Highlights

1. Research trends on energy transition and the associated technologies are reviewed
2. Literature review examined the Special Issues of journals dedicated to SDEWES Conferences
3. Challenges posed by increased share of renewables are solvable by cost-efficient solutions
4. Power-to-heat and district heating are key-technologies for sustainable energy supply
5. Energy saving in the building and industrial sectors contributes to sustainability of energy sector

Sustainable and cost-efficient energy supply and utilization through innovative concepts and technologies at regional, urban and single-user scales

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Abstract

The environmental impact of the energy sector and the security and economics of energy supply and utilization have been raising increasing concerns, stimulating the search for innovative solutions for a sustainable use of resources. This article provides an overview of published research in this area, with a focus on papers contributed in special issues of leading journals dedicated to the series of Conferences on Sustainable Development of Energy, Water and Environment Systems (SDEWES), including the articles in the current special issue. Based on this review, research trends are identified and achievements supporting the energy transition are highlighted. The studies that focused on regional or urban energy planning have aimed at (a) increasing penetration of renewable energy sources, (b) optimizing the mix of centralized and distributed technologies (c) introducing additional flexibility in the power sector and d) identifying solutions for sustainable heating. Conversely, researches focused on individual plants or users have targeted the development of technologies for efficient energy use in industry and buildings, with emphasis on multi-generation and waste heat utilisation. The analysis highlights that future scenarios based on sustainable energy systems are viable, although their implementation will require further efforts by researchers and investors and active involvement of consumers.

Keywords: Renewable energy sources, sustainable heating, low-energy buildings, multi-generation, waste heat recovery, SDEWES

1. Introduction

The sustainable provision and use of energy and water resources has become a crucial topic over the last decades, as continuous population growth and rising living standards have generated increased concerns associated with the environmental impact of anthropogenic activities, compounded by energy security concerns and economics [1].

Since 2002, the Conferences of Sustainable Development of Energy, Water and Environment Systems (SDEWES) have fostered the development of solutions towards sustainable energy use and supply, by offering a platform for effective discussion and dissemination of knowledge in this field, gathering scientists and professionals with different backgrounds from all over the world.

The holistic and multidisciplinary approach adopted to define the scope of the SDEWES Conferences and develop their scientific programs has attracted researchers working in a variety number of related fields.

Among the topical areas explored at the SDEWES Conferences, the following have gained increasing attention in recent editions of the Conference to contribute solutions to urgent challenges posed by the ongoing global energy transition [2-6]:

- Increasing penetration of renewables and electrical grid stability
- Energy markets and renewable resources, effects of regulation, energy pricing and infrastructures
- Smart grids and smart energy systems in districts and islands
- Power-to-heat and power-to-fuel technologies
- Sustainable centralised and decentralised heating technologies and viability of district heating systems
- Energy savings in the building sector
- Energy savings through efficient multi-generation systems (such as co-, tri- and poly-generation plants) and waste heat utilisation
- Measurement of energo-environmental sustainability of processes and systems

The above topical areas are listed and ordered according to the organisation of the manuscript. In this Review paper an overview of scientific publications focused on these topics is provided, outlining current research trends and key achievements. The analysis will clearly reveal that the above topics are strictly interrelated, thus confirming that cooperation between researchers working in different fields is beneficial. This review also discusses the contributions emerging from the 32 papers included in the current special issue of Energy, which is dedicated to the 12th SDEWES Conference held in Dubrovnik, Croatia, from October 4th to October 8th, 2017 and which attracted 525 scientists, researchers and experts from 57 countries.

2. Increasing the penetration of renewables and electrical grid stability issues

Increasing the penetration of renewable energy sources (RES) is unanimously recognized as a promising strategy towards improved sustainability of the energy sector. For regions with scarcity of endogenous fossil fuel reserves, this approach also contributes to reduce the dependency on imported resources [7]. However, since in many developed countries the existing potential for hydropower and high enthalpy geothermal energy is now almost entirely exploited, the growth of installed renewable power capacity mainly relies on intermittent energy sources, essentially wind and solar photovoltaics (PV), with consequent grid stability issues [8]. Research contributions related to increased renewable penetration and electrical grid stability are organised in this section according to two aspects: (i) feasibility of 100% renewable electricity scenarios, (ii) grid stability issues and technological solutions.

2.1 Feasibility of 100% renewable electricity scenarios

A number of studies including [9] have refuted claims that large-scale power generation systems with predominant variable renewable sources may not be feasible, instead providing supporting evidence that systems with 100% renewable electricity generation can be readily designed to meet the key requirements of reliability, security and affordability. If some questionable assumptions are avoided and state-of-art technologies are properly assessed, transition to 100% renewable electricity could occur more rapidly than suggested by historical energy transitions [9]. A recent study by Auer and Haas [10] underlined the need of a “new thinking” to accept a paradigm shift in the whole electricity system. According to the authors, a more flexible and smarter energy system is required to integrate large shares of renewables, through demand participation, energy storage and other flexibility measures.

In some countries several steps toward a 100% renewable electricity scenario have been made, due to a serious political commitment and a synergic energy planning activity involving scientists, system operators and professionals. A study by Lund and Mathiesen [11], based on detailed system design and energy balances, stated that in Denmark a 100% renewable energy system is physically feasible by 2050; the analysis also pointed out that, in order to achieve this goal, an intermediate target with 50% share of renewable electricity could be fixed for 2030. Mathiesen et al. [12] examined, for the Danish case, the contribution that such a strategy could give towards the climate mitigation goals and quantified other positive socio-economic effects, such as the creation of employment and the potential benefits in terms of exports. The same authors also performed, for the Danish case, a comparison among seven technologies (electric boilers, heat pumps, electrolysers with local cogeneration, electrolysers with micro-cogeneration, hydrogen fuel cell vehicles, battery electric vehicles and flexible electricity demand) to facilitate the integration of fluctuating RES [13]. Heat pumps and flexible demand were identified as the most promising technologies in respect of costs, the former one also being by far the most fuel-efficient solution.

In many countries the 100% renewable electricity target is not realistic in the short- and medium-term, but scientific studies have been still conducted to assess what energy policies, market conditions and technological solutions should be implemented towards this target. In a study carried out for Ireland by

Connolly et al. [14], after depicting the country's 2007 status quo with a 96% share of total energy demand supplied by fossil fuels, three different future 100% renewable energy system scenarios were developed focusing on different resources, i.e. biomass, hydrogen and electricity. The main result is that even in regions with large share of installed capacity by condensing power plants, several approaches can be pursued to increase the share of renewables towards 100% penetration, including (depending on the scenario): electric, hydrogen- and biomass-fueled transportation; solar thermal, electric heat pump, biomass-fueled and district individual heating, marine power, biomass as industrial fuel, hydrogen-fueled combined heat and power (CHP) and storage. In a subsequent study by Welsch et al. [15], the risk of underestimating flexibility requirements in long-term energy system models was assessed. It was found that in the Irish case, the inclusion of increased short-term operational details in the 2020–2050 energy system models led to a much more reliable prediction of the cost of meeting climate change and energy security targets. Another article by Krajačić et al. [16] analysed the potential for 100% RES electricity in Portugal. Based on a 2006 status quo with a gross electricity production from renewables (mainly hydro) ranging between 20 and 35%, the software H_2RES was used to develop scenarios with 100% renewable electricity including high shares of intermittent renewables and the required integration with various types of energy storages. The role of storage systems (in particular pumped hydro, batteries and fuel cells with hydrogen loop) was found to be crucial to decrease installed power requirements for generating units and achieve a sufficient security of supply. An interesting sensitivity analysis to the share of renewable energy (ranging from 0% to 100%) in France in year 2050 was carried out by Krakowski et al. [17]. An energy planning model was used and several assumptions on intermittent renewable energy, imports, demand flexibility and biomass potential were tested. The results showed that very high share of renewable electricity, ranging between 40% and 100%, would need significant investments in new capacity and implementation of effective demand-response actions, in order not to affect power system reliability. The feasibility of high penetration of renewables has also been investigated in hydrocarbon producing regions with low-cost fossil fuels. Caldera et al. [18] assessed the potential roles of batteries and water storage in the transition of Saudi Arabia towards a 100% renewable power sector by 2050. In order to simultaneously address the local shortage of drinkable water, the use of seawater reverse osmosis (SWRO) was investigated to provide flexibility via desalinated water storage. However, it was found that flexibility could be provided at a lower cost by solar PV and battery storage, than by SWRO and water storage.

