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Efficiency measures for energy supply and use aiming for a clean circular economy

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ABSTRACT

Energy use minimisation and sufficient energy supply at minimal footprints are crucial for sustainable development. This article considers the key issues and developments in energy optimisation of industrial and urban systems for achieving a clean Circular Economy. The overall system perspective is presented in the form of the Circular Economy Hierarchy, within which the general developments and the contributions of the current Virtual Special Issue from the PRES'20 conference are overviewed and analysed. The review and discussion reveal the need for integrated modelling and optimisation of business and urban processes to minimise energy demands and to satisfy them with minimal environmental impacts efficiently. Several vital directions for future research and development are outlined – the synergy of Process Integration and Process Intensification, the development of novel concepts and tools for unified modelling and optimisation of diverse industrial, business and urban processes, and the need to develop methods for efficient recycling of renewables harvesting equipment disposed of at end-of-life.

1. Introduction

A NASA-supported study [1] measured that the ocean in the Earth's southern hemisphere is absorbing approximately 530 Mt/y CO_2. While significant, it is similar to the annual Greenhouse Gas (GHG) emissions of the European Union (EU) power sector or about half of the United States (US) industrial GHG Footprint. The world's energy demands release even more emissions. This shows that the need for significantly reduced energy consumption and GHG Footprint is apparent, and the scale of the reductions is enormous.

1.1. Motivation for discussing the current problems

Fossil fuels dominate the energy supply to the industry and civic sectors, although reducing their use has reached significant milestones. The main achievement has been transitioning to natural gas featuring medium GHG intensity. This is the case with the US and the EU (Fig. 1). The 2020 GHG emission targets in the EU were met [2], and even more ambitious ones for 2030 have been set [3]. The US industrial energy consumption and the EU power generation are representative motivating examples. The Carbon-Emission Pinch Analysis – CEPA [4] plots for these examples are shown in Fig. 1. The detailed data for building the charts are given in the Supplementary Material to this article.

The US energy consumption has been steady [5], with the structure virtually unchanged in the last decade (2017–2021) [6]. Published data on energy use in the US industrial sector [7] has been analysed (Fig. 1a). The April 2022 target for reducing the GHG emissions of the US by 52% by 2035 [8], compared to their peak in 2005, results in an approximate target of 3500 Mt for the year 2030 [9]. The industry share in this reduction would be approximately 235 Mt. That shows the need to replace a significant share (>70%) of the coal usage in the US industry with a less GHG-intensive source. Alternatively, the overall energy

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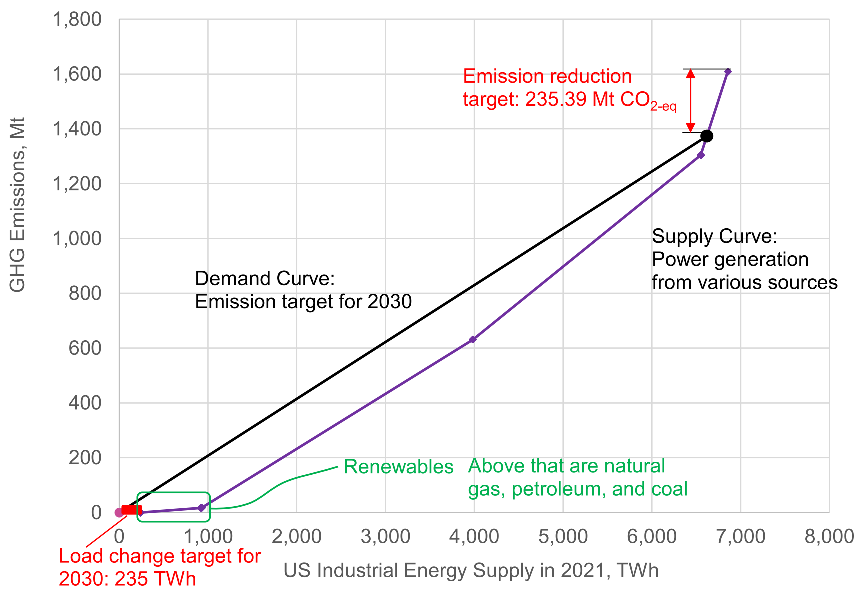
demand can be reduced by approximately 235 TWh/y (3.55% of the 6620 TWh/y demand in 2020).

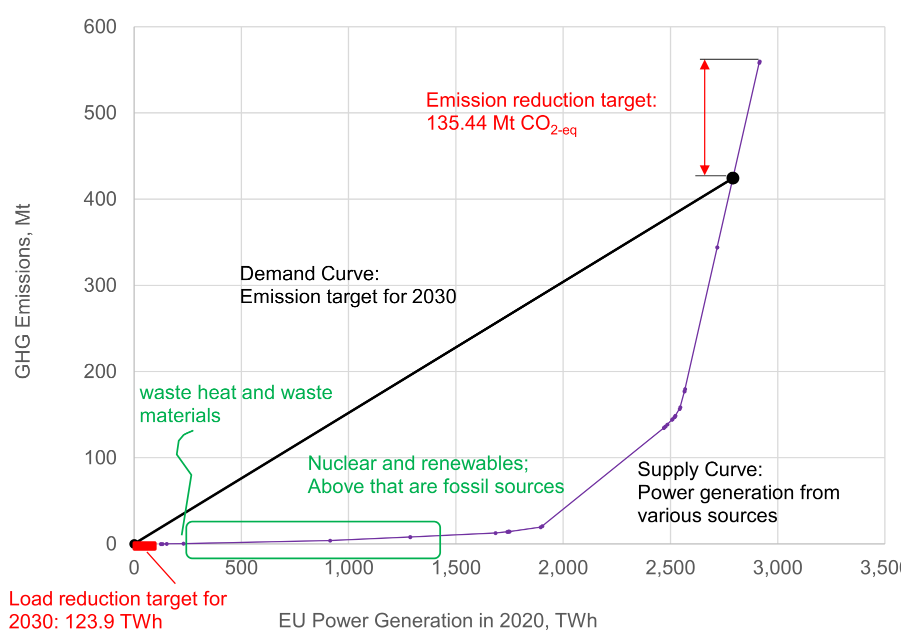
EU power generation and emission contributions have been evaluated (Fig. 1b). The amount of electricity generated (grouped by sources) for 2020 was taken from [10]. The emission factor data have been extracted from a document of the European Investment Bank [11] and a United Nations Life Cycle Assessment [12] of GHG emissions for Europe. Following the goals [3], the analysis shows that the GHG emissions from the EU power sector need to be reduced by 24% (135.44 Mt $CO_{2\text{-eq}}$). This translates to the need to supply 123.9 TWh (4.44% of the 2791.3 TWh demand for 2020) from zero-GHG emission sources or to reduce the annual power consumption by that amount.

While such improvements seem like an easy goal, the EU is a collection of individual countries, and uniform policies for load reduction are difficult to establish. Other factors are complicating the task further:

- The power use in 2020 was constrained by the COVID-19 lockdowns [13], and rebound energy consumption is currently taking place.
- Counteracting that is the conflict in Ukraine, which puts strain on energy prices and threatens the security of the EU energy supply [14]. As of September 2022, the energy security supply in Europe is



(a) The US industrial energy consumption



(b) The EU power generation sector

Fig. 1. Carbon Emission Pinch Analysis of representative energy systems.

diverse and uncertain, with the expectation of further price escalation. The European Commission [15] has initiated market intervention proposals to limit price growth for consumers.

- The natural gas market situation is similar [16]. The EU policy has been adapted to allow the increased use of coal in the short term until sufficient capacities are installed for harvesting solar, wind and other renewables.
- Another significant factor is the future energy demand of the transportation sector. Most terrestrial vehicles use fuels [17]. However, the current trend is to stimulate an increased share of electric vehicles for passenger and freight transport.

Using other resources beyond energy carries an additional set of problems related to material flows. The Circular Economy concept can be traced back to 1988 [18]. By 2020, this has become a mature philosophy [19] of organising the production, supply, use and recycling of products, services, and materials sustainably, minimising environmental and human health impacts. Distinctive features of Circular Economy implementations are (Fig. 2) the reuse (recycling of functionality), recycling (of materials), and energy recovery.

Less known aspects of this pattern are the increased system complexity, the trade-off between the resource intake for the linear and circular parts of the system, and the resulting emission and footprint trade-offs [21]. Significant gains can be obtained by implementing the Circular Economy pattern – up to 65% cost reduction 25–40% GHG and Water Footprint (WFP) reductions. The results show an upper limit in the WFP reduction at 35% circularity and a total cost minimum at 46% circularity. At higher circularity, the recycling performance deteriorates, consuming more resources than saving.

