary process. The maximisation of resource utilisation is in-line with the concept of the circular economy.



**Figure 8.** Proposed exergetic efficiency calculation boundary to access resource consumption and depletion, adapted from Connelly and Koshland [29].

In the light of the mentioned issues, the Special Issue (SI) from the conference PRES 2018 aims to address the issues of boosting energy and environmental performances for processes. Based on Figure 5, this study is targeted to maximise the energy production and saving within the system lifetime period. The collected Special Issues (SI) focus on the process analysis, modelling and optimisation as well as design modifications to minimise the energy loss or exergy destructions. The problem domain size ranges from process level to total site. The studies on the allocation of renewable energy resources in a regional supply chain are collected as well. This SV aims to provide high-end researches in dealing with better energy resource management and product designs, advancing towards the goal of the global circular economy.

## 2. Main Topics in this Special Volume

In this work, the state-of-the-art Process Integration and Intensification strategies through the utilisation of renewable resources towards sustainable production are collected and analysed. More emphasis is given on the efficiency improvements in heat and power usage for various technologies. In this special issue, the strategies used by the researchers are divided into two major groups: (a) Optimisation of process network topology and resources utilisation in a total site; (b) Energy and environmental efficiency analysis of process technologies.

This review paper is supported by the published works in the same journal, within the Special Volume (SV) presented in the conference series “Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction” in 2018 (PRES 2018). This conference has served as a knowledge-sharing platform among international experts from multi-disciplinary domain since 1998, producing high-quality researches through intellectual integration. A total of 40 selected papers invited to be submitted for this SV, 24 of them have been accepted. The contributors in this special issue has a wide range of country distribution, which involve six from the Czech Republic, four from Germany, two from Mexico, two from Spain, one from Colombia, one from Croatia, one from Hungary, one from Latvia, one from Malaysia, two from The Philippines, one from Thailand and one from the USA) The statistics shows the active participation of researchers with a wide variety of nationalities. Upon close

examination of the keywords in this special issue, the articles are further categorised into four main topics that are overviewed to achieve the review's target:

- (a) Design and numerical study for innovative energy-efficient technologies
- (b) Process Integration—heat and power
- (c) Process energy efficiency or emissions analysis
- (d) Optimisation of renewable energy resources supply chain

The biomass-related studies commonly refer to the biomass sources as abundantly found in various agriculture process. The thermochemical conversion of biomass appears to be a promising way to generate process heat. The energy can be potentially used in a gas turbine or steam generation. It could aid in reducing the natural energy resources through upgrading, but the pollutants produced from biomass are hardly identified due to their complex nature. The flue gas generation from biomass gasification contains a complex distribution of solid pollutants with different size ranges. They could cause not only severe air pollutions but also detrimental to human health, specifically the ultrafine particles. Solar energy is also exploited as a clean energy source. The inflexibility of the operation of solar collectors hinders their large-scale industrial application. This issue is also addressed in this SV through designing solar collector arrays to improve operational flexibility.

The process improvements through bottlenecks analysis and technologies shifting are also alternative strategies to consume less energy. The additional insights from the special issue also determine the energy efficiency, environmental performance and economic evaluation of various energy-saving and clean production technologies. For example, the large-scale production of bio-adsorbent chitosan microbeads for wastewater purification is limited by the low exergy efficiencies. The separation units and drying are the main contributors in high exergy destructions. One of the articles determined that the recycling of organic wastes in the existing municipal solid waste collection systems through pneumatic collection could be an energy-saving technology, also reusing organic waste as energy providers. The economic, environmental and energy performance the aspects of the current practice of seawater desalination in China is assessed. By comparing desalination technologies, it provides insights on the potential in process improvements through regional water and energy integration. The technologies shifting through modifying the structures of heat exchanger fired equipment, piping and building supports can enhance the effective heat transfer area and facilitate energy saving as well. The design modifications are validated through empirical and numerical analysis, e.g., Computational Fluid Dynamics (CFD).

This special issue also deals with the enhancement of Process Integration with more robust approaches in driving towards sustainable operation. The cost-optimal synthesis of heat exchanger network (HEN) synthesis is addressed, considering the 2-D and 3-D layout representation of the process. The controllability and complexity of HEN are also determined through network modelling to provide a solid foundation for the location of sensor installation. The operation of cooling utility system is also optimised through the self-adaptive model with non-steady data. Another interesting study is the integration of energy usage in the cryogenic energy storage with the liquefaction process. A large amount of cold and heat generated during the charging and the discharging process can be integrated and reused. The studies also extend to the regional boundary through Total Site Heat and Power Integration. This special issue particularly addresses for total site heating and cooling with tri-generation systems, and robust design of total site heat recovery loops with transient data. The site-wide optimisation of the renewable energy sources supply chain, mainly biomass, is also highlighted in this Special Issue. The targeted processes that consist of polygeneration plant and manufacturing plant are optimised through cost-effective operational adjustments with various energy supply options.

## 2.1. Design and Numerical Study for Innovative Energy-Efficient Technologies

In recent years the share of Renewable Energy Sources (RES) in the total energy budget has increased significantly. Especially in the EU, where it is planned to cover at least 20% of electrical energy production by the year 2020, according to WEO [21]. The major problem related to RES is low efficiency, and electrical energy production depending on the climatic conditions. The solutions to improve the energy-efficiency of RES are highly welcomed. The use of RES requires the advanced energy storage systems, since the operation of solar energy-driven RES is efficient mostly in the spring and summer period, while the efficiency is very low in the heating season. Also, due to the increased electricity production from RES, the conventional power plants, need to improve their flexibility.

### 2.1.1. Core Developments

The primary issue is related to more frequent start-up and shut-down of conventional power units. For this reason, the extensive fundamental research on both renewable energy sources and conventional power plants are carried out. Both related to design optimisation as well as to the improvement of energy efficiency. The following topics are nowadays of high-importance:

- (a) Research on electric energy storage from Khodadoost et al. [30], including: battery energy storage systems (BESSs), flywheel energy storage systems (FESS), supercapacitors (SC) or ultracapacitors, superconducting magnetic energy storage (SMES), and compressed air energy storage (CAES), among others. To minimise the total costs of hybrid power systems (HPS), Jiang et al. [31] proposed a mathematical model for the configuration of BESSs with multiple types of battery. The authors studied the effect of battery types and capacity degradation characteristics on the optimal capacity configuration of the BEES alongside with power scheduling schemes of the hybrid power systems. The performance of the proposed model was verified through the case study of HPS with photovoltaic-wind-biomass-batteries. The authors found the BESS with multiple types of battery is superior to the one with a single battery type. Duan et al. [32] studied a hybrid generation system consisting of a micro gas turbine (MGT) generator system coupled with a supercapacitor (SC) energy storage. The authors proposed two cooperative control methods for the hybrid generation system. The first one was a PI-based control algorithm, and the other is the electric power coordinated control method through MGT output power forecast. The authors found that the electric power dynamic response of SC energy storage can compensate for the low dynamic responses of MGT, which allows achieving a transient power equilibrium state in real-time. Santos et al. [33] studied the possibility of adapting superconducting magnetic energy storage (SMES) in smart grids since the characteristics of smart cities enhance the use of high power density storage systems such as SMES. The authors simulated the effects of an energy storage system with the high power density and designed an electrical and control adaptation circuit for storing energy. The simulation results show the possibility of controlling the energy supply as the storage. The authors also discussed the drawbacks of SMES, such as the high cost of construction and operation compared with other EES, i.e., superconductors. Compressed air energy storage (CAES) is an up-and-coming large capacity energy storage technology, primarily due to the increased share of renewable energy sources. Venkataramani et al. [34] performed a comprehensive thermodynamic analysis for conventional and modified configurations of CAES, with increased round-trip efficiency. The results showed that when the compressed air is kept isothermal at atmospheric conditions, the mass of air stored in the tank will be high, so the size of the storage tank can be reduced. The authors also studied the possibility of cooling energy generation along with power generation during the expansion of compressed air from the atmospheric temperature. The results showed that even the round-trip efficiency is weak, in the case when the heat of compression and cold energy generated during expansion are utilized for other applications, the overall polygeneration efficiency is very high.