2.2 Grid stability issue and technological solutions

The stability of power generation systems can be negatively affected by high penetrations of intermittent renewables, due to a significant reduction of inertia and consequent risks on frequency control. However in particular cases, characterised by endogenous weakness of the power generation or transmission systems, the inclusion of solar PV and wind energy has been found to be beneficial to grid stability. An example was illustrated by Schmidt et al. [19], who analysed long-term metereological data in Brazil and found that an increased installed capacity of intermittent renewables (i.e., solar PV and wind) would contribute to reduce the need for thermal backup and the risk of grid failure, solar PV being slightly more efficient than wind in inducing these positive effects. However, this finding was a consequence of the extreme vulnerability of the Brazilian power system, related to the high share of hydropower production and the consequent hydrological risks.

In the most frequent case where high shares of renewable electricity in energy systems increase the grid vulnerability and induce additional costs for reserve contingency, solutions are needed to allow for safe integration of the new installed capacity. A number of approaches have been proposed to guarantee grid stability in scenarios with high penetration of intermittent renewables. These approaches can be classified as follows, based on the pursued strategy:

- Forecasting electricity demand and supply from renewable sources
- Coordinating the installation of new capacity or the operation of existing power generation units
- Providing additional flexibility on the demand side through appropriate load management or by introducing additional and flexible “electricity uses”
- Introducing direct or indirect energy storage technologies.

The above approaches are discussed in the following sub-sections, and illustrated through a few examples. Some other solutions, which have additional positive effects on energy systems beyond grid stabilisation, are also discussed in more detail in subsequent sections.

2.2.1 Forecasting electricity demand and power supply from renewable sources

A first approach to the face grid stability issues in scenarios with high share of renewable electricity aims at ensuring an efficient forecast on the supply or demand side, in order to minimize the reserve capacity and the associated cost . In a paper by Dedinec et al. [20] an efficient approach based on deep belief networks was used for short-term electricity load forecasting and successfully validated against Macedonian hourly electricity production data over the time span 2008-2014. Kaur et al. [21] investigated net load forecasting as an enabling technology for the integration of microgrid fleets with the utility grid. Additive and integrated approaches to net load forecasting were compared, and the latter was found to provide a more reliable forecast of the load traded between the microgrids and the macrogrid. An alternative approach proposed in the literature and focused on the supply side aims at forecasting the power produced by intermittent renewable sources. In a paper by Scharff et al. [22], internal ex-ante self-balancing was proposed as an efficient way to shift the balancing responsibility from the Transmission System Operators (TSOs) to the power generating companies. The paradigm shift implies a reduction of real-time balancing needs for TSOs to be achieved through a minimization of expected imbalances by the power generating companies. A number of research articles focused on forecating methods and uncertainty analysis for solar PV [23] and wind energy [24] production are available in literature. Such contributions have revealed that compared to the widely-used point forecasts, probabilistic approaches provide additional quantitative information on the uncertainty associated with power generation and thus offer optimal inputs for decision-making. The reliability of the forecasting method is crucial for the system, as demonstrated in a recent study by Higgins et al. [25], where the impact of offshore wind power forecast error in a carbon-constrained electricity market was investigated. Among the main findings of this work, every percent point rise in the forecast error, regardless of its sign, was found to lead to an increase in system marginal prices of approximately 1%.

2.2.2 Coordinating the installation of new capacity or the operation of power generating units

An interesting study by Sabolić et al. [26] investigated the optimal spatial distribution of a portfolio of new wind plants over a set of pre-determined geographical locations, for a fixed installed generation capacity, with the aim to minimize generation variability. According to the authors, the modern portfolio theory successfully led to an optimal allocation of the new generation capacity, contributing to reduce uncertainty in generation variability. Pandžić et al. [27] proposed a mixed-integer linear programming problem to maximize the profit of a virtual power plant incorporating wind turbines and other intermittent renewable power sources combined with dispatchable power sources. The virtual power plant was imposed to fulfill long-term bilateral contracts (thus having power-production constraints) but also to act in the market. Uncertainty in wind and solar power generation was compensated by having both pumped hydro storage and conventional power plants as a backup. Any solution based on an appropriate combined mix and coordinated operation of intermittent renewables and conventional power plants must take into account the technical constraints of each technology. In a study by Tomšić et al. [28], the feasibility of a virtual system including wind power plants and a combined cycle gas turbine plant to participate in the electricity market and offer continuous power outputs was assessed. A detailed analysis of the techno-economic characteristics of ramp rates and different start-up and shut-down strategies was performed to guarantee the techno-economical reliability of the results. The different backup solutions may be hierarchised on the basis of their capability to provide quick response to transient increases or decreases in power supply from intermittent renewable sources. From this perspective, Schlachtberger et al. [29] analysed the flexibility of backup power generation units at three relevant time scales, i.e. diurnal, synotpic and seasonal, in order to verify their capability to follow typical intra-day, intra-week and seasonal load variations. Among their main findings, the additional share requirement of highly flexible backup systems needed when the average renewable power generation passes from low percentages to 70% or above was quantified. Another study by Benato et al. [30] focused on the negative effects of irregular and discontinuous operation of thermoelectric power plants required to compensate for the variability of renewable sources. Transient thermodynamic simulations of plant operation were used to characterize the dynamic behaviour of the components and assess the impact of thermo-mechanical fatigue, creep and corrosion on the lifetime of the most critical components. Finally, Prina et al. [31] provided an interesting integration of combined cycle gas turbine cycling costs in EPLANopt, a simulation software that couples EnergyPLAN with a Multi-Objective Evolutionary Algorithm. The results testify the importance of accounting for cycling costs in energy planning, which at high penetration of intermittent renewables can peak at 33.5 €/MWh.

2.2.3 Providing additional flexibility on the demand side through load management or flexible electricity uses

Another strategy to support increased penetration of intermittent renewables widely discussed in the literature is based on providing additional flexibility on the demand side. In order to implement efficient demand management, dynamic pricing is a main instrument that has been proven efficient both in the building and industrial sectors. A study by Katz et al. [32] investigated the short- and long-term effects of exposing household electricity customers to retail products with variable pricing. It was pointed out that simple pricing schemes, although less efficient than complex ones, play an important role in the earliest phases of developing a household demand response. More complex pricing options can be considered at a later stage, in order to shift consumers' behaviour to follow more strictly the real-time demand rates. A very peculiar application of demand response in buildings was proposed by Barzin et al. [33], investigating the performance of price-based control methods in peak load shifting. The analysis was carried out for a space heating system and for a domestic freezer, also accounting for the role that could be synergically played by the inclusion of energy storage, achieving 62.6% and 16.5% cost saving, respectively. Leobner et al. [34] proposed two simulation-based approaches to integrate demand-response strategies into Energy Management Systems for smart grids: (a) model predictive control of the heating and cooling system of a building and (b) energy use optimization into industrial automation systems. A study by Paulus and Borggrefe [35] discussed the extent to which Demand-Side Management from industrial processes may be expected to provide tertiary reserve capacity and induce economic benefits on the electricity market. The analysis was performed for Germany, and explored future energy scenarios for year 2030 with high penetration of renewables, where increased demand for ancillary services could be expected.