1.2. Analysis of previous reviews and contribution of the current work

The analysis to this point clearly shows three issues. It is necessary to reduce further the environmental footprints of the industrial, commercial, and residential sectors (Fig. 1). The Circular Economy concept has a high footprint reduction potential but cannot achieve sufficient reductions alone. The economy-wide energy losses from primary sources to final use constitute approximately 2/3 for the past decade [6]. Combined with the wide variation of the energy prices for that period [22], this high share persistence indicates that the main reasons for the excessive energy losses and emissions are not due to behavioural factors but are determined by technological and organisational factors. The third problem is the instability of energy supply chains and the energy price escalation, which are expected to persist for the medium term.

Aguilar Esteva et al. [23] developed a Circular Economy (CE) framework for the car manufacturing industry. Based on a methodology set up by the Ellen McArthur Foundation [24], the authors evaluated the materials circularity rate and the share of renewable energy use in the US automotive sector. Their estimates are coherent with the Lawrence Livermore National Laboratory (LLNL) Flowchart [6] for the US economy.

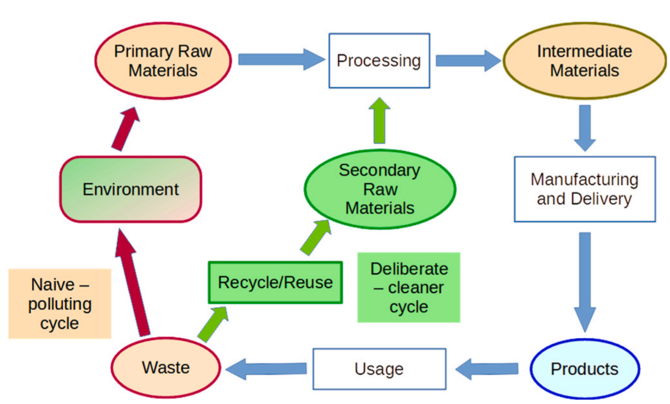


Fig. 2. The Life Cycle of products and services in a Circular Economy context, amended after [20].

Liu et al. [25] reviewed sources related to the Life Cycle Analysis (LCA) of the environmental impact of biorefineries. They concluded that there is a lack of uniform consideration in setting the system boundaries, functional units and impact assessment. The review does not discuss core CE issues and circularity via symbiotic links.

Ingrao et al. [26] reviewed the literature concerning waste food digestion and energy valorisation. They reported a biogas yield of up to 480 m^3/t of food waste when co-digestion with other substrates is applied. Food waste treatment belongs to the outer loops in CE – the last attempt at recovering materials and energy before disposal.

The literature on exchanging energy between eco-industrial parks and nearby urban settlements has been analysed in Ref. [27]. This is a valuable practice when industrial sites with excess energy are present near towns and cities. An example can be a crude oil refinery, which typically has excess heat below 180 °C.

A recent review on reducing the footprints in the automotive sector was presented by Zheng et al. [28]. That article provides a method for evaluating suppliers by automotive manufacturers and minimising the environmental footprints using composite indices. While energy issues were part of the evaluation, energy use was not the focus.

A good step forward is the review [29] of Process Integration and Mathematical Optimisation tools for the design of Eco-Industrial Parks. The authors overviewed many tools, such as process-level Heat Integration, Total Site Heat Integration, Total Site level carbon integration, power integration, and waste integration.

The previous reviews concerning Circular Economy and Industrial Symbiosis show a clear trend. Some studies address the nexuses between energy use, food and emissions but leave out the means for reducing the resource use and emissions – such as demand reduction, reuse, or recycling. On the other hand, the reviews concerning the Circular Economy focus mainly on measuring and increasing the circularity rate and waste valorisation as materials or energy, which is an essential part of the Circular Economy.

A more general framework is missing that would consider the processes of energy supply, production, symbiosis, valorisation, and waste treatment jointly, minimising the footprints. It is crucial to account for the trade-off of energy supply and emissions between the circular and the linear parts of Circular Economy implementations.

The current review offers the perspective of joint consideration of the various building blocks of Circular Economy to derive guidelines for future research and development of industrial and business processes that would minimise the environmental and social footprints of the activities. Since the technologies and organisational tools for achieving this are available, the current review looks at the processes from the viewpoint of minimising the external energy supply to drive the networks that can achieve minimal footprints. The current Virtual Special Issue (VSI) from the Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction (PRES'20) conference significantly contributes to this area, with research articles on the efficiency improvement of energy supply, conversion and use, heat transfer, and renewable energy. The current VSI focuses on process energy use, heat transfer, renewable energy supply, energy conversion and storage technologies, and environmental impact assessment. The extended review follows essentially the same structure and clearly shows the need for it, based on a bottom-up analysis of energy, cost and emission issues.

1.3. Method of the current review

The method of the current review follows the logic of first identifying the main issues linking to the Process Integration hierarchy, selecting recent literature sources representative of the latest achievements and development trends, overviewing those sources individually, and then discussing the overall picture obtained. That provides the basis for drawing conclusions and recommendations for future research and development in energy issues related to the Circular Economy and their environmental impacts. This method is illustrated in Fig. 3.

2. Energy and the sustainability performance of resource reuse and recycling

As illustrated in Fig. 2, non-renewable energy supply occurs by combusting fossil fuels. Typically, the fuel consumption rates are proportional to the footprints – Greenhouse Gas, Water, and particulates, to name a few.

2.1. *User energy demands and energy conservation strategy*

A 2021 UK market analysis [30] shows the problems in operating the subsidy-based mechanism for balancing electricity supply and demand in the UK. A possible alternative for balancing supply, demand and cost can be offered by using electricity storage [31] – bearing the potential for more than 50% GHG emission reduction. The economic viability of such arrangements is confirmed by a US company's successful implementation [32].

A demonstration of a Passive House, including PV panels, in a temperate climate zone has been presented in Ref. [33]. The combination of Passive House and PV generation is reported to result in 13 kWh/($m^2 \times y$) external electricity demand, which for a 100 m^2 house translates to an average of 0.15 kWh/day. A recent study on Passive Houses in Northern Ireland [34] reported the potential for reducing the GHG by 60–70% compared with the current prevailing building stock.

The Active House concept is a possible extension where the buildings become prosumers. A case study from Wales – UK [35] demonstrates that this concept can offer a drastically reduced GHG intensity of supplied electricity compared to the UK electricity grid – ranging from 30% to a 5-fold reduction.

Besides the snapshot of industrial energy consumption for a given time (as in Fig. 1), the temporal trend is also significant. Maaouane et al. [36] published data on the Moroccan industrial sector showing a 10–20%/y growth during 2000–2015. Globally, the situation is similar [37]. The report shows the industry's nearly double energy demand from 2000 until 2020, projecting further growth. With the current technological setup, it is unlikely to achieve the emission reduction targets discussed in section "1. Introduction". The measures to apply include reducing the process energy demand by reduced production rate or by enhanced resource efficiency and reuse/recycling of products, material and energy flow via symbiotic networks. To achieve sufficient results, it would be necessary to follow a hierarchy of actions (Fig. 4a):

1) Reduction of the energy demands of the process and business operations
2) Intra-process mass and energy recovery
3) Inter-process mass and energy recovery
4) Mass and energy recovery, reuse, and recycling in symbiotic networks
5) Minimisation of the logistic overheads throughout the hierarchy

The hierarchy follows directly from the Onion Diagram (Fig. 4b) [38]. At the process scales, represented by the onion's inner layers, the opportunities for resource exchange and reuse are the smallest. Still, the energy overheads for implementing the measures are also the smallest. Increasing the scale increases the opportunities and the energy overheads simultaneously. This is why internal savings must be maximised before external integration is considered.

2.2. *Process-level energy conservation*

The fundamental level of energy management for reduced cost and improved sustainability starts with energy savings. All forms and contexts of energy use can be subject to savings. A few examples are:

- Reducing material use in production leads to reduced energy spending for producing the material.
- In the residential context, energy-saving behaviour can take various forms, from eliminating wastage (of food, water, and energy) to reducing comfort levels in space heating/cooling.