- (b) Research on thermal energy storage, including short-term and long-term storages, based on Guelpa and Verda [35]. Also depending on the physical phenomenon used for storing heat TES: sensible, latent and chemical storages, and depending on the size: small TES with a low capacity, and large capacity TES systems. TES can also be classified depending on the mobility, i.e., mobile and stationary TES. Bhagat et al. [36] proposed the finned multi-tube latent heat thermal energy storage system (LHTES) for medium temperature (approximate 200 °C) solar thermal power plant in reducing the fluctuations in heat transfer fluid (HTF) temperature caused by the intermittent solar radiation. The authors used phase change materials (PCMs) as the storage material in the shell of LHTES while a thermal oil-based HTF is flowing through the tubes. The authors applied thermal conductivity enhances (TCE)—fins to improve the heat transfer in PCM. The fluid flow and heat transfer were studied numerically. The coupling with the enthalpy technique to account for the phase change process in the PCM was also performed. The developed model was validated experimentally. The results showed that the number of fins and fin thickness considerably affect the thermal performance of the storage system, whereas the enhancement in heat transfer for high thermal conductivity material fin is low. Silakhori et al. [37] investigated the potential of copper oxide for both thermal energy storage and oxygen production in a liquid chemical looping thermal energy storage system. Thermogravimetric analysis was used as the assessment method. The significant advantage of liquid chemical looping thermal energy storage is the availability of stored thermal energy (through sensible heating, phase change, and thermochemical reactions) and oxygen production. The authors achieved isothermal reduction and oxidation reactions by varying the partial pressure of oxygen, through the change in concentrations of oxygen and nitrogen. The experimental confirmed that copper oxide could be reduced in the liquid state. However, thermochemical storage mainly occurred in the solid phase. Heat storage plays a crucial role in the buildings. Taler et al. [38] studied the thermal performance of the heat storage unit made of repeatable modules. The heat accumulator proposed by the authors that are used in solar installations may be a separate unit, or it may be a building wall insulated on the inner and outer surfaces. The accumulator works as a heat storage unit with electric discharge using forced airflow through the channels. The authors determined the transient temperature field in the walls of the channel. Three various methods were used: finite volume method (FVM), control volume-based finite element method (CVFEM), and finite element method (FEM). The preferred method, due to simplicity in the discretization of the governing equation, is CVFEM. Therefore, it was chosen for the construction of a full model of the heat storage to model a solid filling of a heat storage unit with a complex shape. The authors also developed a numerical model of the heat storage unit with the airflow through the channel and CFD simulation was employed. The airflow from the laminar, transitional, or turbulent flow regimes was considered. The airflow was modelled using the finite volume method with integral averaging of air temperature over the finite volume length, and the accurate air temperature distribution can be determined even with a coarse finite volume mesh. The performance of the heat accumulator model was validated experimentally in an experimental study [39] and further evaluated using numerical models [40]. Thermal energy storage techniques are highly required during the operation of solar collector networks. Martínez-Rodríguez et al. [41] proposed a stepwise design approach for solar collectors' networks. The approach allows the assessment of the effect that design variables have on the size of the solar collector. Also, a design strategy is proposed to obtain the network of solar collectors with the smallest surface and the most extended operation during the day.
- (c) Research on photovoltaic, and photovoltaic-thermal systems, including the improvement of PV efficiency by PV panels cooling. The efficiency of converting solar energy into electricity is still relatively low, which causes a significant amount of solar energy is not utilised. The excess of solar energy that remains unused is still absorbed, in some part, by a PV module and may cause a significant increase in the PV panel temperature. According to Kalogirou and Tripanagnostopoulos [42], PV efficiency decreases by 0.45% per each 1 °C temperature increase

above 25 °C. In order to increase the energy efficiency of photovoltaic modules by using the effect of PV panel heating, and to increase the efficiency of solar to electricity conversion, cooling systems for the PV modules are used. Few PV cooling techniques may be distinguished, including active and passive techniques. For active cooling, a forced flow of cooling fluid (e.g., water or air) or water spraying may be used, among others. Passive cooling uses natural convection and heat conduction to dissipate and remove heat from the PV cell. Passive cooling techniques increase energy efficiency and cost-effectiveness of the system, but still, active cooling removes more efficient, due to the higher heat transfer coefficient. The analysis of passive cooling for the photovoltaic modules using selective spectral cooling and radiative cooling was performed by Li et al. [43]. The cooling processes are based on the principle of suppressing heating by the PV module itself. The investigation proved that PV modules with selective spectral cooling, passive radiative cooling, and combined cooling could increase the efficiency by 0.98%, 2.40%, and 4.55%. Alizadeh et al. [44] studied the use of a single turn pulsating heat pipe (PHP) for PV cooling. A two-phase heat transfer mechanism ensures high thermal efficiency of PHP. The corresponding 3D numerical models were developed, and PV cooling by applying a single turn PHP was analysed. Moreover, a copper fin with the same dimensions as the PHP for cooling the PV panel was simulated to compare the performance of the PHP with a solid metal like copper. The performance investigation of the PV panel has proved that PHP cooling ensures the reduction of the PV panel surface temperature by 16.1 °C while the use of copper PHP only by 4.9 °C.

- (d) Research on energy systems components monitoring and design. Thick-wall boiler components are limiting the maximum heating and cooling rates during start-up or shut-down of the boiler. Taler et al. [45] presented a method for thermal monitoring stresses in the thick-walled pressure components of steam boilers. The allowable heating rates of the critical pressure components of the boiler shall be determined, alongside with the temperature of the fluid. The rate of change of the wall temperature of the pressure component and the thermal stress on the inner surface are controlled online and compared with the allowable values. The boiler's manufacturers designate thermal stresses on the inner surface of the pressure component on the edge of the hole based on the measurement of the wall temperature at two points located inside it. However, the accuracy of the method used by boiler manufacturers is low. The authors proposed a new method for thermal stress determination. The method is based only on the internal temperature measurement point to determine the stresses on the inner surface of the component. The method employs the inverse heat conduction algorithms to find the internal surface temperature, and then the stresses are calculated. The authors also performed computational tests for cylindrical and spherical elements. The thermal stresses on the inner surface were also determined using the actual temperature data. The significant advantage of the proposed method is the high accuracy even at rapid changes in the fluid temperature. Trzcinski and Markowski [46] proposed a data-driven framework of diagnosing fouling effects on shell and tube heat exchangers using an artificial neural network. The data are continuously sampled and collected to estimate the pressure drop increment or heat transfer drop in the outlet. The fouling effect can thus be predicted using the model automatically and provides a base for tubes cleaning scheduling. Oravec et al. [47] proposed a closed-loop model predictive control using the novel soft-constrained based strategy for plate heat exchanger. The strategy keeps the control inputs and outputs within the required operation ranges. The experimental results show the improved control performance with such a strategy, and future application in laboratory implementation is undertaking. Taler et al. [48] proposed two methods for monitoring of thermal stresses in pressure components of thermal power plants. The first method determines the transient temperature distribution by measuring the transient wall temperature distribution at several points located at the outer insulated surface of the pressure component. Taking the outer surface temperature measurements as the input, the inverse heat conduction algorithm calculates the temperature distribution in the pressure component. Based on the temperature field determined, it is possible to calculate the thermal