A different approach aimed at exploiting surplus electricity from renewable sources consists of introducing new flexible uses of electricity, such as Electric Vehicles (EVs). Actually, the main goal of transitioning to low- or zero-emissions mobility is to reduce the polluting and greenhouse impact of the transport sector, which in the United States and European Union accounts for 29% and 22% of total emissions [36], respectively. Nevertheless, positive grid stabilization effects may be induced by active management of EV charging stations, as proven by a number of studies [37] assessing the full benefits of EVs integration with local renewable generation in future smart grids and internet of energy (IoE). Metz et al. [38] investigated the potential of electric vehicles in filling the gap between a fixed energy demand and stochastic power supply from fluctuating energy sources (mainly solar PV and wind). A novel approach to simulate large vehicle fleets, based on 9744 individual driving profiles derived from the German mobility panel, allowed to identify a subset of potential early users whose charging profiles are suitable for supporting grid balance. The study also pointed out that only coordinated charging loads allow load shifting without limiting mobility. Foley et al. [39] analysed the effects of a large number of EVs, sized according to the Irish government target of 10%

of all vehicles in the transport fleet to be electrically powered by 2020, on the wholesale electricity market. Peak and off-peak charging scenarios were analysed and compared, confirming that off-peak charging is more beneficial. In addition charging EVs was found to potentially contribute 1.5% renewable supply to the target of 10% renewables in transport, with a consequent net avoidance of 210 kt CO_2 emissions. Besides a sufficient infrastructural development of distributed EV charging stations, Knez and Obrecth [40] pointed out that the growth of the electric vehicles market would also benefit from promotional policies targeted to customer preferences on alternative fuel vehicles. The authors identified the total vehicle price and fuel economy as key factors for a successful promotional campaign, pointing out the main weaknesses that have led the EVs promotion actions in Slovenia to be unsuccessful. Škugor and Deur proposed a dynamic programming-based optimization method of charging an EVs fleet modelled as a so-called "aggregate battery" [41]. The approach was applied to an isolated and electrified delivery truck transport system supplied by both the grid and renewable energy sources. The optimization method was found to be computationally efficient and suitable for use in energy planning studies, and at the supervisory/aggregator level of hierarchical EV fleet charging strategies.

2.2.4 Introducing direct or indirect energy storage technologies

A very efficient approach to guarantee grid stability in energy scenarios with high penetration of intermittent renewable power is based on providing adequate energy storage capacity. Several approaches have been proposed in the literature, either based on accumulating surplus electricity (direct energy storage) or converting electricity into some other form and then exploiting the stored medium to produce electricity at a successive time (indirect energy storage). In both cases, storage systems are aimed at making the surplus electricity subsequently available when additional supply is required to face demand from consumers.

A paper by Luburić et al. [42] discussed the role of energy storage in increasing power system adequacy and security. A method of defining the energy storage charging/discharging schedule was proposed and applied to the Croatian power system, in order to maintain the system within its operating limits and provide the system operator with sufficient time to redispatch the stored energy.

Electric storage by batteries is the most widely reported solution for direct electricity storage. Morel et al. [43] investigated the stability enhancement of the Japanese power system, accounting for a high share of solar and wind generation. The Fukushima disaster, and associated concerns relating to the security of energy supply, prompted growing interest in distributed generation and increased renewable generation capacity. The study demonstrated that the reduced inertia of the power system due to renewable generators and transient stability issues could be efficiently addressed by installing a sufficient sodium-sulfur battery storage capacity.

With regard to indirect energy storage, a typical example is the so-called pumped hydro storage system, which mitigates fluctuations of supply by converting surplus electricity from renewables into gravitational potential energy of water, that is pumped from a lower to an upper reservoir, and then converting it back to electricity through a turbine exploiting the head between reservoirs [44]. Another solution widely investigated by researchers is Compressed Air Energy Storage (CAES), which converts electricity into pressure exergy of compressed air, which is subsequently utilised to produce electricity when needed. Foley et al. [45] examined the impact of CAES facilities in a pool-based wholesale electricity market with a large renewable energy portfolio. The results confirmed that a CAES system implemented in the Single Energy Market between Northern Ireland and Republic of Ireland can optimise, under the current market rules, energy arbitrage opportunities and achieve reductions of CO_2 emissions in the order of 3% by 2020. A different approach to allow a more flexible use of electricity consists of producing storable products, such as desalinated water. An interesting study proposed by Novosel et al. [46] evaluated the impact of pump storage combined with desalination on the penetration of intermittent renewables in Jordan. As a main achievement, the design of a highly flexible reverse osmosis capacity contributed to reduce the Critical Excess of Electricity Production (CEEP), and to increase the share of wind and solar PV electricity to meet up to 32% and 37% of the total annual electricity demand, respectively.

A recent article by Pavković et al. [47] provided a useful hierarchisation of low-to-medium scale energy storage technologies, such as flywheel, compressed air, batteries and ultracapacitors, comparing their investment and operating costs, size and durability, and also formulating practical guidelines for the case-oriented selection of an appropriate storage system.

3. Energy markets and renewable sources: effects of regulation, energy pricing and infrastructures

The bidirectional interaction between energy market conditions and penetration of RES has been widely investigated in the literature, also focusing on the relation with regional and long-distance transmission infrastructures. In a paper by Andresen et al. [48], the potential for arbitrage of wind and solar power in the current Danish market was assessed, based on scenarios including 100% supply by these two renewable sources. The authors pointed out that surplus energy grows rapidly when the share of wind increases well above 50%, but in this case the potential for arbitrage (by means of either flexible demand or energy storage) was limited, since the average "cycle count" (ratio between energy discharge and storage volume) did not justify a significant amount of storage. Another study by Hvelplund [49] analysed the two phases of renewable energy implementation in Denmark, the first where RES technologies (wind in particular) represented a niche and were brought close to cost competitiveness, and the second where RES technologies became a major player in electricity production and new challenges emerged for further increases in penetration. The author pointed out that in the second phase local energy markets have to be established in order to secure the technical integration of intermittent renewable suppliers into the system. The study underlined the importance of an appropriate institutional framework and governance system, to promote local and regional acceptance of high shares of renewables and create an infrastructure which can cope with increased production fluctuations. This link between the energy market regulatory framework and the penetration of renewables is also analysed by Moreno et al. [50], who investigated how to decompose the effects of both electricity liberalisation and increased generation from RES on electricity prices. An empirical investigation was carried out by developing econometric panel models to assess the relationship between electricity prices, RES and competition framework in the market. On a EU-27 basis and incorporating the additional cost for the support mechanisms, it was found that electricity generated from RES had a small but positive estimated effect, with 1% increase in electricity from renewables causing 0.018% increase in household electricity prices. Antonelli and Desideri [51] focused on the relation between feed-in premium tariffs guaranteed to solar PV in Italy and the capital and installation cost of PV components, pointing out that, due to their structure, support mechanisms in Italy led to shifting financial resources from productive sectors and private citizens to banks and investment funds.

Another emerging research trend aims at assessing the potential benefits of direct connections between regional and national energy systems via long distance electricity transmission. Technological and economic viability, as well as restrictions, have been discussed by Humpert [52] in a recent paper focused on the potential of Ultra-High Voltage Direct Current (UHVDC) systems. However, the market implications are also very relevant, as shown by Zakeri et al. in a study [53] where the impact of energy transition in Germany on the Nordic power market (including Norway, Sweden and Finland) was investigated using a market-based multi-region energy system model. The model accounted for the effects of grid congestion and demonstrated that energy transition in Germany induced system-level benefits (in terms of the so-called *social welfare*, resulting from consumer, production and congestion surpluses) also in the Nordic regions, although not equally distributed among the countries. Zakeri et al. [54] assessed the potential benefits of the planned sub-sea power transmission line between the United Kingdom (UK) and the Nordic power market. Their model simulated, on a hourly basis, the operation of the Nordic-UK power market coupling, also accounting for the District Heating systems in each country. The results indicate an estimated socio-economic benefit of 230 million euros per year, without considering the cost of the interconnector itself, and show that the UK-Nordic market coupling enhances the flexibility of the UK power system in wind integration.