Consider again the annual LLNL Flowchart [6]. For years, it has shown a stable 2/3 share of the energy losses from all sourced energy for the United States economy. An observation of the energy use pattern during the COVID-19 period has been analysed in Ref. [38], where the Circular Economy Hierarchy is linked to the Onion Diagram. The energy use during the lockdown and social distancing phases dropped sharply by nearly 20% but was quickly restored to previous levels after the measures were lifted. This analysis indicates that the main challenges before further energy savings and reduction of waste and emissions are, in the first place, organisational and technological. At the same time, behavioural energy-saving measures can play only a supporting role.

Saving energy at the industrial process level can be achieved in several ways [39]:

(a) Inherent reduction of waste of resources, energy and product – by, e.g. sharing a resource base for co-production or co-

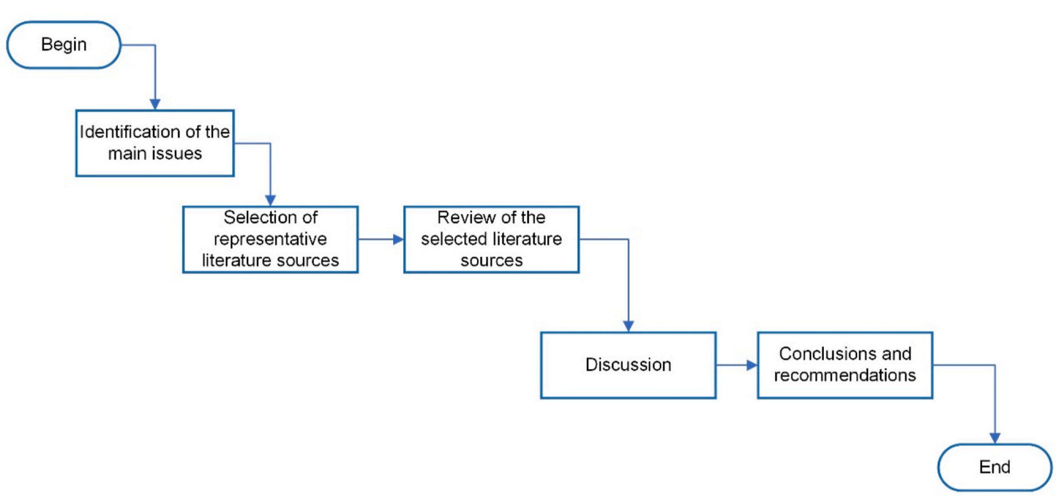


Fig. 3. Workflow of the review method applied in the current work.

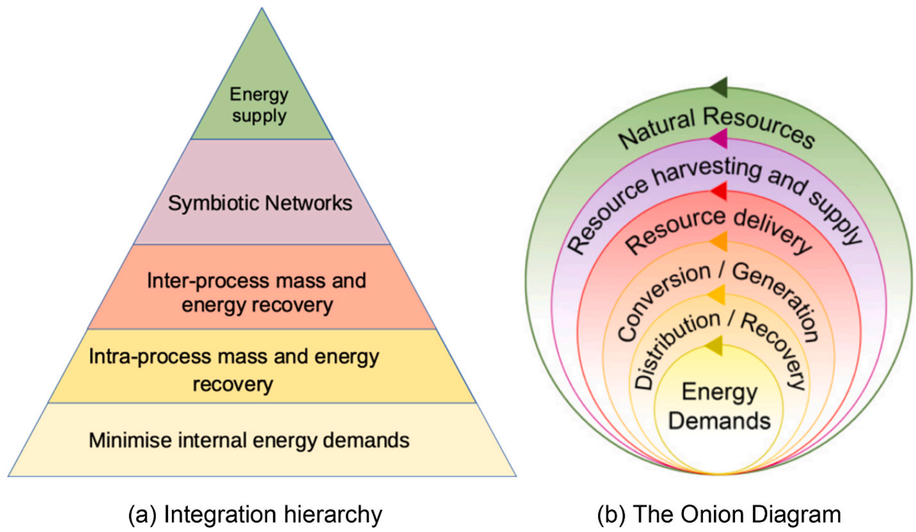


Fig. 4. Hierarchy of Circular Economy (a) resource-saving related to the Onion Diagram (b) updated in [38].

generation of product streams, better housekeeping, elimination of leaks, better insulation, material saving
(b) Installation of devices converting or using energy more efficiently
(c) Use of reaction media and materials with more favourable thermodynamic properties
(d) Process Intensification and Process Integration

Food supply chains feature significant energy demands for heating, cooling, and transportation. A Potato Cold Storage case study [40] demonstrated a tangible 16% energy demand reduction by improved insulation and electricity conversion. However, the energy quality is not explicitly considered, and the process is considered alone.

Polygeneration brings the benefit of sharing the resource base between several product streams – e.g., the joint production of methanol alongside power generation from coal [41]. Changing the core process design from traditional gasification to coal-steam gasification with polygeneration improved the energy from 51% to 63%.

An example of Process Intensification is the application of ultrasound to the leaching of metals from spent lithium-ion batteries [42]. The authors indicated that the ultrasound application reduced the leaching times by 50%. However, the energy effects of the proposed measure were not analysed. This prevents the quantification of potential energy savings.

Demirel et al. [43] demonstrated a limit to the effect of Process Intensification alone. The minimal GHG Footprint with a high return on investment was achieved by combining partial intensification with Heat Integration – up to 80%/y ROI, at 44–46 kt $CO_{2\text{-eq}}$/y.

A systematic review and analysis of energy use in distillation [44] provided similar reasoning to apply Process Integration alongside Process Intensification. Additional separation processes must be combined with distillation to reduce energy demands effectively.

Zheng et al. [45] investigated the energy-saving potential of two process modifications to a solvent-based CO_2 capture process – a variation of the absorbent and the process design. The reported energy consumption reduction of process design modifications reached 9.8% in the moisture evaporation part, while it was negligible for the other parts of the process. When the absorbent is varied, the estimated saving potential was up to 49% for the sensible heat consumption and up to 17% for the desorption heat demand.

2.3. Process Integration – heat, power, mass, spatial aspects

Process Integration for energy savings has been practised for nearly 50 y, as Heat Integration [46] and Process Integration in general [47]. More recent reviews focus on the spread of Pinch Analysis applications [48] and the broader contributions related to the conferences PRES [49].

Successful implementations of Heat Integration are regularly published – as seen from the case study on the Heat Integration of a paper mill [50] describing Data Extraction, Pinch Analysis and retrofit measures for saving up to 33% of the energy demands. Recent developments propagate the principle to other cascading arrangements for resource-saving – water systems with multiple contaminants [51], food-energy-emissions nexus [52], minimisation of plastic waste and environmental footprints [53], and adaptation of the process industry [54] to the temporal excess of renewable electricity by electrification of process heating and cooling.

The targeting and PI of a spray dryer [55] is an excellent example of selecting the most efficient base process configuration. The reported process retrofit saves up to 74% of the heating utility. Total Site Heat Integration targeting published by Boldyryev et al. [56] suggested economically justified measures for saving 31% of the cooling and 80% of the heating demands of the site.

A methodology combining PI methods in an overall framework [57] provides a hierarchy corresponding to the inter-process mass and energy recovery layer in Fig. 4. The systematic combination of PI tools produces significant reductions in resource demands – a nearly complete reduction of power demands, reducing steam consumption by 45%, cooling water by 27%, and 50% CO_2 emission reduction.

The spatial aspects of Process Integration relate to supply networks – biomass energy supply [58] or combination with waste valorisation [59]. Symbiosis networks are another avenue [60] for this strategy. Some such networks are for supplying specific products or energy – e.g. optimisation of biodiesel supply chains [61]. This strategy allows cascading of functionality – in the case of product upcycling, e.g. shipping containers [62] or food ingredients [63], materials in the case of waste material recycling [64], energy in the case of energy integration [59], and chemical substances in the case of chemical recycling [65].

An attempt was made in Ref. [66] to model biomass-based fuel supply to the iron and steel industry as a fuel replacement strategy. The authors reported that the SNG route is more economically viable, especially in injecting the SNG into the regional gas supply network, achieving 11.5 EUR/MWh supply cost. However, the study does not deal with the environmental footprints of the proposed options – not even GHG footprint evaluation. Adding footprint considerations would complete the picture and allow for making more informed decisions. In this regard, the Carbon Emission Pinch Analysis – recently applied to regional electricity trading [67], can be combined with that type of fuel supply analysis.