stresses. The second method proposed by the authors involves the finite element method (FEM) calculation of thermal stresses, taking as the input the measured fluid temperature and heat transfer coefficient. The method is suitable for pressure components with complex shape. Other applications of inverse heat conduction algorithms in the monitoring and optimisation of the heating rate of pressure components of steam boilers are presented in [49] dealing with the thermal stresses in the pipes and in [50] focusing on thick-wall components. Perić et al. [51] performed a numerical analysis of longitudinal residual stresses and deflections in a T-joint filled welded structure using a local preheating technique. FEM calculations were performed. The authors found that by applying a preheating temperature prior to starting of welding, the post-welding deformations of welded structures can be considerably reduced. The authors also studied the effect of inter-pass time (i.e., 60 s and 120 s) between two weld passes on the longitudinal residual thermal stress state and plate deflection. The results showed that with the increase of inter-pass time, the plate deflections significantly increase, while the effect of the inter-pass time on the longitudinal residual stress field is marginal. Fialová and Jegla [52] proposed a novel framework for the efficient design of fired equipment. The authors supplemented the traditional thermal-hydraulic calculation of the radiant and convective section by the low-cost modelling systems taking into account the real distribution of heat flux and process fluids. The application of the low-cost models was demonstrated in the industrial steam boiler case. The significant advantages of the proposed approach are that the presented framework links calculations of radiant and convective sections in the combustion chamber, and offers a fast rating calculation of complex fired equipment. The proposed approach can successfully supplement CFD simulation, that should be used for critical components of power boilers. Sriromreun and Sriromreun [53] studied the numerical and experimental characteristics of the airflow impinging on a dimpled surface for air at Re numbers varied from 1500 to 14,600. The authors compared the heat transfer coefficient between the jet impingement on the dimpled surface and the flat plate. The CFD simulations results showed the different airflow characteristics for the dimpled surface and the flat plate. For a particular case, it was shown that a thermal enhancement of up to 5.5 could be achieved by using the dimpled surface. Flow boiling heat transfer is characterized by high heat transfer coefficient. Sun et al. [54] performed an experimental investigation to explore the flow boiling characteristics of R134A and R410A refrigerants flowing inside enhanced tubes. The experimental conditions included saturation temperatures of 6 °C and 10 °C, mass velocities from 70 to 200 kg/(m<sup>2</sup> s) and heat fluxes from 10 to 35 kW/m<sup>2</sup>. The inlet and outlet vapour quality was equal to 0.2 and 0.8. The results showed that the dimples/protrusions and petal arrays are the effective surface structures for enhancing the tube-side evaporation. Moreover, the Re-EHT tube has the largest potential for boiling heat transfer enhancement. García-Castillo et al. [55] also discovered new opportunities to utilise plate-fin surfaces as a secondary surface in a multi-stream heat exchanger. They considered the theoretical design study of such new heat exchanger design, emphasising on the surface design to improve heat transfer coefficients. However, since the design is at the conceptual stage, reliable and accurate thermal-hydraulic correlations are needed. Heat transfer enhancement is highly required in energy equipment. Valdes et al. [56] studied the effect of twists in the internal tube of tube-in-tube helical heat exchanger keeping constant one type of ridges. The CFD simulations were performed to study the effect of the fluid flow rate on heat transfer in the internal and annular flow. The counter-current flow mode operation with hot fluid in the internal tube and cold fluid in the annular domain was considered. The flow and thermal development in a tube-in-tube helical heat exchanger were predicted. The double passive technique was provided within the internal tube to improve the turbulence in the outer region. The results showed that the addition of four ridges in the inner tube increases the heat transfer up to 28.8% when compared to the smooth tube. Kukulka et al. [57] also studied the flow characteristics for condensing and evaporating streams inside Vipertex stainless steel enhanced heat transfer tubes using R410A refrigerants. They proposed that using the Vipertex

enhanced tubes are more energy-efficient than using old technology for phase change streams. As condensation and evaporation processes increase the interfacial turbulence, the proposed technology produces flow separation, secondary flows and higher heat flux from the wall to the working fluid.

### 2.1.2. Possible Future Development

From the performed literature survey, it is evident that efficient energy technologies are needed to improve the energy efficiency of energy systems. This can be achieved by improvement of the unit processes occurring in energy devices, such as enhancement of heat transfer, improvement of energy storage techniques, or improvement of the flexibility of power systems. A very good example here is the improvement of the electrical efficiency of PV panels by using active or passive cooling. Gaining heat from PV allows one to use it as low-temperature waste heat, and couple the PVT systems with heat pumps or underground energy storage systems. This kind of energy systems may attract widespread attention in the near future, due to the high efficiency, and utilization of waste heat. In the author's opinion, the major improvement may be made in the field of energy storage, which is crucial for electrical and thermal energy storage from renewable energy sources. A very important and challenging topic is also increasing the flexibility of hard-coal fired power units. This topic is important due to the large fluctuations in the power of wind farms, and due to the significant fluctuation in PV electricity production. In every moment, the generated power and demand should be equal. In case of rapid decrease of renewable energy production by wind farms and photovoltaics, the rapid start-up of steam boilers is needed. Thus, it is very important to improve the flexibility of thermal power units to shorten their start-up. Therefore, the new method on online calculation and monitoring of thermal stresses occurring in boiler's pressure components are highly needed by the industry, to allow safe start-up and shut-down of power units.

## 2.2. Process Integration—Heat and Power

The PRES conferences have been traditionally providing momentum to Process Integration research and development, not for more than 20 years and been analysed in detail at a jubilee PRES'17 conference [58]. The initial idea was based on the Heat Integration pioneered by the Centre for Process Integration at UMIST (Manchester, UK) started from 1998 hosted in Prague (Czech Republic). Process integration development continues to increase in scope and coverage. This has been in the recent period overviewed and analysed by several review papers. The methodology has been consistently extended to the Water Integration, combined energy and water, hydrogen network synthesis, regional resources planning and power system planning. The illustration of using graphical Pinch Methodology for Heat Integration is shown in Figure 9. In the aspects of heat and power, the methodology is consistently extended from process level to total sites, see Figure 10. The previous period was assessed by Klemeš et al. [59] in 2013 and more recently by Klemeš et al. [60] in 2018. It is worth to remind the contribution from Bandyopadhyay [61] who provided a detailed mathematical formulation of Pinch Methodology.

### 2.2.1. Core Developments

Pereira et al. [62] created a web-based Pinch Analysis tool for heat management called FI<sup>2</sup>EPI. The tool can handle several energy management scenarios automatically, saving a significant amount of time for tedious routine calculations. It not only features energy or cost targeting, but it also identifies the optimal heat exchanger network design opportunities based on the heat exchanger loops and utility paths. The trade-off between design for minimum total annual cost or minimum temperature difference can also be identified, based on the preferences of the users. It is especially useful for Process Integration practitioners, saving extensive time or efforts in performing targeted calculations or network optimisation.