4. Smart grids and smart energy systems in districts and islands

The development of smart grids and energy systems at municipal and district scale has received significant attention in the past few years, due to the possibility of achieving at such scale higher level of integration between different energy conversion technologies, and interaction between energy suppliers and consumers. A recent paper by Batas-Bjelic et al. [55] investigated the optimal design of a smart municipal energy grid including cogeneration and several renewable technologies, with the aim of decreasing total annual energy costs for the community. Several electricity pricing scenarios were considered, achieving in all examined cases reasonably high internal rates of return of investments (ranging between 6.8 and 15.3%) and CO_2 emissions reductions (ranging between 4.88 and 5.16 Mton/year) relative to the reference system consisting only of connection to the national electricity grid. Holjevac et al. [56] assessed the potential ability of aggregated groups of loads and generators to provide flexibility and balance the variability and uncertainty of

RES. After optimizing the microgrid configuration (which includes Electric Heat Pumps and CHP units, integrated with heat storages and auxiliary boilers) using a Mixed Integer Linear Progamming (MILP) technique, a Model Predictive Control (MPC) approach was proposed in order to capture the behaviour of the microgrid interaction with the distribution grid. The MPC control of microgrid operation contributed to alleviate internal balances by re-dispatching flexible units (i.e., cogeneration units and electric heat pumps). Consumer demand response is a promising solution to achieve power balance in microgrids that include intermittent renewables. Ravindra and Iyer [57] identified a set of decentralized energy options for demand-supply matching within a community, focusing on the Vijayanagar neighbourhood in Bangalore, India. The study pointed out that simultaneous interventions on the supply and demand sides provide the highest benefits for the community, due to the low cost and high reliability. Together with the contribution of active demand-response to the balance of the microgrid, such systems greatly benefit from decentralized smart appliances at single-user level. Arghira et al. [58] proposed two novel day-ahead predictors for the electricity consumption of several residential services. The predictors were shown to be more efficient than previous models (such as the so-called "will always consume", the "will never consume" and the "Auto Regressive Moving Average" predictors), and their use could be very useful to the power management of smart microgrids. A more comprehensive perspective on the planning of smart municipal systems was adopted by Kılkış [59], who proposed an approach to develop net-zero energy districts, also keeping into account the quality (i.e. exergy content) of energy flows. The proposed method was applied to the city of Uppsala and required the implementation of a number of measures such as District Heating and Cooling, Smart Home automations and systems, efficient lighting and appliances, and bioelectricity-driven transport.

Four recent studies have also focused on the potential of smart grids in a specific location, such as small islands, where grid stability is of utmost importance for energy planning. Jantzen et al. [60] analysed both the social and technical sides of the transition towards a fossil fuel-free energy system by 2030 for the Danish island of Samso. The analysis investigated the trade-offs between aspects related to housing, jobs, agriculture, tourism, biomass and energy, leading to recommendations for policy makers to achieve this target. Pfeifer et al. [61] proposed an integrated strategy based on the smart grid concept in order to achieve 100% renewable penetration in islands. Key elements of the strategy were the interconnection within a group of islands, the use of electric vehicles (coupled to smart charging systems, i.e. vehicle-to-grid) as a demand response technology and electricity storage based on either one large central battery or several smaller distributed batteries. A different aspect was analysed by Marczinkowski and Østergaard [62], who compared two approaches, the first based on ensuring self-reliant households and the second on installing centralized/collective technologies at municipal level. The analysis, carried out for the Danish island of Samso, indicated that communal batteries would be preferable from a systems perspective (in terms of reduction of imported electricity and opportunity to create synergies to other sectors by offering the battery's stored electricity to local EV charging stations or to the heating sector), while residential batteries tend to generate higher consumer motivation and involvement in energy system transition. Beccali et al. [63] carried out an on-field analysis of possible retrofit actions for a hotel in Lampedusa island, in order to support the local grid operator in ensuring grid balance. Different energy storage options, as well as automation control technologies, were considered, and their effects on the average daily electric load profile assessed. Among the main findings, installation of PV modules with an optimal sizing of electricity storage reduced the energy demand to the local grid by 61%, while the adoption of Building Automation Control System with LED lighting led to an energy saving of about 30%.

5. Power-to-heat and power-to-fuel technologies

Power-to-heat and power-to-fuel technologies are widely recognized as a set of enabling technologies towards high penetration of renewables. Recent studies focusing on the integration of these technologies into energy systems are reviewed in this section.

5.1 Power-to-heat and the transition from "smart grids" to "smart energy systems"

Increasing the penetration of renewables in the heating sector is a challenge that involves several technological solutions, such as power-to-heat and district heating, but it also opens enormous margins for decarbonisation of industrialized societies. Lund [64] compared two alternative pathways based on the "smart grid" concept, in which electricity represents the only energy carrier, and the "smart energy system" concept, which involves a cross-sectoral use of all grids and infrastructures. With reference to the Danish case, the study highlighted that much larger investments for grid expansion and storage capacities would be required in the "smart grid" than in the "smart energy system" pathway. Smart energy systems can exploit existing infrastructures in the gas and heating sector, facilitating the transition to and reducing the cost of 100% renewable scenarios. Mathiesen et al. [65] showed that a Smart Energy System approach, conveniently merging several sectors such as electricity, heat and transport and including various intra-hour, hourly, daily and seasonal storage options, can significantly contribute to create the flexibility required to integrate a large share of fluctuating renewable energy.

Efforts to quantify the Power-to-Heat (PtH) potential in the European energy system include [66-68]. Yilmaz et al. [66] reviewed the country-level potential for PtH in several countries (i.e. Austria, Denmark, France, Germany, Italy and Netherlands), using a novel quantitative approach to determine this potential and possible business models that enable its exploitation. Bačeković and Østergaard [67] developed and modeled using EnergyPLAN [68] two possible strategies to achieve 100% renewable penetration in the city of Zagreb, the first based on non-integrated energy systems, where each sector is developed independently, and the second based on the smart energy concept, where different sectors (heating, electricity, mobility via smart charging and Vehicle-to-Grid) are linked. The smart energy system with PtH and power-to-transport enabled 49% share of intermittent renewables compared with 20% for non-integrated energy systems. Fitzgerald et al. [69] analyzed the potential of electric water heating to contribute not only to load control and peak shaving, but also as a demand response and grid balancing solution with measurable effects on the wholesale electricity market. The results, obtained for the case study of Ireland, confirmed that an efficient operation of electric water heaters, operated by appropriate algorithms, facilitates the integration of variable wind power in the wholesale electricity market. Gou et al. [70] investigated the optimal planning of capacity and spatial distribution of electric heaters and heat storage devices to reduce wind curtailment in power systems. Using a mixed Integer Linear Programming (MILP) algorithm for cost minimization, the optimal heater/heat storage device distribution cost reduced by approximately 45% compared with uniformly distributed heaters and storage systems. Waite and Modi developed a model [71] to evaluate the effects of coupling large-scale wind power installations with increased use of electric heat pumps for space- and domestic water heating. The method was applied to the State of New York and the results showed that the integrated supply-demand approach significantly contributed to emissions reductions. In a paper by Kirkerud et al. [72] the impact of grid electricity tariffs in terms of promoting or hampering the flexible use of PtH was investigated. The operation of several boilers integrated in a district heating plant was scheduled using a cost minimisation model. The annual share of heating supply by the electric boilers was found to significantly vary (i.e. from 2% to 17%) with the tariff structure, based on which a novel tariff scheme was proposed to increase the profitability of PtH. Sowa et al. [73] analysed the inclusion of PtH systems as controllable loads in virtual power plants with high shares of renewables, owing to the capability of PtH devices to supply flexibility through ancillary services or balancing group operation. The power plants' operating strategies were evaluated with respect to economic and technical performance. Sorknæs [74] proposed a simulation method for a seasonal thermal energy storage system with a heat pump, based on well proven operational conditions of the storage system. This method led to reliable results and could assist the transition of district heating towards lower temperatures and increased cross-sectoral integration. Dominković et al. [75] proposed a model for an integrated urban energy system, that accounted for the interactions between the power, cooling, gas, mobility and water desalination sectors. The analysis focused on tropical regions, characterised by yearly high temperature and humidity conditions, with limited seasonal load fluctuations. A number of energy scenarios were evaluated, comparing alternative options such as district versus individual cooling, with significant reductions in CO_2 emissions and socio-economic costs achieved in the best performing scenario. Another paper by Simeoni et al. [76] investigated the viability of smart multi-energy systems for industrial districts, based on an appropriate mix of renewable sources and efficient technologies including combined cooling, heating and power. An optimization model identifying trade-offs between different objective functions was employed, and the results highlighted the potential of smart energy systems to make industrial districts more sustainable and cost-efficient.