Aiming at CO_2 management of industrial parks, Munir et al. [68] developed Pinch-based targeting and network design based on data input for CO_2 source and sink processes, showing that net CO_2 emissions can be reduced by up to 95%. However, that work did not account for the energy used by the various processes, and such modelling features are necessary for obtaining more realistic targets. A good development in this direction is another work [69] by the same group, which proposed a Mixed Integer Nonlinear Programming (MINLP) model for optimising renewable energy supply to an eco-industrial park. The authors show that achieving self-sufficiency in energy supply is possible, reducing GHG emissions by 70% and increasing profit by 39%.

2.4. Energy balance of symbiosis processes and waste valorisation

Studies on material recycling often miss potentially significant energy effects [70]. Recycling reduced the energy intensity of glass supply by 5–7% compared to virgin glass production. Although tangible, such saving is not significant and can be explained by the high energy consumption of re-melting. Plastic recycling was assessed as more energy-efficient – resulting in up to 76% energy savings compared to the supply of virgin material.

The recent acceleration of Pinch-based methods for solving Circular Economy problems [71] has brought the realisation of the opportunity to cascade compatible materials of different quality – in the example of the Plastic Pinch Analysis [53], followed by a method for the network synthesis exploiting material cascading [72]. The critical property determining the feasibility, cost and environmental performance is the process energy demand, as shown in the method [72] for energy targeting of plastic recycling networks.

The iron and steel industry is a significant energy user [73], with approximately 6% of the World's energy demand. A step towards emission reduction is the work of Yue et al. [74], where several different modes and paths for steel production are evaluated – based entirely on ore and primary raw materials and paths using scrap metal recycling. While not eliminating energy use and GHG emissions, the scenarios with increased steel recycling exhibit up to 40% reduction of energy consumption and GHG emissions compared with using only primary raw materials.

Tomić and Schneider [75] proposed a model for evaluating the energy performance of multi-stage municipal waste processes on a Life Cycle basis. They demonstrated the model's applicability to a case study and reported that the most energy-beneficial and sustainable scenario maximised material recovery. The authors explain this with the effect of energy saving from virgin material substitution with recycled materials. This correlates with the findings in Ref. [76], where the Exergy Profit of material substitution was found 3 times more significant than Waste-to-Energy.

3. Energy conversion and supply from renewables and fossil sources

Energy supply corresponds to the resource harvesting and supply layer in Fig. 4b and the energy supply priority item in Fig. 4a. While many obstacles exist, the promise of renewable energy sources is straightforward [77] – they eliminate or significantly reduce the GHG Footprint within the operation phase of the facilities.

Much research and media attention is devoted to hydrogen as an energy-related commodity [78]. While it is undeniably an efficient energy carrier, hydrogen has to be produced from hydrocarbons or by electrolysis of water. The hydrocarbon way is associated with releasing CO_2 and defies the "green" goals. If powered by renewable electricity, the electrolysis route holds a certain potential – provided efficient hydrogen storage is available. This is the bottleneck of using hydrogen as an energy carrier. It is impossible to liquefy at a reasonable temperature, making the storage energy wasteful and expensive.

3.1. Biomass, biofuels, and waste processing

The main challenges before biomass utilisation are connected with the spatial distribution of its availability [58]. It was convincingly reasoned by Ponton [79] that from the energy return viewpoint, it is most advantageous to exploit waste biomass in preference to dedicated energy crops. Jain et al. [80] presented a clustering algorithm to minimise the GHG overheads from logistics.

Sharma et al. [81] discussed hydrothermal carbonisation for processing wet waste. The method improves the transport, storage, and fuel characteristics by enhancing the grindability, pellet durability, hydrophobicity, energy density, combustion behaviour and calorific value.

Process Intensification can be beneficial in Waste-to-Energy processes, as shown by the ultrasound and microwave treatment of food waste prior to anaerobic digestion [82]. Ultrasound treatment resulted in a methane yield increase above 40%. This can be explained by the enhancement of the mass transfer properties of the substrates. The mechanisms of the reported improvements are not explicitly discussed, leaving room for further investigation.

3.2. Solar, geothermal and wind energy

Solar energy utilisation can significantly reduce the GHG footprint of energy supply if the weather can be precisely predicted. The GHG intensity of power generation with PV panels can be approximated [83] (assuming 25 y lifetime) as 0.029 $kgCO_2/kWh$ generated power. Compared to the typical autumn grid intensity relying on coal (Poland, 0.65 $kgCO_2/kWh$) [84], the potential reduction is of an order of magnitude.

The Beijing-based electric power company Huaneng Power International (HPI) has unveiled the world's largest floating solar project in Dezhou [85], Shandong - China. The power station can generate 320 MW of electricity. A larger floating PV farm of 600 MW is under construction in India. However, the Life Cycle footprints of such large power-generating projects must be properly evaluated to quantify the potential gains compared with traditional power generation. A similar point is made in an overview of other implementations of floating PV fields [86]. The idea's feasibility is demonstrated even in a colder climate, such as in Poland.

Fundamental research into PV cells [87] proposed adding several layers of mixed oxides, combining Ti with other metals – Ba, Sr, and Ca. An electricity current increase of three orders of magnitude is reported compared with cells based on $BaTiO_3$ alone. A significant technological development is seen with the discovery and evolution of Perovskite Solar Cells. As of 2015, they were still seen as an emerging technology [88], with prototypes reaching 18–20% efficiency. A recent review [89] quoted values exceeding 25% but pointed out stability issues with the materials. There are scarce publications on the environmental impact of perovskite cells – e.g. Ref. [90], discussed an LCA of the embodied GHG Footprint in an 8 × 8 cm perovskite solar cell module. The paper reported nearly 32 kg CO_2 eq. for the module. Evaluating other relevant footprints such as water, nitrogen, and toxicity is further necessary.

Zima et al. [91] described a mathematical model to simulate the operation of an innovative double U-tube sun-tracked Parabolic Through Collector (PTC). The proposed model has a modular structure. A test stand with the analysed PTC was built to verify the obtained accuracy. The results proved the high computational efficiency and accuracy of the proposed model, achieving very low error levels.

To improve the power generation efficiency of PV panels, the Photovoltaic-Thermal (PVT) technology was developed [92]. Based on this, buildings can be equipped with systems for combined heating, cooling and power generation – as the RESHeat project [93], which features PVT panels with energy storage, ground heat regeneration, and heat pumps. It has been shown that the system can satisfy up to 90% of the energy needs of single-family houses [94] and can easily be combined with district heating networks [95].

Wind use for power generation has reached maturity, and ever larger turbines in massive farms are being deployed – as seen in the example of China [96]. The article reports a turbine size of 16.6 MW in a farm planned as exceeding 500 MW. While the mentioned turbines are of the horizontal type, Vertical-Axis Wind Turbines are under heavy development [97] in an effort to be commercialised, pursuing the advantages of much lower noise levels and better safety for animals.

A potentially significant innovation in wind-based power generation is the INVELOX technology proposed around 2014 [98] for capturing and concentrating wind airflow before passing it to wind turbines mounted close to the ground level. The authors showed that the proposed configuration generates 80% and up to 560% more power than an equivalent Horizontal-Axis Wind Turbine (HAWT). The other main advantages compared to traditional HAWT are reported as the minimisation of noise release and the elimination of the harm to birds flying in the vicinity. An overlapping team [99] developed a configuration with multiple turbine stages. They demonstrated that adding a second stage increases power output by 52% while adding the second and third stages results in a 72% increase compared with a single wind turbine. However, credible studies of the energy and environmental performance of the technology are still pending.

The RidgeBlade® wind turbine [100] is a recent development by a Canadian start-up company, available in three configurations – residential, commercial and hybrid installation with solar PV panels. The product presentation claims 2.7 kW peak (2 kW continuous) power generation per set of 5 rotors. This is a promising technology and, for successful commercialisation, may benefit from a credible evaluation of the environmental impact and economic viability.

3.3. Energy storage

Energy storage is critical for utilising renewable energy due to its intermittent nature [101]. Two classes can be considered prevailing – electrical and thermal energy storage [102]. In some cases, mechanical energy storage [103] can also be considered as a separate class. There are various energy storage options – mechanical, electrochemical, chemical, thermal, and electromagnetic. They have been evaluated in detail by Acar [104]. That review has shown that there is no clear winner when the technologies are compared by all important criteria – including energy density, efficiency, lifespan, self-discharge rate, cost, technology maturity, and environmental impact. The remainder of the current section reviews the most developed and the most mentioned energy storage technologies for the last 3 years.

3.3.1. Electrical energy storage

The progress in commercialising large-scale battery technology is underway, reaching important milestones. A facility of the RWE company into a pair of Li-ion battery electricity storage in Germany [105] will support a 220 MW power supply for short durations of up to 1–1.5 h. Such facilities may be crucial in handling peak loads. A similar trend is observed in the United States [106], installing nearly 11 GWh battery capacity in 2021 and more than 20 GWh in 2022, while new wind and PV capacity dropped by 78% and 18%.