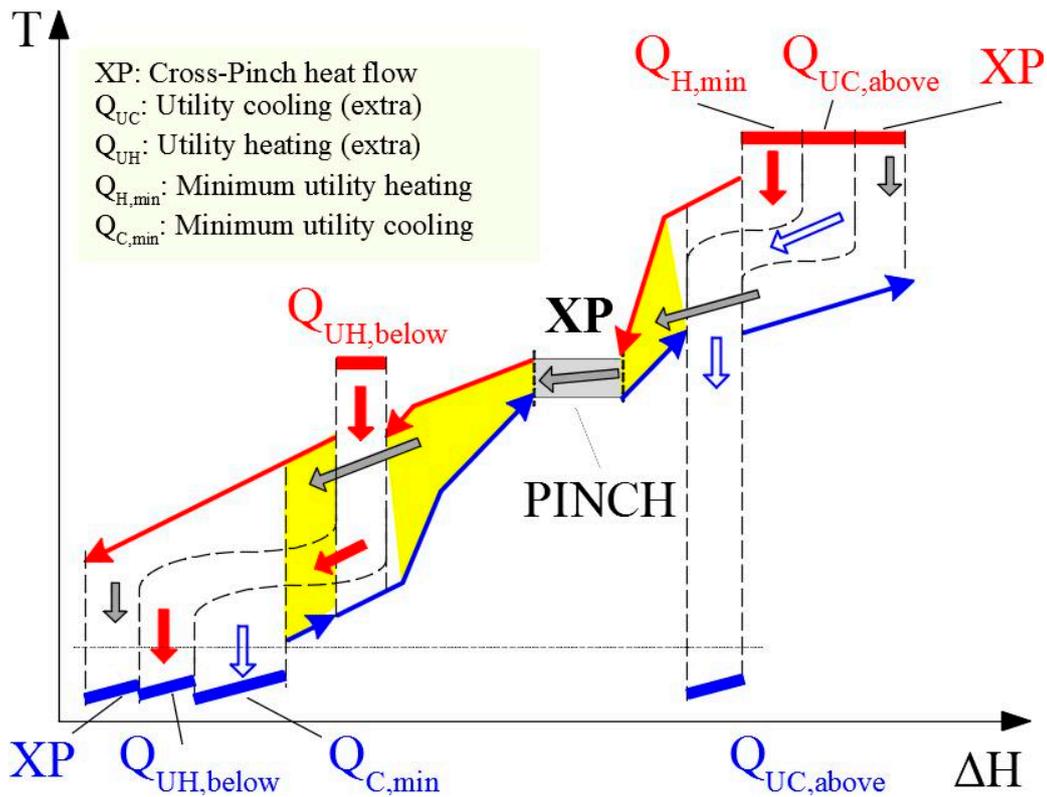


Figure 9. Pinch Methodology in energy targeting (adapted from Klemeš et al. [59]).

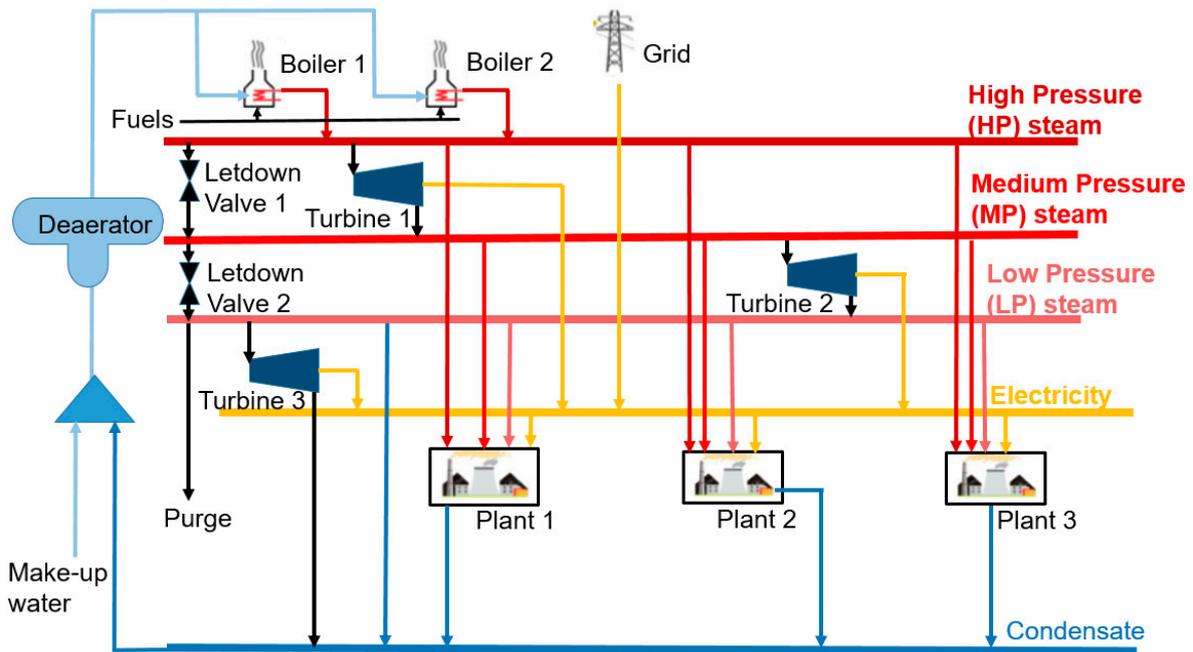
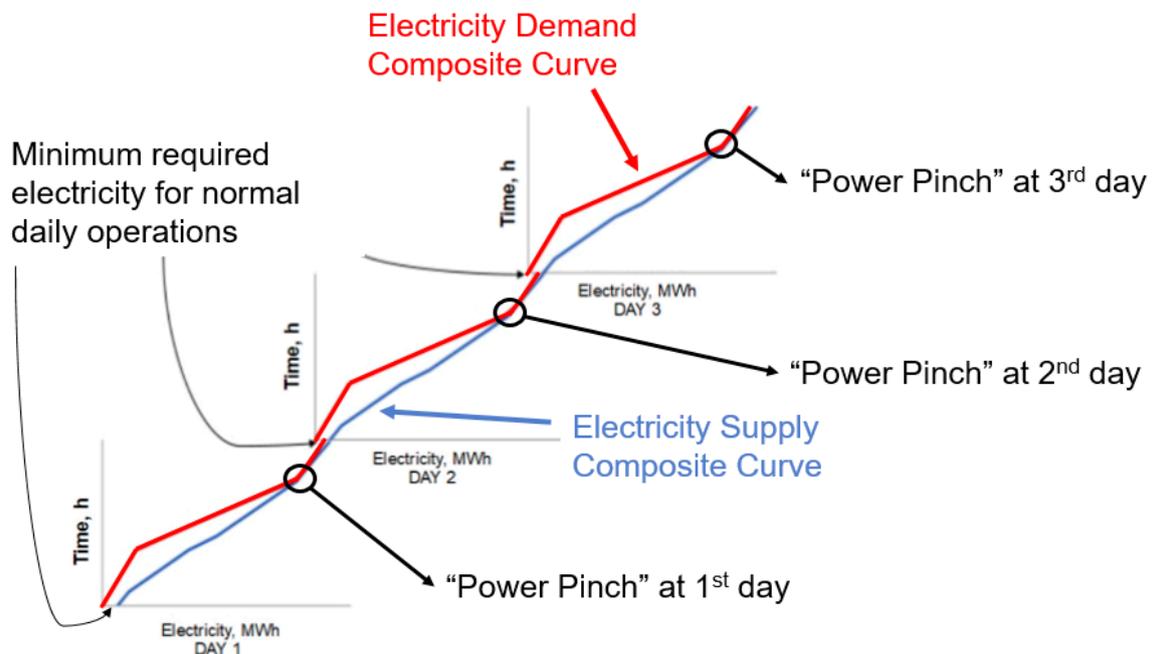


Figure 10. Illustration of industrial Total Site processes with central utility system (adapted from Klemeš et al. [60]).