Another aspect widely investigated is the coordinated development of infrastructures in the cross-sectoral use of energy. Kusch et al. [77] proposed a virtual power plant model based on an integrated layout including decentralised CHP systems and heat pumps, as well as heat storages. Future scenarios involving low-energy or passive buildings and high penetration of wind power, were examined. High energy performance building under the passive-house scenario and the consequent dramatic decrease in heat demand resulted to affect the operation of CHP units, influencing their rated electrical output and increasing the electricity purchase from the grid. The new challenges to energy systems operators associated with the interdependency between electric power and natural gas systems, and the heterogenous uncertainties of both these systems with regard to future loads and contribution of renewables, were punctually examined by He et al. [78]. A two-stage robust model was proposed to study day-ahead coordinated optimal scheduling of the power and gas systems, pointing out that dual-fuel units contribute to enhance the secure and economical operation of both systems. From the technological viewpoint, the potential of PtH as a mean to favour the feasibility of low-temperature district heating was examined by Østergaard amd Andersen [79]. The economic viability of a district heating system driven by very low water supply temperature sources, with decentralised booster heat pumps for the production of domestic hot water was evaluated. A threshold capital cost of booster heat pumps to guarantee their viability is calculated, based on economic assessment of the positive effects induced on the operation of the distribution network.

5.2 Power-to-fuel and power-to-chemicals

An alternative approach to provide flexibility to the power system involves converting surplus power into synthetic fuels or chemicals. The concept of power-to-fuel has been recognized as a promising option for smart energy systems. Kouchachvili and Entchev [80] highlighted the capability of Power-to-Gas (PtG) to absorb excess electricity and bridging electricity, gas and heat networks in a Smart Energy system. The feasibilities of either injecting the hydrogen produced into the gas pipeline/storage or use it to produce synthetic methane were compared. García et al. [81] investigated technological aspects of power-to-methane processes based on use of surplus electricity for hydrogen production by electrolysis and subsequent carbon dioxide methanation of hydrogen to obtain methane to be injected into the natural gas network. Different operating conditions for nickel- and alumina-based methanation catalysts were investigated and the optimal ones identified. Ipsakis et al. [82] conducted an experimental campaign to monitor a stand-alone power system based on PV and wind generators and an electrolyser for hydrogen production, to assess the influence of the excess power supplied to the electrolyser and the state of charge of the accumulator on the performance of the integrated system. Krajačić et al. [83] pointed out that computer modelling can efficiently identify optimal energy planning solutions based on integration of renewables and PtG in sites such as small islands, where grid stability issues are critical. Using H2RES software applied to the analysis of several island energy systems (i.e., Porto Santo – Madeira, Corvo, Graciosa and Terrciera – Azores, Sal Island – Capo Verde, Mljet – Croatia and Malta), the feasibility in all the cases of 30% penetration of renewables was confirmed, with potential for 100% penetration to be further investigated for each island. Welder et al. [84] worked on the optimization of future power-to-hydrogen applications in Germany, to reduce the spatial and temporal mismatch between electricity supply and demand that arises from fluctuating renewable electricity generation. Electrolytic hydrogen was assumed to be used for mobility and industrial applications. Another study by Colbertaldo et al. [85] investigated future country-scale energy scenarios, focusing on the role of PtG. A multi-node model was developed, including electrical load from plug-in electric vehicles, energy storage (battery and pumped hydro) and hydrogen production from excess electricity for fuel cell vehicles.

For Italian 2030 and 2050 energy scenarios, up to 57% share of renewable sources in the electricity mix could be achieved. The production of liquid fuels (e.g, synthetic diesel and kerosene) from solar, wind and hydro energy was examined in another paper by Trieb et al. [86]. A preliminary design and performance model was presented for a small-scale power-to-fuel plant with 100 barrels per day capacity. The plant technical and economic performance were found to be very promising, with an efficiency of approximately 50% and a competitive product cost.

An example of alternative solution to use excess electricity in the synthesis of non-fuel chemical products is provided by Ikäheimo et al. [87], who proposed Power-to-Ammonia (PtA) to achieve high shares (up to 100%) of renewables in the power and heat sectors. PtA was shown to contribute significantly to system balancing over both time (energy storage) and space (energy transfer), while producing at a low marginal cost ammonia for use in the fertilizer industry.

6. Sustainable centralised and decentralised heating technologies

Decarbonising the heating sector is one of the main challenges in the undergoing energy transition, and several studies have addressed this topic by assessing the potential for use of waste or excess heat and the possibility to produce heat efficiently in decentralized systems or by centralized plants coupled with district heating networks. A comprehensive study by Hansen et al. [88] in the framework of Heat Roadmap Europe investigated conditions when the cost of heat saving becomes more expensive than the cost of sustainable heat supply, thus making not convenient to invest on heat saving measures. The analysis was carried out for different countries in Europe, assessing their heat saving potential, the associated costs and also socio-economic costs. Differences emerged among the European countries, but as a main conclusion it was found that investments in heat savings could be limited to a certain extent, at a level around 30-50% of projected future heat demands, while the remaining heat can be supplied with sustainable heat sources. A similar problem was analyzed from an energy policy perspective by Späth and Rohracher [89] for a specific case study, the city of Freiburg in Germany, comparing two strategies for the reduction of environmental impacts of space heating, i) the use of efficient cogeneration combined with district heating and ii) the reduction of heat demand by low-energy design and ambitious energy standards for buildings. A recent study by Möller et al. [90], produced in the framework of the aforementioned Heat Roadmap Europe, presented version 4 of the Pan-European Thermal Atlas, which spatially disaggregates national demand data to high-resolution geospatial data on urban structures. The results are extremely useful for post-processing aimed at grouping areas into prospective supply zones, outlining supply curves for these zones and calculating local energy mixes on the basis of eventual excess heat or RES. Ben Amer et al. [91] analyzed the cost-optimal mix between district heating, individual heating and heat savings for the small Danish municipality of Helsingør. Results for 2030 and 2050 energy scenarios indicate a convenience in implementing heat saving measures to reduce the demand by 20-39% and to deploy a gradually increasing share of district heating, ranging between

32% and 44%. Zivkovic et al. [92] explored potential future scenarios of the heating sector in the city of Niš (Serbia), resulting from a participatory strategic planning process involving local stakeholders. Substantial improvements in energy efficiency and security by 2030 were demonstrated to be achievable through a so-called "Efficiency for the green future" scenario including high standards for low-energy buildings, increased share of renewables in the heating energy mix, expansion of district heating system and use of smart technologies and green architecture. Babak et al. [93] examined the possibility of using heat pumps (HPs) in hot water supply systems, developing a novel design for the heat module, with heating water of the in-house circuit of the building heating system being used as a heat source for the HP. Popovski et al. [94] compared different technological solutions for sustainable heat and cold supply for the city of Matosinhos (Portugal). The results showed that the use of excess heat from a refinery to be distributed via a DH network represents the most economically attractive option, with a second most promising scenario including heat pump systems combined with photovoltaics. Finally, Dehghan and Pfeiffer [95] investigated a sustainable heating system for a passive solar building in Norway. The building was able to store heat using phase change materials. The results of simulations indicated that the solar heating system would be efficient in winter even in sites characterised by cold climates.