There are serious concerns that terrestrial Li reserves are insufficient for installing pervasive batteries [107]. Developing novel electricity storage materials and devices is quite important. An example of a new approach to electricity storage with a potentially high impact is the PolyJoule [108] battery. It is based on an organic polymer in which the carbon chain contains alternating single and double C-to-C bonds. There are no research publications on this technology yet. However, some general information has been published in MIT (Massachusetts Institute of Technology) Technology Review [109], aiming at a cost level of 20 USD/kWh storage.

Na-ion battery technology [110] is in intensive development. This essentially mimics the Li-ion technology. A UK startup, Faradion, developing the technology, was acquired by CATL and Reliance Industries in 2022 [111]. The companies have plans to build utility-scale facilities with storage density up to 200 Wh/kg.

3.3.2. Thermal and thermo-chemical energy storage

Thermal Energy Storage (TES) maturity is demonstrated by operating an industrial-scale (24 MWh) thermal energy storage facility in Italy [112]. This project is based on Sensible heat storage in rocks at high temperatures serving a neighbouring power plant. TES can reduce peak demand, CO_2 emissions and costs at roundtrip efficiency as high as 95% [113].

Another example of sensible heat storage is that in sand silos [114] developed by the US National Renewable Energy Laboratory. The silos are reported to store heat for up to 100 h at a low heat loss rate of approximately 1%/day. The demonstrated heat storage system (26,000 MWh) could run a 130 MW electricity generation system based on a gas turbine. A similar smaller-scale demonstration was also reported in Finland [115].

Mahdi et al. [116] modelled a PCM-based energy storage system. The impact of using different arrangements of multiple PCMs – including variations with nanoparticles and with cascaded foam on the time-based solidification evolution was investigated. An adequate small number of multiple PCMs and foam segments was considered the optimal choice. The authors reported a 94% shortening of solidification time compared with the single-PCM benchmark configuration.

Yu et al. [117] applied varying amounts of Single-Walled Carbon Nano-Tubes. The addition of SWCNT resulted in a 38% enhancement of the material thermal conductivity and a 6% rise in the specific heat capacity. That was achieved at the expense of melting enthalpy drop by 36%, forming a trade-off that needs further investigation.

Salt hydrate-based gas-solid Thermo-Chemical Energy System (TCES) is a promising technology for employing low-grade energy. Li et al. [118] proposed a classification of salt hydrate-based TCES systems. While relatively high storage density is achievable – in the range of 1300–1700 kJ/kg [119], it was found that the technology still needs significant improvements in terms of more robust cyclability and environmental safety.

TCES technology using adsorption has made significant progress. A 2014 study [120] for short-term storage reported 805 kJ/kg with a cycle energy efficiency of 96%. The system was based on Mitsubishi Plastic FAM-Z01 as the sorbent and water as the sorbate. Yan et al. [121] synthesised composite sorbents with high sorption and energy storage capacity. The energy storage density was up to 1580 Wh/kg, at cycle efficiency exceeding 90%. More recently, $MnCl_2$–NH_3 were evaluated as a working pair [122], achieving 2729.82 kJ/kg storage density and maximum cycle efficiency of nearly 94%.

A redox cycle of the CuO–Cu_2O pair was investigated as a potential basis for storing heat [123] at 950-1050 °C. The authors reported 470–615 kJ/kg energy storage densities for granules consisting of 50–65 wt% yttria-stabilized zirconia. The round-trip energy efficiency of the cycle was not discussed.

3.3.3. Mechanical-based energy storage systems

Gravity Energy Storage has been demonstrated by the company Energy Vault [124]. The proposed system [125] uses blocks of dense material – lifted, consuming power (charge) and let down while generating power. The company is refraining from stating a specific value of obtained or expected round-trip efficiency. Moroccan authors [126] estimate the possible efficiency at 65–90%. Another company [127] reports 80% efficiency. No data on the potential environmental performance and energy storage density is available. Other projects investigate energy storage on the gravity principle – Gravitricity [128] uses underground shafts, and another project [129] uses rail-based solutions.

3.4. Sustainability issues of renewable energy technologies

A systematic framework is necessary for evaluating the sustainability contribution and the degree of circularity when recycling renewable energy equipment. It is claimed in [130] that among wind, run-of-river hydro and photovoltaic power generation, hydro generation has the lowest Global Warming Potential. The reported outperformance is of several orders of magnitude and is explained by the long service time of hydropower technology. The article does not describe the method well, which reduces the message's credibility. Water footprint or a similar metric is not included in the analysis.

An attempt to formulate a comprehensive Life Cycle Assessment method was published by Abokersh et al. [131] based on the Life Cycle Assessment standard [132]. The proposed circularity criterion derived from [133] is relatively clear, while the sustainability assessment criterion is not defined. The authors report circularity rates up to 46%.

The current technologies for PV panel recycling are reported [134] to cost up to 25 USD/panel, while only 3 USD/panel can be salvaged by selling the materials. A new technology project funded by the US Department of Energy aims at environmentally-friendly deep recovery and recycling of the materials contained in PV panels – including silver, tin, copper, and lead. The author notes that cost-effectiveness remains a challenge even for deep recovery. A recent research article evaluated multiple scenarios [135] and concluded that economic viability is the main obstacle before scaling up PV panel recycling. Neither of these sources quantifies the energy spending or the footprints from recycling.

3.5. Recent energy price instability, post-pandemic economic recovery, accumulated inflation

The effects of the COVID-19 pandemic on the economy were evaluated recently [136] on several scenarios in China – including "business as usual" and the COVID-19 scenario which took place. The sharp energy demand drop of approximately 9%, in turn, led to a drop in fossil fuel prices, which have become economically even more attractive than renewables, at least temporarily. By extrapolation, this has the potential for a sharp increase in GHG emissions in the post-pandemic recovery. The European Central Bank [137] has shown the significant price effects of the pandemic – boosted by the inflation from the massive economic stimuli worldwide. That was noted to overlap with the initial effects on the energy markets of the first months of the war in Ukraine.

The conflict in Ukraine, in addition to the on-site destruction and emissions, has had a significant "Domino Effect" on the energy supply and use across Europe. The effect has come in the dimensions of supply security, price increase, and change in the structure of used primary energy sources, directly affecting the GHG intensity of the economies. The security dimension [138] is linked to the energy supply disruptions and natural gas market reshaping towards increased use of renewables in Europe and coal in South-East Asia. It remains to see how the security implications will play out in the long term. A UK-based consultancy expressed serious concerns [139] that many countries would relax or even abandon delivering on their commitments to reduce GHG emissions. A United Nations report [140] reflected on the price increases with double digits of key products – including food and energy.

A snapshot for Europe from the "Electricity Maps" platform [141] on January 29, 2023 is given in Fig. 5. The GHG intensity of countries traditionally using coal – such as Poland, the Czech Republic, and Germany – is very high, with Poland exceeding 700 g CO_2/kWh. Even countries traditionally having lower emissions turned to energy sources with higher GHG intensity – including Austria and Switzerland.

Moreover, the future of several key nuclear power plants in Europe, based on Soviet technology, is now uncertain [142] since the nuclear fuel has to be restocked every few years. The source shows that those countries are trying to replace the supply from the Russian Federation with alternatives. However, since the alternative nuclear fuel is not designed for those plants originally, the process is slower and may hold unforeseen obstacles.