Esfahani et al. [63] extended Power Pinch Analysis (EPoPA), which was developed by Wan Alwi et al. [64] in 2013 and extended by Rozali et al. [65] in 2017 for the integration of renewable energy systems with battery/hydrogen storage systems. This concept is based on the usage of hydrogen as an energy storage medium for the wasted electricity, which cannot be stored by the battery bank in the conventional PoPA [66], see Figure 11 for the original concept representation. This graphical

tool not only provides visualisation by targeting the minimum required external electricity source and wasted electricity, but the appropriate hydrogen storage system capacity can also be identified during first and regular operation. They showed that integration of renewable hydrogen storage with a diesel generator is cost-effective. More renewable energy storage systems can be considered for in future work, to provide a more sustainable supply of electricity.



**Figure 11.** Illustration of Power Pinch Analysis (PoPA), adapted from Wan Alwi et al. [66].

The relation and contribution of process integration to cleaner production were studied by Fan et al. [67]. This paper indicated a very considerable contribution in process sustainability improvement, by reviewing recent progress in waste-to-energy, pollution prevention and remediation. The relation to CO<sub>2</sub> and GHG generally was highlighted by Manan et al. [68]. Another attempt to extend the Pinch Analysis was presented by Li et al. [69] focusing on the retrofitting of heat exchanger networks. The graphical approach provides interfaces to the users to get insights into the system bottlenecks. Iterative Pinch Analysis to address non-linearity in a stochastic Pinch problem was very recently studied by Arya and Bandyopadhyay [70]. Jain and Bandyopadhyay [71] developed multi-objective optimisation for segregated targeting problems using Pinch Analysis, which again extends the scope of Process Integration.

Interesting work was presented by Martinez-Hernandez et al. [72] dealing with the conceptual design of integrated production of arabinoxylan products using bioethanol Pinch Analysis. The Mass Integration allows significant advances in biorefineries achieved by retrofitting existing biorefineries. High value-added integrated production could be achieved through this method, which in turn provides potential in heat and power saving.

Walmsley et al. [73] developed another significant enhancement by analysing the possible contribution of Process Integration to the circular economy. The extensions of Pinch Analysis to other fields were reached by Roychaudhuri et al. [74] energy conservation projects through financial Pinch Analysis, and Ekvall et al. [75] presented a series of works developing and applying material Pinch Analysis.

From the heat and power field come a couple of useful analyses. Jamaluddin et al. [76] presented an enhanced targeting tool for trigeneration problems. Chauhan and Khanam [77] reported enhancement of efficiency for the steam cycle of thermal power plants using applying Pinch Analysis—identifying and eliminating Cross-Pinch heat transfer in the steam system of the power plant.

Tie et al. [78] studied a specific impact of Process Integration on a classical chemical engineering issue—the production of glycol ether. Bandyopadhyay et al. [79] applied a combined pinch and exergy analysis for the energy-efficient design of the diesel hydrotreating unit. Malham et al. [80] contributed with hybrid exergy/pinch process integration methodology. Chen et al. [81] succeeded with another extension of process integration optimal heat rejection pressure of CO<sub>2</sub> heat pump water heaters based on Pinch Analysis.

The PRES 2018 Special Issue also contributed very significantly to the following topics:

Jankowski et al. [82] applied process integration methodology of ORC plant using a multiobjective approach to recover low-potential heat. It has shown some new possible implementation of Process integration.

Schlosser et al. [83] paid attention to robust total site heat recovery and applied a Monte Carlo simulation successfully. Jamaluddin et al. [84] attempt to deal with the Heat and power at a total site by a trigeneration system and reached an extension of the methodology. Another contribution to a most studied issue dealing with this topic a cost-optimal heat exchanger network synthesis enhanced with flexible cost function network was presented by Rathjens et al. [85]. The utilisation of an air-PCM heat exchanger in passive cooling of buildings was presented by a team from the VUT Brno Energy Institute [86]. From the same research group came the contribution presented by Kudela et al. [87] stressing heat accumulation, an essential issue in district heating pipes. Leithoid et al. [88] dealt with controllability and observability of heat exchanger networks, the key equipment used and studied by Heat Integration. Kamat et al. [89] studied the heat integrated water regeneration networks, considering variable regeneration temperature. They formulated a linear model to optimise the freshwater use, utilities requirement and regenerated water. Sequential and simultaneous optimisation are also considered. Sensitivity analysis between water regeneration unit vs the total operating cost is also performed. The higher the temperature, the higher the operating cost due to more expensive heating utility required.

Outside the Special Issue, the thematic support provided by the work of Ong et al. [90] dealing with the total site mass, heat and power integration using process integration published in 2017 and Kim et al. [91] with clean and energy-efficient mass production of biochar by process integration should be considered.

### 2.2.2. Possible Future Developments

From the review of the area, one can note a clear trend of expansion of the scope of integration problems, which increases the complexity of the obtained models. One example to be given includes the addition of the power management domain to the family of Process Integration areas. Other examples are the combination of Heat Integration with power generation (leading to the CHP domain) and with Mass Integration.

Another noteworthy development is the attempt at developing tools for further improvement and application of the Process Integration methods—as in the web-based tool by Pereira et al. [62]. This is by no means the only tool on the market. One can mention the flagship products—SuperTarget (version 7.0.15) that comes bundled with the PetroSim software (version 7.0) by KBC in London, UK [92] as well as the software suite for process integration by the company of the same name [93]. While these tools are quite suitable for final use by industrial and consultancy companies, their use for research is inherently limited by the fixed context and procedures built into the software. To support new research and further improvement of the Process Integration methods, including their interactions and combinations, the development of an integrated software platform tailored to the Process Integration thinking would be very beneficial. This should allow researchers and users to define new methods and algorithms while reusing a unified code base of already established core methods like Heat Integration and Water Integration and the well-known resource cascades.

### 2.3. Process Energy Efficiency/Emissions Analysis

As has been reasoned previously by Varbanov et al. [94], one of the core problems with achieving sustainable development lies in the reduction of wasted energy. This is often referred to as increasing energy efficiency. It can be achieved by heat recovery and reuse [60], as well as by heat upgrade and recycling—widely known as heat pumping in the energy engineering community [95].

#### 2.3.1. Recent Developments

There has been the argument that increased energy efficiency is bound to lead to decrease in the prices for the energy services, in turn inducing increased demand and finally—compensating or even overshooting the prior consumption of primary energy resources, which is referred to as the “rebound effect”. An empirical study from Greening et al. [96] based on USA data sources corroborates this argument to a moderate extent. A more recent study for China [97] also supports the existence of such an effect, varying between 50% and a 2-3-fold increase in energy demands as a result of energy efficiency improvement.

While the reasons for these trends are under investigation, one has also to pay attention to a subtle difference in the argument to reduce energy waste. While Varbanov et al. [94] put forward the argument that energy waste has to be reduced, the official statistics detect only the energy waste within the supply chain of delivering energy services. This implicitly excludes the waste of the energy-based services themselves. This is the core of the problem. If one analyses the extended onion diagram for integrating user demands to production processes and supply chains based on Walmsley et al. [73], the picture becomes much clearer. The use of food, lighting and direct energy use all involve waste. Further emissions reduction studies should consider all opportunities for wasting energy and minimise them.