One key requirement to enable sustainable heating using waste or excess heat and by efficient or renewable sources is the capability to distribute the heat from centralized suppliers toward the distributed consumers. Increasing efforts have been invested by researchers in studying the performance of DH systems and improving their efficiency and viability. In the next subsection recent papers on this topic are reviewed.

6.1 District heating networks

In Europe research interest and investment in district heating is increasing, as discussed by Sayegh et al. [96]. The authors reviewed recent activities in the field and observed that DH is expected to further develop if additional flexibility is achieved by increasing the contribution of renewable sources and the participation of dynamic prosumers. Coupling DH with efficient technologies such as cogeneration or RES is a promising solution towards the decarbonisation of the heating sector. A study by Soltero et al. [97] proposed a method for assessing the potential of cogeneration-based DH at regional level, based on the regulatory framework, the available resources, the existing infrastructures, and the demand. The method, applied to the Spanish continental area, identified a potential of over 3000 MW of high efficiency distributed power. Lončar and Ridjan [98] assessed the potential of biomass and natural gas fired district heating cogeneration plants for a midsize town in Croatia, based on the features of local energy market and accounting for the possible financing barriers and the need for adequate public involvement. With regard to DH with renewables, Felipe Andreu et al. [99] analyzed the integration of a Centralized Solar heating plant with seasonal storage into the district heating system of Velika Gorica, which currently supplies 32% of total heat demand in the city. The economic and environmental assessments were performed for either pessimistic or optimistic scenarios that led to different design solutions, but in all cases a solar heat cost lower than the current cost of heat on the district network was achieved. Østergaard and Lund [100] investigated the possibility of integrating locally available renewable resources to supply the DH network serving the Danish city of Frederikshavn. The focus was on the integration of geothermal energy, and the analyses performed on an aggregate annual basis as well as on a hourly basis confirmed the high potential benefits for exploiting this source in combination with absorption heat pumps. Verda et al. [101] proposed a procedure to identify, within a DH network, possible users that could be supplied by geothermal heat pumps and others that should be eventually served by alternative technologies, in order to limit, in urban areas, the subsurface thermal degradation caused by heat pumps which could negatively affect the performance of surrounding installations. Tomić et al. [102] presented a viability assessment for the use of biomass and municipal solid waste to fuel the district heating plants serving the city of Zagreb. The results indicate that a large waste powered plant can be profitable if coordinated with a regional waste management planning and co-combusting waste imported from surrounding counties. A paper by Rämäa and Wahlroos [103] discussed the potential benefits from introducing a renewable energy supply system (based on solar collectors) in an existing DH network currently supplied by CHP plants, boilers and large-scale heat pumps, also examining the positive effects of lowering the distribution temperatures. The EnergyPro modelling tool was used and the results indicate that solar thermal is not profitable when the network operates at normal temperature, but it could be favoured at lower temperatures; also, the share of heat supply from CHP is expected to gradually decrease until 2030, being replaced by a higher contribution from heat pumps that are currently more profitable. A performance analysis of a hybrid DH system serving a small town in Croatia was proposed by Mikulandrić et al. [104], who analyzed several possible energy sources and performed a cost-oriented optimization. The results indicated that renewable energy based district heating systems could reduce the heat production costs up to 30% compared with the most efficient technologies based on conventional fuels. A recent paper by Hoyo Arce et al. [105] described an approach for efficient dynamic modelling of district heating and cooling networks, developed in the framework of an European project. A Modelica® library comprising detailed and validated models of the distribution and consumption components commonly included in DH systems was developed, also adding special features such as the possibility to decouple mass flow rates and temperatures without losing accuracy in the distribution pipe model. The potential of district heating to contribute to sustainable heating has been investigated in several large and small towns, also performing comparative studies to verify the asymmetries in design and operation results due to specific local conditions. Čulig-Tokić et al. [106] proposed a comparison between the district heating systems in Zagreb and Aalborg. The study pointed out that the system in Aalborg is more advanced in several aspects related to supply, demand, distribution and economics. A roadmap of possible urgent interventions for Zagreb was provided, which include lowering specific heat and water losses, systematically replacing old pipes of the network and limiting the hot water temperature well below its current values. A paper by Hast et al. [107] investigated possible scenarios at 2050 for district heat production in the Helsinki region, in Warsaw and in Kaunas. Increased use of biomass, wastes, geothermal and waste heat resulted as the most promising solutions (to be eventually coupled with energy efficiency measures, carbon capture and storage technologies), leading to CO_2 emissions reduction ranging between 75% and 90%. Another study by Dominković et al. [108] investigated the influence of different technologies on dynamic pricing in DH systems. Two case studies are considered, the towns of Sønderborg (Denmark) and Espoo (Finland), pointing out that dynamic pricing (possibly resulting from innovative ownership schemes where heat supplying plants and DH networks are operated by two different operators) could foster third party access to deliver excess heat to the network. In a study by Ashfaq and Ianakiev [109] the cost-minimized design of a heating network including large-scale heat pump and heat storage was proposed, based on real hourly heat loads for the city of Aarhus, Denmark. The analysis showed that 100% decarbonisation of the heating sector is possible, based on a wind and solar power generation mix of 85% and a renewable energy penetration of 100%.

Other specific aspects related to DH systems design and operation or degradation of performance have been examined in the last few years. Nielsen and Möller [110] analysed how excess heat production from solar thermal collectors in Net Zero Energy Buildings could influence the operation of different types of DH systems, providing a technical assessment for three technological solutions. The inclusion of solar thermal resulted to be beneficial to the DH system, reducing the amount of conventional fuel or biomass consumed in the centralized generation unit, unless there are large amounts of waste heat are available. Integration of district heating with the “ring network” technology (where each user is assumed to have “equal pipe lengths” in the network) and plate heat exchangers in consumer substation was analyzed by Kuosa et al. [111], who developed a control model optimizing the mass flow in the primary and secondary hot water distribution circuits to achieve higher temperature reduction with diminished pressure losses. Fouling-induced degradation of heat exchanger performance in DH systems’ sub-stations results in increased maintenance costs, and its prediction is generally hampered by the lack of robust physical models. Genić et al. [112]. experimentally characterised the fouling factors in eight plate heat exchangers of Belgrade’s DH system sub-stations after one year of service, to assist the future modeling and design of DH heat exchangers. An average fouling resistance was derived for radiator water circuits, while a predictive wall shear stress-resistance correlation was proposed for Domestic Hot Water (DHW) heaters.