Apart from the supply security and safety issues discussed in the

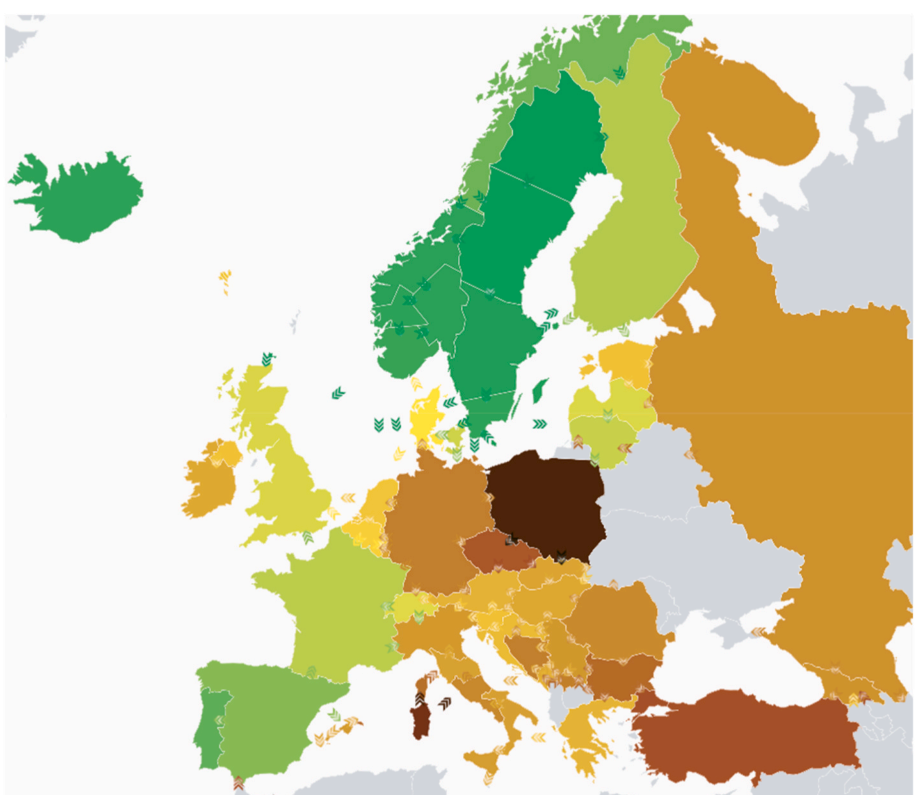


Fig. 5. Electricity Map snapshot for Europe as of January 29, 2023 [141].

previous section, nuclear energy is capable of contributing to the carbon footprint reduction of the energy supply. One analysis [143] of the role of nuclear energy in reducing the carbon footprint on five islands during 2001–2020 showed that 5.539% of the carbon footprint could be reduced by nuclear power over the next 10 y. Another case using the data of BRICS countries showed that the mix of nuclear and renewable energy sources can achieve both economic and environmental benefits.

4. Topics of the current VSI

The current VSI has sourced its contributions mainly from extensions of the research presented at the 23rd Conference on Process Integration for Energy Saving and Pollution Reduction – PRES'20 hosted by the Xi'an Jiaotong University at the height of the COVID'19 pandemic. A few external contributions added value to the collection.

4.1. Energy use in processes and services

Dong et al. [144] proposed an optimal design method for Heat Integrated Water Allocation Networks, minimising the Total Annualised Cost (TAC). The superstructure has three blocks: water source, water sink, and HEN. This model doesn't have a HEN sub-model, which reduces the computational effort. The results showed approximately a 2% reduction of the TAC compared with benchmarks due to network simplification and lower investment. This method needs further development to evaluate the implications of the simpler topology on the operability and cost.

Ferchichi et al. [145] provided a good example of following the Process Integration Hierarchy (Fig. 4) They proposed a Genetic Algorithm integrated with a flowsheet simulator to minimise the TAC of a pressure-swing distillation process. They evaluated cases of absence of Heat Integration, partial Heat Integration, and full Heat Integration – combined with heat pumps. Partial Heat Integration achieved a 23.7% TAC reduction compared to the non-integrated case. The heat pump-assisted configurations achieved 50% specific GHG footprint reduction compared to the base case.

Hakimian et al. [146] tried to use the oil sludge as the co-feedstock of the catalytic pyrolysis of cellulose over various catalysts. Results showed that Ni/HZSM-5 has the lowest apparent activation energy (97.6 kJ/mol) and contributes to the high production of xylenes (BTEXs). The 1/3 cellulose/oil sludge had the highest synergy when it served as the feedstock.

Ongpeng et al. [147] developed a hybrid decision framework to evaluate energy retrofit strategies with all stakeholders involved. DesignBuilder was applied because of its advantage of simplicity and accuracy in the simulation. Economic, environmental, and technical performance metrics were proposed. A Multi-criterion decision analysis using Analytic Hierarchy Process VIKOR was conducted to rank the scenarios. A four-story building in the University of the Philippines was used as the case study. The cost-optimal and eco-friendly scenarios – using combinations of improved insulation and renewable energy technologies, achieved 84% and 72% energy gain potential compared to the Net-zero energy scenario.

Shi et al. [148] developed a cascade cooling system considering waste heat recovery via Organic Rankine Cycle and Absorption Refrigeration (AR). A mathematical model was proposed, minimising the TAC. The case study showed that the AR and ORC schemes could reduce the TAC by 37.5% and 42.8%.

Yin et al. [149] developed a systematic method for the Reactor-Distillation sequence-Recycle-HEN (RDRH) system synthesis. The subsystems and their integration were considered, and each distillation sequence was integrated with the reactor, the recycle, and the HEN. The comparison with the simulation of Aspen Plus illustrated relative errors lower than 5.5%.

Structured network fins have been developed [150] to improve the charging/discharging performance of paraffin wax-based latent heat storage units. The results indicate a 10–14% improvement in the charging and discharging rates.

4.2. Heat transfer processes and equipment

To develop a high-efficiency natural convection radiator, Ding et al. [151] have modelled experimentally the heat dissipation in vertically oriented 3-D finned tubes under non-forced convection. An empirical correlation for predicting the Nusselt number was obtained based on the experimental data, which can be used in practical design. In Ref. [152], a novel model was elaborated for commercially produced plate heat exchangers with different corrugation geometries. The waste heat recovery from exhaust gases after tobacco drying was analysed in a case study. A considerable heat saving was achieved – up to 2090 kJ/kg of exhaust gases.

The pressure drop has been modelled [153] in a two-phase condensing flow of air-steam mixture inside channels of a plate heat exchanger with different corrugation geometries. The correlations show good agreement with the experimental measurements, achieving deviation levels under 20%, which is helpful for preliminary design. The parity plot indicates a lack of systematic errors.

Jia et al. [154] applied a finite element method to understand the electromagnetic-fluid-thermal-mechanical stress coupling process in an oil-immersed transformer. The results showed that the thermal load is the primary reason for the coil deformation, and the electromagnetic force only plays a small part. Density loss was in the range of 14–18%, indicating the need for reducing the thermal stress of the transformers.

Picón-Núñez and Rumbo-Arias [155] investigated welded plate heat exchangers to reduce the number of units and heat transfer areas in HENs. A thermohydraulic model was developed to determine the unit dimensions that satisfy the heat duty and pressure drop requirements. The reduction of the units was achieved by using multifluid structures. The proposed welded plate heat exchangers help to save both heat exchange area (50%) and energy demands (25%).

Qi et al. [156] analysed the design of a ribbed channel heat sink in a limited volume, maximising the heat transfer capacity. A Mixture Multiphase Model was applied to characterise the boiling performance of the two-phase flow. The results showed that with the increase of the rib diameter, the average heat transfer coefficient increases, and the wall temperature decreases. The reported results indicate a nearly two-fold increase in the heat transfer coefficients.

A novel combined structure with pin fins and vortex generators was developed in Ref. [157], applying a method to optimise the structure and an integrated microchannel heat sink to enhance its thermal performance. A combination of Al_2O_3 nanofluid and DI-water was used as the working fluid. The results indicate a 30% performance improvement for the cases with vortex generators compared to a rectangular microchannel.

Zhu et al. [158] used the Lattice Boltzmann method to study the influences of different parameters, such as volume fraction and aspect ratio, on the thermal conductivity of fibre-reinforced composites. The results showed that to improve the thermal conductivity performance, the thermal conductivity of the fibre and the coating layers should be focused on. The paper presents several correlations for predicting the values of the heat transfer coefficient.

4.3. Renewable energy harvesting and use, energy storage

Burić et al. [159] evaluated the resource potential estimation of tidal current energy in regions with low-energy currents but easy for energy structure installation by a high-resolution 3D hydrodynamic model. The authors concluded that turbine-type energy converters should be developed to exploit this energy resource.

A mathematical model was presented [160] for the optimisation of industrial-sector-scale utility networks and clean electricity networks. The results showed that the cost could be reduced by about 20% after optimising three industrial cases.

Kong et al. [161] developed a Pinch-based method for multiperiod electric power system optimisation, minimising the electricity bills for specified emission limits and energy demands. The system uses fossil-based and renewable energy sources. The authors reported a simultaneous reduction in the electricity bill (35%) and in GHG emissions (71%).