Biomass is viewed as one of the ways of increased use of renewable energy sources and decrease GHG footprints, but it is also associated with other issues—such as increased nitrogen footprint in the study by Čuček et al. [98] and increased release of fine solids by Bartington et al. [99]. While it is common knowledge that coal combustion causes significant release of particulate matter (PM), it is less-known that burning biomass causes similar problems, but on a smaller scale. Al-Naiema et al. [100] evaluated the PM emissions from the co-firing coal and biomass, reporting reduced PM levels, compared to burning coal alone, including solids (PM) by 90%, polycyclic aromatic hydrocarbons by 40% and metals by 65%.

Poláček et al. [16] presented a parametrical study that assessed the influence of the composition of the atmosphere and the temperature on the formation and release of ultra-fine solids (PM) by micro-scale combustion of biomass. The described laboratory procedure employing thermogravimetric analysis (TGA) and a detailed assessment of the size distribution of the produced fine particles. The authors concluded that the particle sizes feature a strong correlation to the concentration of light volatiles released from the heated wood sample. They have also established a trend of increased formation of PM with the reduction of oxygen content in-stream fed to the test chamber, featuring twice more PM particle count for pyrolysis (zero oxygen) than for regular combustion in normal air.

Biomass gasification is also associated with PM formation and release, as discussed in [101]. The authors investigated experimentally the content and properties of polluting solid particles present in the synthesis gas, resulting from a test gasifier of the “Imbert” type. The analysis also included an evaluation of the particle size distribution. The author’s reason that it is more efficient to clean the synthesis gas before burning than to leave the cleaning to the flue gas stage. The analysis of the filtration cake established significant amounts of aluminium, calcium and silicon oxides, as well as SO<sub>3</sub>—all in the range of 12-16 mass%. There was also non-negligible and dangerous content of metal oxides—including MnO (7.6%) and Na<sub>2</sub>O (2.4%), as well as heavy metal oxides (Cr<sub>2</sub>O<sub>3</sub>, CdO, TiO<sub>2</sub>, SrO) and even P<sub>2</sub>O<sub>5</sub>. These results indicate the need to deeper investigate the process of biomass gasification, for establishing the true extent of the resulting pollution and footprints and the means of their minimisation, for providing sustainable solutions.

Agricultural activities are associated with a number of environmental impacts and risks [102]—including business risks of varying prices and regulatory uncertainties, as well as environmental impacts and risks such as unforeseen emissions when the activities are conducted inappropriately. Such issues can be tackled by comprehensive optimisation methods—such as the maximisation of Sustainability Net Present Value [103].

There have been increasing concerns in providing sufficient food at acceptable quality to the continuously rising human population worldwide, addressed in [104] for the case of Spain. The study applies a combination of life-cycle assessment and data envelopment analysis to assess the energy efficiency of the Spanish agri-food system. Potential improvement actions, aimed at reducing energy usage and GHG emissions, were also proposed. Energy Return on Energy Invested (EROI) is used as a criterion. For more complex food types (meat, eggs, seafood) the primary energy and GHG footprint contributing stage have been the core product, while for vegetables, this was found to be the energy use for cooking and cooling. The authors report that, for sufficient efficiency of the system, it is necessary to implement energy-saving measures, resulting in approximately 70% energy savings.

Water-related issues involve the need for reliable supply. Evermore frequently, it becomes necessary to generate freshwater by desalination. Due to the high cost of the product, its reliable distribution is also a vital issue [105]. Water desalination industry is a good illustration of water-energy linkages. Some technologies rely on membranes—for instance, this is the case with some installations in Jordan [106]. The strength of the links and their correlations to energy consumption and GHG emissions have been evaluated by Jia et al. [107]. The authors presented an overview of the seawater desalination developments in China and evaluated the annual energy consumption, GHG emissions, and cost of seawater desalination plants from 2006 to 2016. The results indicate that the energy consumption increased from 81 MWh/y to 1,561 MWh/y during the 11 y period, and the GHG emissions increase from 85 Mt CO<sub>2</sub>eq/y to 1,628 Mt CO<sub>2</sub>eq/y, representing an increased rate of 180%. The authors concluded that the current unit product cost of seawater desalination in China is still higher than other water alternatives, but it has good potential for reduction with the improvement of desalination technologies. The unit product cost shows a decreasing trend with increasing the processing capacity.

It has been well-known that the intermittence of supply is the critical barrier before the effective integration of renewable energy sources, which is made even more dynamic by the variability of the user energy demands based on Varbanov and Klemeš [108]. Many energy storage technologies are available—both for thermal as presented by Alva et al. [109] and electrical forms as discussed by Cheng et al. [110]. The popularity of storing electrical energy grows further, fueled by the increased attention to electric cars, as can be traced by the search for novel materials for electrochemical energy storage according to Chen et al. [111]. The availability of storage technologies fulfils only part of the task. To use them, they need to be integrated with the energy supply, delivery and use systems. Rozali et al. [112] mentioned that the efforts include the optimisation of electrical storage size, based on the dynamics of power generation and use. Jamaluddin et al. [76] provided a further extension has been the optimisation of a combination of electricity and heat storage facilities, for catering for heating, cooling and power flows.

A hybrid energy storage method, based on cryogenics, has been investigated by Hamdy et al. [113] and reported in this Special Issue. Cryogenics-based energy storage (CES) is a technology for thermoelectric energy storage at a larger scale. Using this method, electricity is stored in the form of liquefied gas at cryogenic temperatures. The charging process consists of the gas liquefaction process. That represents the limiting factor to the round-trip efficiency (RTE) of the storage method. During discharge, the liquefied gas is pressurised, evaporated and then super-heated to drive a gas turbine. The cold released during evaporation can be stored and supplied to the subsequent charging process. In the research by Hamdy et al. [113], several liquefaction processes are evaluated to identify the most cost-efficient one, using exergy analysis. The authors have concluded that the integration of cold storage enhances the liquid yield, in this way, reducing the specific power requirement by 50–70%.

Besides the evaluation of the energy conversion networks, exergy analysis is starting to play an essential role in also evaluating production processes and their energy relationships. For instance, Ghannadzadeh and Sadeqzadeh [114] have used exergy analysis as a scoping tool for optimising an ethylene production process. This is an energy-intensive process, in which the authors have successfully identified significant efficiency improvement options. The same type of analysis can also be used for decision-making in comparing process design alternatives [115].

Meramo-Hurtado et al. [116] presented an exergy analysis of a bio-adsorbent production process, aiming at the identification of opportunities and measures for reducing the energy demand of the process. Three bio-adsorbent production process networks for large-scale production of chitosan microbeads have been evaluated. Exergy efficiencies, total process irreversibilities, energy consumption, and exergy destruction were calculated for the analysed alternatives. While the authors could not find crucial differences among the evaluated processes, they did identify process improvement opportunities in the product drying and washing water recovery stages of all investigated processes.

Municipal solid waste (MSW) collection is an essential activity in modern cities, which, when combined with appropriate separation, materials recovery and waste-to-energy recovery based on Tomić and Schneider [117], can bring about several synergies. This is practised world-wide for simultaneous reduction of fresh resource intake, fuel use and for GHG emissions reduction. Since door-to-door collection generates significant direct greenhouse gas emissions from trucks, pneumatic collection emerges as an alternative to the trucking system. While this technology apparently reduces local direct air emissions, it has a large energy demand caused by the need for generating vacuum for waste suction. Laso et al. [118] presented an analysis that compares conventional door-to-door and pneumatic waste collection systems using Life Cycle Analysis. The considered system boundary includes accounting for the creation, installation, maintenance, and decommissioning of the waste collection system, as well as for the waste transfer, sorting and waste processing sub-systems. The focus is on the biodegradable fraction of the collected waste. The authors report that the energy savings from the recycling of the organic fraction outweigh the energy requirements for the operation. Based on that, they suggest that pneumatic collection could be an environmentally-friendly option for MSW management under a circular economy, pointing out that waste could be a valuable source of materials and energy.