7. Energy savings in the building sector

A second pillar in the routes towards sustainability, besides the above discussed solutions for an increased share of renewables in power and heating supply, consists of reducing the demand through increased efficiency and improved design of energy-consuming structures and appliances. As buildings energy use accounts for over 40% of total primary energy consumption in the U.S. and E.U. [113], large efforts have been devoted to the design and implementation of innovative solutions for low-energy buildings. Ó Broin et al. [114] proposed a bottom-up modelling to quantify the impact of energy efficiency on the EU building stock up to 2050, under three different scenarios. The analysis was performed in details for 8 European countries, and the results indicate that the final energy demand can be reduced by 50% compared to 2005 levels if efficiency improves by over 2% per annum. Energy performance assessment is a very crucial point to support the spread of sustainable design and management of buildings. Herrando et al. [115] proposed a systematic method to assess the Energy Performance Certification of buildings and applied the method to 21 Faculty Buildings at the University of Zaragoza (Spain). The study moves from a critical review of the state-of-art in energy certification of buildings, and the proposed method addresses the main critical points, achieving estimated energy consumptions in very good agreement with the actual ones. A paper by Lizana et al. [116] proposed a novel energy modelling procedure to assess the energy performance of school buildings based on a limited number of input data to be collected. The method, which is integrated into a tool that allows the analyst to perform hourly dynamic simulation with a reduced set of inputs, was successfully applied to two pilot schools, achieving very high accuracy levels through a simple calibration against energy bills. Several technological solutions have been analysed to reduce energy demand in buildings. Gil-Baez et at. [117] analyzed the potential of natural ventilation systems in warm regions, as a viable alternative to maintain indoor comfort conditions in nearly Zero Energy Buildings. Experimental campaigns conducted in two school buildings in southern Spain confirmed that the natural ventilation reduces energy use over the academic year, even accounting for the heat losses in the winter period. In another paper by the same authors [118], energy efficient solutions for the renovation of school buildings were examined, focusing on a set of affordable passive refurbishment actions (based on insulation, shading and glazing) to improve the building envelope. The results showed a high potential for energy performance improvement, with savings above 15% both for space heating and cooling.

Charde et al. [119] compared the performance of static sunshare and brick cavity wall to reduce the energy consumption in buildings located in sites with highly variable climatic conditions. The experimental campaign indicated that static sunshade ensures relevant heat gains, and consequent raise in Indoor Air Temperature (IAT) in winter, while the brick cavity wall is efficient in lowering IAT in summer, thus being the installation of both measures highly beneficial in sites with cold winter and hot summer conditions. A paper by Beccali et al. [120] proposed an artificial neural network-based method to optimize the position of photosensors in Daylight Linked Control systems and verify their performance in terms of indoor illuminance on work-planes. The proposed technique revealed an efficient instrument to design artificial lighting systems that simultaneously guarantee appropriate illuminance and high energy efficiency, in agreement with technical standards. Dubovsky et al. [121] investigated the performance of phase-change paraffin wax, stored under the floor of a building located in a subtropical climate region, as a heat source in winter. The wax was supposed to be heated up to its complete melting in night hours consuming off-peak electricity, and to release its latent heat during the day. Two different heat gain rates through the window were considered, and the results indicated the potential for a 20% reduction in electricity consumption. Another attractive solution to lower energy consumption in buildings is based on extended use of automation. In a study by Marinakis et al. [122] an integrated building automation system which includes remote control technology to enable real-time monitoring and optimization functions was presented. The proposed prototype software tool was proven to ensure enhanced interactivity of the automation systems and to guarantee achievement of energy efficiency requirements of the incorporated EN 15232 and ISO 50001 Energy Management Standards. Finally, in a study by Rödder et al. [123] a novel residential system design based on thermal interconnection between the heating systems and domestic appliances such as washing machines, dishwashers, dryers, refrigerators and freezers was proposed. This connection, namely “energiBUS”, was simulated for a four-person family home in a passive house and guarantees a relevant reduction in annual electricity consumption.

8. Energy savings through efficient multi-generation technologies and waste heat utilisation

Two technologies widely recognized as very promising solutions for an efficient use of energy resources are reviewed in this section:

– Integrated multi-generation systems, either operating in co-, tri- and poly-generation, as opposed to separate production of the same energy/material products
– Industrial waste heat utilization for on-site heating/cooling or power applications or DH.

8.1 Advances on integrated multi-generation systems

The combined production of multiple outputs (i.e., power, heating, cooling, chemicals, and desalinated water) using either fossil or renewable energy can contribute significant energy savings and associated reductions in environmental emissions. Several recent studies have investigated the use of co- and polygeneration schemes for small islands not connected to the main grid, where secure and cost-efficient supply of energy is critical. Beccali et al. [124] analyzed the viability of CHP retrofit for diesel engines-based power plants operating in several small islands in Italy. The size, orography, population, touristic fluxes and climatic conditions of the island were found to largely influence the economics of investments required for a district heating and/or cooling network, with large islands with populations above 3000-4000 inhabitants being the most suitable. Calise et al. [125] presented a thermoeconomic analysis of a novel hybrid renewable polygeneration system powered by solar Parabolic Through Collectors (PTCs) and geothermal sources with fossil fuel backup boilers. The proposed system was designed to supply the Island of Pantelleria (Italy) with electricity, desalinated water and heat and cooling energy to be distributed via small-scale district heating and cooling networks. Based on one-year dynamic simulation, the investment payback time was estimated at 8.5 years. Another application of integrated systems was proposed by Buonomano et al. [126] and is here presented, although it is not actually focused on a multi-generation plant but rather on a hybrid scheme that simultaneously exploits multiple renewable sources (in particular, wind and solar energy) integrated with battery storage to serve a tourist centre, hotel and offices. Based on a thermoeconomic hourly simulation model developed in TRNSYS environment [127], the system was found to be economically feasible at the current cost of technologies only for users having a stable energy demand. Thermal desalination systems require very low-grade heat as input that can be supplied by an efficient cogeneration system, instead of conventional fossil fuel boilers. Catrini et al. [128] performed an exergy analysis and thermoeconomic cost accounting of a CHP steam cycle integrated with a Multiple Effect Distillation (MED) and Thermal Vapor Compression (MED-TVC) desalination plant. The recovery of brine exergy for power production via reverse electrodialysis was also investigated. The electricity and desalinated water production costs were estimated at 78 €/MWh and 1.3 €/m^3, respectively, which are promising results for sites with severe water scarcity. Baccioli et al. [129] undertook a thermodynamic and economic analysis of a waste heat driven Organic Rankine Cycle (ORC) integrated with a small-scale MED plant. Assuming to supply excess heat available at 200°C, the ORC-MED exergy efficiency was found to be very sensitive to the size of the MED unit for a "serial-hybrid" configuration (between the ORC and the MED sections), but weakly sensitive to the same parameter for a "cascade" plant configuration. A profitability index as high as 2.4 was obtained in the most convenient scenarios. Katsaros et al. [130] investigated a novel trigeneration system based on the gasification of municipal solid wastes, a solid oxide fuel cell and a single-stage water ammonia absorption chiller to produce power, heating and cooling. A sensitivity analysis was performed, identifying optimal air equivalent ratios and gasification temperatures and achieving a 4.5 years payback period. Bogdan and Kopjar [131] investigated the use of district heat storage to reduce the annual energy consumption, cost and emissions of the Elektrana-Toplana Zagreb cogeneration plant. Using an optimized operation strategy (i.e., charging the accumulator during peak-hours and discharging it by supplying the DH network during night hours), annual savings of 1.8 M€ could be achieved with 23,000 tCO_2 emissions avoided .

The viability of multi-generation schemes is influenced by energy prices, subsidies or support mechanisms, and other context conditions. Angrisani et al. [132] assessed the performance of small-scale cogeneration and trigeneration systems for applications in residential and tertiary sectors, in terms of primary energy savings, greenhouse gas emissions reductions and economic viability. Novel indices were also introduced, based on a critical review of well-established assessment criteria. The study concluded that a thermo-economic analysis of polygeneration systems with reference benchmark scenarios allows the analyst to correctly assess the benefits achieved by an installation. Kavvadias [133] carried out a survey at European level in order to assess the role that the "energy price spread" (i.e. an original indicator based on the ratio of electricity to fuel prices) can play in facilitating or hampering the implementation of cogeneration in a national or regional market. Based on the energy price spread, the operational profitability of cogeneration systems can be mapped, and empirical rules were provided to estimate the effects of energy prices on the profitability of investments. Finally, Mancarella et al. [134] discussed arbitrage opportunities for distributed multi-energy systems, highlighting that the flexibility in varying the power request from the grid (based on appropriate operation of the multi-generation unit) could be used to provide ancillary services, while guaranteeing the supply of end-use energy demand. Profitability maps were presented, to identify shifting strategies between different energy vectors (namely, heating, cooling and power) and components (cogeneration unit, boiler, heat pump, etc.) that maximise the profit of ancillary services.