Martínez-Rodríguez et al. [162] studied integrating solar thermal energy into industrial processes. Pinch Analysis evaluation was performed for different values of ΔT_{min}. Case studies from the dairy industry and 2G bioethanol production were studied. The integration reduces the solar collector network area up to 24% and 49% for the two cases. Zima et al. [91] developed a method allowing the simulation and optimisation of larger-scale system models for solar energy harvesting and utilisation. The model achieved a high computational efficiency at high accuracy.

Liquid Air Energy Storage (LAES) offers high energy density independent of geographical location. The method in Ref. [163] proposed improvement measures of the LAES round-trip efficiency (RTE). Multi-Component Fluid Cycles (MCFCs) and Organic Rankine Cycles (ORCs) were tested and optimised. The reported optimal configuration has dual MCFC with an RTE of 62.4%.

Li et al. [164] studied the design, simulation, and analysis of a hydrogen liquefaction process which combines bioethanol-based hydrogen production and a multistage compressor. By varying the hydrogen compression ratio, the specific energy consumption of hydrogen generation was reduced from 5.41 to 4.71 kWh/kg_{LH2}.

Stančin et al. [165] conducted experiments to determine the suitable utilisation method for producing alternative fuels from waste materials. Mixtures of polyurethane foam (PUR) and biomass waste were evaluated. The introduction of polyurethane decreased activation energy compared to sawdust. The results revealed that the heating rate and mixture composition are key issues for the process dynamics.

Wu et al. [166] proposed an operational optimisation model to reduce the utility cost of co-processing fossil and bio-oil. The impurity distributions of the fluid catalytic cracker and hydrogenation reaction kinetics of the hydrotreating unit were integrated into the model. A 6.7% utility cost reduction was reported by adjusting the impurity removal degrees.

Elfeky et al. [167] investigated the impact of the change charge/-discharge cut-off values on the thermal performance of six different TES tank configurations. The results showed that the thermocline zones shrink when the charge cut-off value rises, and the discharge cut-off value reduces. When the cut-off values of the charge/discharge change simultaneously, the combined sensible-latent heat storage configuration has the best efficiency. The capacity ratio of the combined sensible-latent heat storage case is 90.55%, which is the highest.

The influence of compression stages, expansion stages, and water mass flow rates on the charging and discharging processes of an Adiabatic Compressed Air Energy Storage System (ACAES) were analysed [168]. The energy efficiency of the trigenerative ACAES improved from 0.62 to 0.87.

Kudela et al. [169] studied a residential heating system with a heat pump, low-temperature heat storage, and a control unit. The insulated water heat storage and underground water heat storage, assisted by the heat pump, were tested. A case study from Brno demonstrated a 5% improvement in the Seasonal Coefficient of Performance.

Naderipour et al. [170] proposed an optimisation method for a hybrid energy system, minimising the total net present cost. The system receives energy from PV arrays and wind turbines through an adaptor to a DC bus. The surplus energy can be stored in batteries. The sizes of the energy capture devices and the batteries were optimised with an improved grasshopper optimisation algorithm. A 50% electricity cost reduction was reported compared with the previous method. The environmental footprint is another key aspect that should be accounted for [171].

A digital Proportional-Integral-Derivative (PID) controller was proposed to maintain a constant hot water temperature in a storage tank [172]. The novel contribution of this control system is in the improved speed and accuracy of the PID controller by determining the fluid temperature based on the inverse problem solution of the thermometer heat conduction. The system temperature comparison of second and first-order thermometer models results in a difference smaller than 0.1%.

4.4. Energy conversion, transmission, environmental impact

Chen and Pan [173] developed a superstructure for combined cooling, heating, and power (CCHP) system optimisation. The proposed system has two complementing power-and-heat conversion subsystems. The proposed method reduced the CCHP system energy consumption by 12.8% compared with a single-structure CCHP system.

Qu et al. [174] developed a bi-level Reduced-Order Models approach to quickly identify the optimal exergy fields in Closed Wet Cooling Towers accounting for weather variations. The optimal exergy efficiency ratios ranged from 0.37 to 0.74, with an expected value of 0.56.

Dokl et al. [175] developed a Non-Linear Programming model for an integrated design and optimisation of an Organic Rankine Cycle for waste heat recovery in aluminium production. The objectives are the maximum electricity production and the Net Present Value. A Slovenian aluminium company case study compared the efficiency of three working fluids. R245fa has the best performance up to 7.9%, 1.4% higher than R1234yf and 1.0% higher than R1234ze.

Novotný et al. [176] proposed a three-step method to increase the energy efficiency of a lubrication system using GA. The verified case indicated a 35% reduction of the bearing mechanical losses, leading to 20% energy savings in the lubrication system.

Fang et al. [177] performed a bench-scale experiment with CFD simulation to study the effect of coal particle size on the performance of a swirl burner. The asymmetry of the continuous flow field is enhanced with the increase of the particle diameter, and the central recirculation zone gradually deflects toward the periphery. The authors suggested that the pulverised coal particle size should be below 50 μm.

Kadam et al. [178] reasoned that conventional vapour absorption refrigeration working fluids and the limited information on systems with sufficient capacities relevant to district cooling plants prohibit their scale-up. The coefficient of performance of the Vapour Compression Chiller (VCR) in the VCR-Vapour Absorption Refrigeration was increased by 252% compared with the stand-alone VCR cycle.

A three-step optimisation method for an ORC Waste Heat Recovery System (WHRS) was developed by Kang et al. [179] to satisfy the multi-period and multi-source heat recovery requirements. The formulated multi-source and multi-cycle WHRS optimisation model was solved, resulting in a 38.6% improvement in the output for a three-cycle system compared to the single-cycle system.

Li et al. [180] tested the Environmental Kuznets Curve hypothesis and the Pollution Haven Hypothesis of 89 Belt and Road Initiative countries, evaluating the link between the economy and the environment. The analysis showed that these countries should reduce their fossil fuel consumption, and a more specific green policy that fits the countries should be adopted. Environmental degradation reduction of 0.01%–0.12% can be achieved by a foreign direct investment increase of 1%.

Lopez et al. [181] proposed a modified Carbon Emissions Pinch Analysis to minimise the renewable energy target for a group of countries with an electricity trading agreement. The results from three case studies indicated that electricity trading helps to reduce new aggregated renewable energy capacity by 9 TWh. Countries with lower carbon reduction targets could import electricity from high-target countries to increase the flexibility of the group.

Ocłoń [182] presented a method to optimise the material cost for a 400 kV cable line under various values of soil thermal conductivity and cable ampacity. The solution showed that Fluidized Thermal Backfill contributes to reducing the cost at a low soil thermal conductivity for a scenario that has 1400 A current loading and 0.7 W/(m K) thermal conductivity, as the technique reduces the cross-section area of the cables.

Song et al. [183] developed an infrastructure-based energy supply system planning model considering multiple regions and periods to enable the low-carbon transition of China. It is concluded that the power and hydrogen systems play the main role in achieving carbon neutrality, and a 115% increase in infrastructure investment was recommended to help achieve carbon neutrality.

Wei et al. [184] proposed a roadmap to a carbon-neutral industrial park with an optimal construction plan. The minimum cost was set as the objective function, and the electric and thermal decarbonisation was considered the constraint. The result indicates the NPV of the industrial park is $3.95 billion, and the scheme presents a compromise between the environment and economy that would cost $3.95 billion while bringing a 61% emission reduction compared with the baseline.

Zhang et al. [185] studied the pyrolysis behaviour of bituminous and lignite coal at elevated pressure by a pressurised drop tube furnace. The results show that the pressure, atmosphere, and coal rank could affect the volatile release and char evolution significantly. A considerable increase from 0.55% to 4.25% for char gasification has been achieved at elevated pressure.

Zhang et al. [186] studied the supercritical carbon dioxide (SCO_2) Brayton cycle by developing three commonly used models (recompression, reheating and intermediate cooling) in MATLAB and Simulink. Under the 5% leakage condition, the recycling efficiency of the recompression model increases by 2.58%, while the efficiency of the reheating model and the intercooler model decreases.

5. Discussion

It has been shown that there is a direct link between energy consumption and emissions. Energy is spent even on recycling products and materials. The resource integration hierarchy and the Onion Diagram point to the need to maximise integration at lower levels before wider-scope integration due to the logistical energy overheads.

5.1. Energy integration and intensification issues

Within the scope of a single process, the key energy conservation approaches include housekeeping measures, sharing the resource base, Process Intensification (the published examples lack proper quantification of the potential benefits), and Process Integration. The published studies on material recycling demonstrate an energy and emission intensity reduction, but the recycling rates do not exceed 40–60%.