### 2.3.2. Possible Future Developments

It has been shown in the previous section that the optimisation of energy sourcing, conversion and use has to be considered holistically. This involves two key dimensions of the problem. One is the consideration of the complete product chains—from “cradle” to “cradle”, as advocated by some Life Cycle Analysis branches [119]. The other dimension consists of accounting for the trade-offs in emissions and other footprints when substituting currently used fossil fuels by renewable alternatives.

Important directions for further research include providing additional degrees of freedom in the energy-related networks that would allow the increased use of renewables, compensating for or eliminating some of the problems associated with their exploitation. Such directions certainly include energy storage—using all forms: thermal, electrical, chemical, mechanical, to name a few.

Another key topic is innovation for separation and neutralisation of harmful emissions of sulphur and nitrogen compounds resulting from biomass use. In this regard, especially in the utilisation of biomass waste, it is important to minimise the CO<sub>2</sub> emission overhead of logistics. A good step in this direction has been the framework by How et al. [120], which needs, however, further development of technology solutions that are closer to practical implementation.

The development of more durable and efficient energy conversion technologies should also be kept on the front burner. In this regard, fuel cells and the microbial fuel cell variety, for generating power from organic waste, are a good example. The development of lower-cost materials [121] is a good step that should be followed by similar studies in related areas.

#### 2.4. Optimisation of Renewable Energy Resources Supply Chain

Renewable energy is clean and can be efficient in energy supply if adequately developed, based on Kong et al. [122]. The significant advantage is no fuel consumption and relatively low costs when compared to conventional power plants. Therefore, green electricity can be competitive with conventional electrical energy in a long time period. Kong et al. [122] built a renewable energy electricity supply chain collaboration model by employing the revenue-sharing contract to achieve the green power grid-connection and consumption optimisation. The authors used continuous random variables to describe the intermittency of green power output intensity and the fluctuations of power market demand. Afterwards, the authors coordinated the profit distribution between the power generator and the grid company by adjusting the revenue-sharing contract and analysed the optimal decisions taken by the companies for different power market demand price. Through the numerical simulation analysis, the authors obtained the equilibrium solutions of contract satisfied various conditions and investigated the relationship among the optimal variables and profits, obtaining the management suggestions. The critical point is, the authors also investigated the influences of market demand price elasticity and power output efficiency.

##### 2.4.1. Core Developments

A sustainable supply chain should involve coordination among resources, flows and stocks with a well-defined sustainability concept. Saavedra et al. [123] presented a literature overview on system dynamics modelling applied in the renewable energy supply chain, considering works published between 2007 and 2017. The review provides new insight into the analysis of the supply chain in renewable energy using systems dynamics. The authors showed that the system dynamics approach provides harmony between its subsystems and processes, understanding the system behaviour, testing policies for improvement, and assessing impacts over time. The system dynamics approach was presented for the Biomass Scenario Model (BSM). The authors discussed the scenario analysis process to determine the most significant factors affecting the overall performance of the supply chain model. Beside this was discussed the application for the Hybrid Modelling Framework that integrates multiple tools to study complex system problems, such as different actors in the supply chain with various needs, objectives and decision-making behaviours.

Fernando et al. [124] studied the effect of energy management practices on renewable energy supply chain initiatives in 151 certified manufacturing companies in Malaysia. The results showed three dimensions of energy management practices, i.e., top management commitment, energy awareness and energy auditing. Those practices were positively linked with the development of renewable energy supply chain initiatives. The authors found that insufficient knowledge of energy efficiency means does not allow to manage energy effectively, constraining opportunities such as converting waste into energy to support business' targets. The authors suggested transferring the energy efficiency management knowledge and technology from multinationals to local companies. Local companies would be able to generate renewable energy through supply chain networks.

Nugroho and Zhu [125] developed a biofuel platform for planning and optimisation. The platform unifies biofuel product, production process and networks design. The authors considered the design of the biofuel supply chain network under various production paths. The authors studied the optimum region of the composition ratio between rice straws and waste cooking oils and found its value between 0% to 50%. The results showed that the combined raw materials increase the supply flexibility and supply chain responsiveness. The hydrocarbon biofuels are favoured over ethanol in minimizing the overall carbon emissions.

Sarker et al. [126] controlled the supply chain costs of biomethane gas (BMG) production systems, optimised the location of BMG plants and determined the routing network for transporting the feedstock and the work-in-process materials. The authors proposed an efficient mixed-integer nonlinear model to optimise biogas a plant location problem. The algorithm was used to find a solution to locate hubs, reactors and condensers to minimise the total costs.

Li et al. [127] stated that renewable energy systems are constantly affected by weather or climatic conditions (i.e., solar irradiation, wind speed, external temperature). In order to handle the effect of external disturbances on RES systems performance, the dynamic forecasting, as well as energy storage, shall be provided. The advanced prediction algorithms like coupled autoregressive and dynamic system (CARDS) from Huang and Boland [128] or artificial neural networks (ANN) from Gupta et al. [129] can be applied for solar radiation and wind speed, wind power and solar power prediction among others. Even more challenging is the long-term forecasting for future power output, according to Zhao et al. [130], with multiobjective optimisation from Behzadi et al. [131]. Luo et al. [132] mentioned that deep learning techniques are also commonly used in long term prediction of wind speed.

Azevedo et al. [133] performed a comprehensive bibliometric analysis of studies in the field of supply chain performance and renewable energies. The review was focused on the most productive authors and institutions, as well as the most cited articles from the field. According to Azevedo et al. [133], most articles in the field focus on the design optimisation of renewable energies supply chain. Among the analysed methods, the mixed-integer linear programming (MILP) model is the most popular. Nevertheless, other methods, like case studies, surveys, simulations, modelling, genetic algorithms, multi-scale modelling, and optimisation, are being used successfully.

Zakaria et al. [134] reviewed stochastic optimisation techniques in renewable energy applications. The authors found that the stochastic optimisation exhibit enhanced performances and can deliver accurate representations in capturing the uncertainties of renewable systems. The authors also found that with a rapid increment of data and size of renewables' problem, the model-driven approaches alone could not adequately address and handle with the underlying complexity in vast multivariate and expanding renewable systems. The data-driven scenario generations could be an excellent future choice. Chen et al. [135] presented a method for scenario generation, which has been complemented with complete scenario-based forecasting by Chen et al. [136]. Also, in the field of renewable energy integration, when the problems are of higher dimension, there is a need to hybridize the existing optimisation methods with intelligent search. Those methods can reduce the computational time with proper accuracy, as can be seen from the work of Dufo-López et al. [137] on the optimisation of stand-alone energy systems on the optimisation of stand-alone energy systems on the optimisation of stand-alone energy systems, comprising photovoltaics, wind and diesel generators, combined with batteries for electricity storage. Another work by Rahmani-Andebili [138] focuses on the management of power storage systems with the goal of minimising the power losses. Sharafi et al. [139] discussed the stochastic optimisation of renewable energy systems. Zakaria et al. [134] also identified further research areas in the field of stochastic renewable energy problems such as (a) plug-in electric vehicles integration—for example. Thompson [140] considered charging and scheduling of plug-in EV, renewable energy integration via vehicle to grid operation (b) demand-side management (c) multi-scale and multi-time-scale distributed renewable energy systems.