8.2 Waste heat utilisation

Waste or excess heat recovery represents a very promising solution for the decarbonisation of heating sector. Significant waste heat potential exists in the industrial sector (as estimated in Ref. [135] in European industries), the utilisation of which could contribute significant energy savings in heating/cooling or power applications. Industrial heat is typically rejected from a number of streams at different grades, which poses technical and economic challenges. Heat (including waste or excess heat) distribution via DH networks was discussed in Section 6.1; in this section additional approaches investigated for on- or off-site exploitation of industrial waste heat are reviewed. Varga and Palotai [136] compared waste heat-driven ORC and Kalina power cycles (both using cooling water as a heat sink), as possible alternatives to the use of conventional dissipative air or water coolers for cooling low temperature streams ($T<150°C$). The Kalina system achieved higher efficiency and CO_2 emission reductions, at the most advantageous process conditions, while the investment payback time was of order five years in both cases. Somogyi et al. [137] investigated the heat recovery potential from wastewater entering the treatment facilities, and its use to supply district heating and reduce heat pollution. The analysis focused on the feasibility of hot water distribution from the wastewater treatment plant to potential users in the vicinity of the plant. Under the assumptions made, only a low fraction of the examined investments resulted viable, achieving payback time below 10 years. In the glass industry, Dolianitis et al. [138] investigated a solution for waste heat recovery from exhaust gases from the glass furnace for batch and cullet preheating. A 3-D computational model was used to simulate the process and identify optimal heat recovery system design configurations, which minimise process energy consumption (with energy savings of 12-15% compared to the base case with no heat recovery) and CO_2 emissions. Moser et al. [139] examined the feasibility of seasonal heat storage of industrial waste heat (mainly from steelmaking, chemical and paper industry), mostly available in summer months, to supply heating in winter for the city of Linz (Austria). The number of annual cycles was found to be a crucial parameter, with payback periods highly sensitive to electricity, gas and CO_2 prices, but approximately equal to 20 years. Waste heat recovery in water treatment and sewage sludge processing was also investigated in Refs [140-142]. Tańczuk et al. [140] analyzed the recovery of process waste heat from a digested sewage sludge medium-temperature belt dryer. The air-air waste heat recovery exchanger was optimized, based on annual simulation of operating conditions and maximization of the net present value. Montorsi presented an economic assessment of a waste to energy system in an urban sewage treatment plant [141]. The integrated anaerobic digestion and gasification system converted residues from the plant to bio-fuels for use in a CHP unit. The final wastes to landfill were decreased by 73%, with up to 25% of the plant electricity demand by the covered by waste and a payback time of approximately three years. Kollmann et al. [142] addressed the practical aspects of exploiting the heat generation potential of wastewater treatment plants to produce electricity for the public distribution grid through a CHP unit fueled by sewage gas. Geographical

Information Systems to map the future energy demands and Process Network Synthesis were used for economic optimization. The results indicate that spatial analysis including estimation of heat demand allows for reliable feasibility studies and, in the examined case, the economic optimisation provided evidence that heat generation from wastewater can be achieved at competitive costs.

9. Measurement of energo-environmental sustainability of processes and systems

It is needless saying that research activities on sustainability of the energy sector must cover not only the technological and socio-economical aspects, but also the rational of metrics needed to properly assess the impacts. Scarpellini et al. [143] proposed a multi-criteria analysis for the assessment of sustainable energy innovations in the transport sector. Their approach was based on saving-investment curves, and aimed at capturing key economic, social and environmental factors used by public and private investors. The proposed method revealed efficient in hierarchizing possible sustainability improvement actions and in identifying priorities in the transport sector (where bikes and buses were identified as most attractive means of transport, depending on the assumed target). Buceti [144] formulated a power density-based metric to assess the sustainability of renewable power generation systems and compare it with those of conventional fossil fueled plants. A unique parameter was proposed, capable of reflecting pros and cons of all energy options into a single graphical instrument, intended to support decision-making in energy policies. Blanco-Marigorta et al. [145] presented a component-level exergo-environmental analysis of a reverse osmosis desalination plant in Gran Canaria (Spain), comparing different plant configurations in terms of energy recovery, number of reverse osmosis stages, filtration technology and feed water pressure. Their analysis combining the exergy and life cycle assessments, permitted the environmental impacts associated with operational exergy destruction and other phases of the plant life cycle to be determined. Exergy destruction was found to have the largest environmental impact. Usón et al. [146] performed a thermoecological evaluation of a trigeneration engine to calculate the ThermoEcological Cost (TEC) of the products. This method allows a rational allocation of cost related to exergy destruction and external impacts to the individual material flows, and permitsthe cost of the products to be compared for different trigeneration scenarios with regard to the consumed fuel and its origin. Rocco et al. [147] proposed a theoretical reassessment of the Extended Exergy Accounting method, which is an exergy-based procedure to evaluate the total equivalent primary resource consumption in a system, accounting also for the consumption of “non exergetic” resources and externalities such as human labour, capital and environmental remediation, on the basis of well defined principles and postulates. Catrini et al. [148] proposed a combined use of Thermoeconomics and Life Cycle Assessment to provide a comprehensive view of all the individual impacts of energy systems, disaggregated by type of impact and by life cycle phase that contributes to generate the individual impact. This approach was applied to the design optimization of a water-cooled rooftop air conditioning unit, allowing to detect trade-offs between concurring effects of design variables on specific environmental impacts. Finally, Zvingilaite [149] proposed a novel approach to incorporate local externalities in energy system modelling, when reducing the impacts of energy use-related air pollution on human health is sought. The method was applied to the Danish heat and power sector and confirmed that it is less expensive for society to include externalities during the planning phase of an energy system, than to subsequently pay ex-post for the effects of induced damages.

10. Conclusions

In the present review paper some recent scientific contributions focused on sustainability of energy supply and utilisation were analyzed, with a particular attention paid to the articles presented in Conferences on Sustainable Development of Energy, Water and Environment (SDEWES). Due to the broad and multi-faceted scope of the SDEWES Conference Series towards the sustainable and efficient use of energy resources, a variety of topics was examined, covering the regional and supranational planning of energy supply and demand, increase in share of renewables for sustainable electricity and heating provision, smart grids and energy systems, cross-sectoral interactions, power-to-heat and power-to-fuel technologies, low-energy buildings, efficient integration of components into co-, tri- or polygeneration schemes, waste/excess heat utilization, and methodologies to assess energo-environmental sustainability. As discussed in this paper, the extensive body of work published in the above areas has led to significant progress in the more sustainable use of energy resources, at technology development to implementation level, with measurable outcomes. These achievements are among other factors the result of effective cooperations between researchers combining different areas of expertise. In fact, the analysis let clearly emerge how different levels of investigation are actually interconnected. As an example, it was shown that the goal of increasing the share of electricity supply from renewable sources may be achieved by implementing a number of different measures, related with energy policy actions, use of power-to-heat technologies eventually coupled to district heating, energy storage (under different forms) and flexible electric demand management, also involving other spheres such as societal impacts and involvement. Then, future research activities addressing the still-existing research gaps in these fields would highly benefit of such cross-sectorial fertilization within the scientific community, and future SDEWES Conferences can be expected to give a contribution in this direction.

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