The discussed sources applied the identified measures in isolation. One exception to this was the application of Heat Integration alongside intensification to reactive distillation processes [43], doubling the economic performance of resource-saving. The minimisation of footprints and resource (energy) use of industrial symbiosis or waste management networks is not dealt with.

A fundamental obstacle preventing such modelling is the heterogeneous character of symbiosis networks. They involve processes of different types – separation, transportation, heating, cooling, mass exchange, and reactions. A different modelling paradigm is needed, uniformly treating all operations. The Energy Quality Pinch Analysis [187] is a potential unifying concept to model resource use and recovery by symbiosis networks.

5.2. Issues with renewables and hydrogen

The recent developments in energy supply from fossil and renewable sources show that hydrogen is a promising energy carrier. However, it still needs much research and development to fulfil its potential. Biomass utilisation as an energy source has also seen development. Hydrothermal carbonisation showed potential in treating waste with varying water content. An interesting development is the ultrasound pre-treatment of waste before anaerobic digestion, leading to nearly 70% biomass conversion efficiency to methane.

Solar irradiation as an energy source has made significant progress. PV technology is actively developing, commercially approaching GW-scale deployments. Perovskite PV can reach nearly 40% efficiency by combining several complementary layers. Another innovation to maximise the efficiency of the equipment investment is the demonstration of PVT panels. The demonstrations are concerned with seasonal ground heat regeneration and the use of hot water together with heat pumps.

Wind use for power generation has seen significant development of ever-increasing capacities of the deployed wind turbines. The INVELOX technology shows a considerable potential for HAWT efficiency increase. The RidgeBlade® turbine technology is more recent and not as well established but shows significant potential for high efficiency and low noise levels.

5.3. Issues of energy storage

In energy storage, mainstream lithium-ion technology has entered the saturation stage regarding resource base and only incremental improvements to its efficiency and operation. An analogous resource base using sodium-ion batteries is being actively developed [111] with the promise to achieve lower cost, albeit at lower energy storage densities and limited portability. Gravity-based electricity storage promises a round-trip efficiency of around 90%. However, it needs substantial elevation differences.

Thermal energy storage is already a mature field, and round-trip efficiency exceeding 95% is pursued. The thermal losses and discharge should be characterised by accounting for load and temperature losses. Thermo-chemical energy storage has also made significant progress, exceeding the storage density of 1500 Wh/kg (5400 kJ/kg).

5.4. Environmental impact and cost issues

The environmental impacts of the current technologies for renewable energy harvesting and supply are not yet well evaluated. While the base methodologies are available, specific data are missing. In the case of PV panels, even the recycling investigations have begun only recently.

The recent energy price increases are a result of two main factors. One is the post-COVID-19 recovery, and the other is the conflict in Ukraine. Both factors stimulate inflation and make natural gas too expensive or even unavailable, resulting in the use of fuels with a higher GHG Footprint.

The current VSI contributes to solving various problems in these areas – including enhanced heat transfer, heat recovery and valorisation, and reducing emissions, as shown in the applications to ORC. Further investigations should focus on assessing the operability implications and quantifying the environmental impact. Thermal retrofit in buildings showed great potential for energy gain of up to 80%. This should be further investigated for potential RESHeat [93] technology synergies. The VSI contributions to improved heat transfer and exchange technologies have also shown remarkable progress, with tangible double-digit gains in efficiencies in terms of transmission rates or reduction in the heat transfer area. However, to put into use those achievements, they need to be properly summarised and introduced into system-wide technologies.

6. Conclusion

The World is in a period of energy transition – switching from fossil fuel technologies to renewables, which has overlapped with the effects of COVID-19 and the war in Ukraine. These factors and their domino effects on energy supply and prices revealed the importance of supply security as an essential part of sustainability. The current review has analysed the potential energy efficiency measures necessary to achieve a cleaner circular economy. The findings, the contribution of the current VSI, and the important future work directions are summarised next.

Several barriers before renewables implementation are apparent – including lack of flexibility of existing power plants, renewables dependence on weather, insufficient energy storage capacity and round-trip efficiency, high unit installation costs and long return on investment. It has been shown in the review that while isolated technologies and scientific developments achieve significant progress, the resulting technology base and the overall economic performance still result in wasting 2/3 of the sourced energy for decades. Energy storage technologies have progressed a lot, some reaching high round-trip efficiency but suffering from several problems – such as depleting resource base (Li-Ion), limited portability (Na-Ion) or insufficient storage density (gravity storage).

A key lesson from this is the need to investigate the behaviour of the entire hierarchy of unit processes, industrial sites and building complexes, towns, cities, and regions. The hierarchy defined in Fig. 4 must be modelled consistently at each level, minimising the interface flows – energy inputs and emissions-before attempting wider-scope integration. In this way, the net energy and resource demand of the regions and overall economies have the chance to become sufficiently small to be manageable by renewable resource supplies.

Without a proper retrofit of the building stock and industrial processes, it will be impossible to match the energy supply from renewables. A radical reduction in the fundamental energy demands is necessary. At the base of the Circular Economy Hierarchy, it is essential to research further the paths and methods for increasing resource utilisation efficiency before waste streams are generated and passed on to integration. Special attention has to be paid at the integration level to the synergy of Process Integration and Process Intensification, which can offer step-change benefits.

The environmental impact of the technologies for renewable energy utilisation needs to be well studied and still poses a significant challenge. Related to this is the need to improve the decommissioning performance of PV and wind technologies, especially to improve their recyclability in terms of the material cycles and energy use minimisation while allowing economic viability.

To enable such scientific and technological breakthroughs, it is necessary to develop novel concepts and visualisations that allow linking processes of different nature in a uniform optimisation framework. Those concepts should be supplemented by advanced tools for modelling and efficiently converting mathematical models into working practical solutions. The recommendations from the current review are valid for general process systems and Circular Economy projects. However, their validity has to be checked for extended and similar areas – such as general business processes, residential activities, hospitality industry or administrative activities. While the same principles and types of analysis can be applied, those areas have their own specifics, and the research has to be adapted.

Credit author statement

Petar Sabev Varbanov: Conceptualization, Methodology, Writing-Reviewing and Editing; Bohong Wang: Writing-Reviewing and Editing. Paweł Ocłoń;: Writing-Reviewing. Elżbieta Radziszewska-Zielina: Writing-Reviewing and Editing. Ting Ma: Writing-Reviewing and Editing. Jaromír Klemeš: Funding Acquisition, Project Supervision; Xuexiu Jia: Figures Drawing, Writing-Reviewing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Professor Jiří Jaromír Klemeš has worked on the manuscript. Sadly, he passed away before its submission. However, the authors would like to show their appreciation for his leadership and scientific excellence and would like to keep him on the list of authors.

Nomenclature

ACAES	Adiabatic Compressed Air Energy Storage System.
AR	Absorption Refrigeration
BRICS	The BRICS nations are Brazil, Russia, India, China, and South Africa
CATL:	Contemporary Amperex Technology Co., Limited
CCHP	Combined Cooling, Heating, and Power
CE	Circular Economy
CEPA	Carbon-Emission Pinch Analysis
CFD	Computational Fluid Dynamics
COVID-19	Coronavirus Disease 2019
DC	Direct Current
EU	European Union
GHG	Greenhouse Gas
HAWT	Horizontal-Axis Wind Turbine
HEN	Heat Exchanger Network
HPI	Huaneng Power International
LAES	Liquid Air Energy Storage
LCA	Life Cycle Assessment
LLNL:	Lawrence Livermore National Laboratory
MCFC	Multi-Component Fluid Cycle
MINLP	Mixed Integer Nonlinear Programming
MIT	Massachusetts Institute of Technology
NASA	National Aeronautics and Space Administration
ORC	Organic Rankine Cycle
PCMs	phase-change materials
PI	Process Integration
PID	Proportional-Integral-Derivative
PRES	Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction
PTC	Parabolic Through Collector
PV	Photovoltaic
PVT	Photovoltaic-Thermal
PUR	polyurethane foam
RDRH	Reactor-Distillation sequence-Recycle-HEN
ROI	Return on Investment
RTE	Round-trip Efficiency
SCO_2	Supercritical Carbon Dioxide
SNG	Synthetic Natural Gas
TAC	Total Annualised Cost
TCES	Thermo-Chemical Energy System
TES	Thermal Energy Storage

UK: United Kingdom
US: United States
VCR Vapour Compression Chiller
VSI Virtual Special Issue
WFP Water Footprint
WHRS Waste Heat Recovery System

Appendix A. Supplementary data

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