Ubando et al. [109] proposed a fuzzy mixed-integer linear programming model to achieve an optimal operational adjustment of an off-grid micro-hydropower-based polygeneration plant and maximize the satisfaction levels of the community utility demands, which are represented as fuzzy constraints. The authors considered three case studies to demonstrate the developed model. The results showed that the use of a diesel generator for back-up power is considered as an option to mitigate inoperability during extreme drought conditions.

Éles et al. [141] developed a new P-graph model to study the synthesis of the energy supply options of a manufacturing plant in Hungary. The authors applied a multi-periodic scheme for heating and electricity demands. The modified P-graph was applied to model the pelletizer and biogas plant investments. The authors found the best solution in terms of total costs. The results showed that a long-term investment horizon is needed in order to make incorporation of sustainable energy sources into the system economically beneficial.

San Juan et al. [142] developed a MILP model for optimising a biomass co-firing supply chain network. The model considers feedstock properties while minimising economic cost and environmental

emissions through goal programming. The effect of feedstock, transportation and pre-treatment requirements was incorporated in the model. The authors found that minimising either the financial or environmental objective individually emphasised the conflicting nature of the two objectives. Simultaneously optimising both objectives created a network which balanced performance on both objectives. The results showed that without considerations for feedstock properties, costs and emissions were artificially decreased, leading to the purchase of insufficient fuel and combustion of inappropriate fuel. This situation may lead to damage or loss of inefficiency of the equipment. The model proposed by the authors is a better fit to design and manage a biomass co-firing network.

Peesel et al. [143] proposed a predictive optimisation algorithm to calculate the optimal operating conditions of multiple chillers. The authors applied a sprinkler tank that allows storing cold-water for later utilization. The load shifting potential of the cooling system was demonstrated by using a variable electricity price as an input variable to the optimisation. The dynamic simulation was used to adjust the setpoints from the optimisation continuously. The results showed that by applying an optimal chiller sequencing and charging strategy of a sprinkler, tank leads to electrical energy savings of up to 43%. The purchasing electricity on the EPEX SPOT market leads to additional costs savings of up to 17%. It was shown that the total energy savings highly depend on the weather conditions and the prediction horizon.

Barmina et al. [144] studied the electric field effect on the thermal decomposition and co-combustion of straw with solid fuel pellets. The fixed bed experimental setup with a heat output of 4 kW was used. The authors found that the co-firing of straw with wood or with peat pellets provide the enhanced decomposition of the mixture, with the best performance when straw mass share in the mixture is about 20–30%. The authors performed extensive experimental research and found that the field-induced ion current in the space between the electrodes is responsible for the field-enhanced reverse axial heat/mass transfer of the flame species, that provides the enhanced heating and thermal decomposition of biomass pellets. The results also showed that the electric field-induced processes of heat and mass transfer allow to control and improve the main combustion characteristics so enhancing the fuel burnout and increasing the heat output.

Recently due to the increased share of electricity from renewable energy sources, many studies are performed by integrating them with the electrical energy network. Fichera et al. [145] studied the energy mapping of the urban flows using the implementation of the network theory. The scenarios analysis for the elaboration of the energy strategies for the promotion and installation of cogeneration systems using the RES was performed. The authors developed a tool that characterises the energy profile of an urban area, and the model was tested with the data of Catania municipality. What is important, the developed model is able to define the interaction between the nodes and enables to formulate the urban energy trajectory relatively to the energy demand of each district.

Gonzalez de Durana et al. [146] presented a generalised energy networks modelling approach using the agent-based method. The model proposed by the authors can be used to represent integrated utility infrastructures, including the systems in which not only one but different carriers are managed together by a multi-energy utility. The application of the proposed method can be performed from small, rural or microgrid systems up to large energy infrastructures in an urban context. What is also important, the model can be used to perform exploratory simulations to better understand those systems behaviour, and further to test and develop operation management strategies. In other work, Gonzalez de Durana et al. [147] developed a complete and self-contained model of a simple microgrid. The procedure based on the system dynamics not making use of any technological parts is adopted. The model can be applied to simulate the energy performance of a number households in a neighbourhood, at high time resolution, including energy generation and consumption, allowing the user for trying and designing particular generation and storage methods or demand-side management procedures.

Another study that considers microgrid modelling was performed by Kremers et al. [148]. The authors created a systemic modular model for a microgrid with a load flow calculation. The communication layer was also included in the model. The applied agent-based approach

enables to include the intelligent strategies on every node of the studied system. Classical tools struggle with the implementation of dynamic interaction and message passing among individual devices. The agent-based approach, which is used alongside a classical load flow treats the simulation from a different side. The case study performed by the authors shows the interest of being able to reproduce both effects on the power grid and the communication network and observe the complex system behaviour as a whole.

One of the promising methods of electrical energy storage involves the use of stationary battery energy storage systems (BESS), Zeh et al. [149] studied the application of battery energy storage systems to provide primary control reserves (PCR) in the Union for the Coordination of the Transmission of Electricity (UCTE) area. The authors discussed the technical requirements for BESS operation as PCR provision systems, provided explanations of the PCR market and regulation; and demonstrated the approach for operating BESS as PCR storage systems, showing potential outcome for such a system.

Tran and Smith [150] investigated residential rooftop photovoltaic (PV) systems for long-term thermos-economic benefits from PV homeowners' perspectives and for impacts on the electrical distribution network from grid operators' perspectives. The authors studied the costs of generating electricity from grid-connected PV systems with and without Energy storage. The case study was performed for three different scenarios, including net metering, wholesale pricing, and no payback. PV systems in Utah. The simulation results showed that the addition of PV systems reduces the annual electricity bill up to 75%. A net metering policy offers PV homeowners with the most benefit in terms of annual electricity bills. However, the addition of energy storage under the net metering and wholesale pricing policies increases the annual electricity bills compared to similar systems without energy storage. The reason is related to losses associated with charging and discharging the battery.

#### 2.4.2. Possible Future Development

Due to the rapid increase in renewable energy electricity demands, there is a need to develop an efficient method for the integration of renewable energy sources and coal-fired power plants. A first important research area here is the efficient energy demand prediction and optimization of RES electricity usage, to address the customers' needs. The second important research area is the electrical and thermal energy storage, which can assure the proper usage of renewable energy sources in case of high energy demands. The third research area of high interest is the optimization of RES operation, including photovoltaics, wind farms, and biomass plants, to allow those energy systems operate in the most efficient mode. In authors opinion those two research directions will be on the highest priority in the following years since the EU demands a significant contribution of RES in the energy supply chain.

### 3. Conclusions

This review editorial was initiated by the Special Issue for carefully selected papers from the 2018 Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction (PRES 2018) conference. The conference, which attracted more than 550 leading researchers worldwide, boosted the interest in a number of highly appealing scientific issues: Design and numerical study for innovative energy-efficient technologies, Process Integration—Heat and Power, Process energy efficiency or emissions analysis, Optimisation of renewable energy resources supply chain. These issues are having a strong influence on sustainability and the circular economy. The authors endeavoured to overview this field by adding relevant and recent references and suggested some conclusions for future research directions. The feedback from the readers and especially researchers in the field is most welcome and appreciated, and it should provide a ground for the next PRES'19 panel discussion devoted to the future Special Issues of the journal Energies.

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and 2.4 and been responsible for the overall arrangement and graphics. P.O. has contributed with Section 2.1., P.S.V.—for Section 2.2 and partly Section 2.3 and provided the overall advise.

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