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From single to multi-energy and hybrid grids: Historic growth and future vision

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ABSTRACT

Interactions between different energy carriers (electricity, heat and gas) are considered beneficial for using renewable energy and reducing carbon emissions in the energy system. Nevertheless, the establishment of such hybrid grids or systems, also called multi-, integrated or smart energy systems, remains relatively unexplored. The concept is characterised by great complexity, questioning the common isolated view of energy grids. This paper analyses the changing requirements from historically grown, isolated energy grids towards renewable hybrid energy systems and the associated potential and challenges.

A hybrid grid offers alternative use options, which make energy production and consumption more flexible. No peer-reviewed research provides quantitative analysis on the expected utilisation of the electricity, gas and thermal grid in a hybrid grids scenario. However, the traditional grids will compete among each other and increasingly with distributed power generation and consumption by prosumers. In addition, a reversal and reduction of the gas grid and possible new structures of a hydrogen network have to be considered. To achieve the desired savings in energy demand and carbon emissions while maintaining the security of supply and economic feasibility in hybrid energy systems, appropriate technologies, infrastructure financing, integrated system planning based on the relevant data and supportive market frameworks are required.

1. Introduction

The ambitious targets concerning the decarbonisation of electricity recently defined by the European Commission lead to a steep increase in the capacities of variable renewable energy (VRE) sources (wind and solar power) in Europe. Between 1997 and 2018, the share of power generation from 'new' renewables, excluding hydro power, grew from less than 1 % to about 22 %. Initially, this was mainly triggered by wind power, while during the last few years, the installed capacity of photovoltaics (PV) has increased significantly. According to the European climate and energy framework, one of the targets for 2030 is to achieve at least a 32 % renewable energy source (RES) share in total energy consumption [1]. This target is valid across all sectors (i.e. heat, electricity and transport), leading to an increase in electricity generation from RESs, as stated in the National Renewable Energy Action Plans (NREAPs). Similar goals and approaches are defined all over the world, striving for carbon neutrality. However, several studies show that this will cause frequent situations in which electricity generation exceeds demand. The awareness of the fact that interactions between the different energy carriers (e.g. heating/cooling, electricity and gas) may be beneficial for further integration of renewable energy, a decrease in carbon dioxide (CO2) emissions, and an increase in energy efficiency through additional flexibility options, is growing [2]. Mancarella [3] defined such an approach as a multi-energy system (MES). Still, similar methods may also be found in the literature as smart, integrated or hybrid energy systems with the same objectives. MESs align the operation of electricity, heating, cooling, transport fuels, etc., on all possible levels of aggregation, aiming at an increase in renewable energy shares. In our research, we will always refer to this concept as hybrid grid or system. The main goal of hybrid grids is to improve system efficiency and reduce carbon emissions by providing sufficient flexibility to adapt loads to the volatility and generation behaviour of RESs. Connolly et al. [4] highlight the challenge of flexibility in future energy systems.

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Abbreviations

a	anno
AC	alternating current
ASEAN	Association of Southeast Asian Nations
ASG	Asia Super Grid
C(C)HP	combined (cooling) heat and power
DC	direct current
DSM	demand-side management
DH	district heating
EJ	exajoule
ENTSO-E	European Network of Transmission System Operators for Electricity
EV	electric vehicle
GW	gigawatt
CO_2	carbon dioxide
HVAC	heating, ventilation and air conditioning
ICT	information and communication technologies
IoT	internet of things
IES	integrated energy system
IH	individual heat
km	kilometre
kWh	kilowatt hour
kV	kilovolt
LNG	liquefied natural gas
m^3	cubic metre
MES	multi-energy system
MECM	multiple energy carrier micro-grid
MW	megawatt
NREAP	National Renewable Energy Action Plan
P2X	power-to-X
P2G	power-to-gas
P2H	power-to-heat
P2L	power-to-liquid
PJ	petajoule
PV	photovoltaics
RES	renewable energy source
SC	sector coupling
S(M)ES	smart (multi-)energy system
TWh	terawatt hour
VRE	variable renewable energy

Whereas currently, the flexibility provided in the energy system is primarily based on energy stored in fossil fuels, future renewable systems need to generate affordable energy while utilizing sustainable resources. This situation can only be solved by detecting new forms of flexibility that support the efficient use of RESs within a smart energy system (SES) [4].

A major target of hybrid energy systems is to enhance the technical and economic system efficiency from an energetic and economic point of view. An example would be the transformation of excess electricity into heat and injection into a district heating (DH) grid. Additionally, cooling is gaining importance and research on the efficient use of thermal grids for heating and cooling purposes is growing. Nevertheless, such solutions require appropriate incentives within market structures to achieve an attractive business case. Currently, these scenarios can only be imagined from an energy planning perspective or realisation within the regulatory framework of natural monopolies for the sake of security of supply. They are not realistic to be implemented within the existing market environment. The transformation of electricity into hydrogen (H_2) or methane (CH_4) in hybrid energy systems is promising for feed-in to the natural gas grid. Gas is also considered a more favourable large-scale energy storage option than electricity. However, the technically possible share of hydrogen feed-in varies locally and may bear the risk of accidents. Therefore, even a separate hydrogen infrastructure could exist in the future, specifically designed to promote green hydrogen. Theoretically, H_2 could also be re-electrified during low availability of RESs or used as fuel or product component in industry or transport. These various options of interaction between existing and new infrastructure and technologies add essential flexibility to future renewable energy systems and require further research on a technical, strategic and economic level.

This paper analyses the changing requirements from historically grown, isolated energy grids towards renewable hybrid energy systems and the associated potential and challenges. The challenges related to integrating growing shares of renewable energy sources are detected, and the capability to address them using hybrid grids is evaluated. This work investigates the historical development and state of the art of energy grids, current ideas on how to provide flexibility in a system of increasing shares of large-scale VRE sources, the combined production of different energy carriers, such as heat and electricity, and the integration of grids by transformation technologies. The paper on hand starts with a review on the historical development of individual energy grids towards state of the art in Section 2.1, covering the gas, electricity and thermal grid. Section 2.2 continues with a literature review on hybrid grid concepts to integrate these energy grids as a new way of thinking before applications and enablers of hybrid energy systems are described in Section 2.3. Finally, Section 3 discusses a vision of future hybrid energy grids, the role of sector coupling within this approach, and remaining challenges for a successful implementation of the concept.

2. The path towards modern hybrid energy systems

Energy grids historically have grown separately as the gas, electricity and thermal grid. They have been subject to vast development from the first detection of gas in China, the first electric power plants in the mid-nineteenth century in Europe and the first heating applications already in ancient Rome. Rising energy demand due to growing populations and economic growth, and associated greenhouse gas emissions require more efficient and sustainable use of natural resources—a global goal for climate change mitigation. The increasing share of RESs and their natural intermittency impose new challenges on global energy systems.

The climate goals implemented by the EU and the national goals for greenhouse gas reduction demand a transformation from fossil to renewable fuels in the electricity, transport, industry, residential and trade/services sectors. Currently, about two-thirds of the final energy consumption is covered by fossil energy carriers in the transport, heating/cooling and electricity systems ([5,6]). The roadmap towards more RESs might also change the role of these systems in the future. In 2015, 28 % of the global energy consumption were grid-related, including DH, electricity, and natural gas consumption (see Fig. 1). 72 % was non-grid-related or individual energy consumption, representing the consumption of transport fuel, individual heat pumps, oil and biogas heating, etc. ([7,8]). Half of the grid-related part was distributed through the electricity network, 41 % through the gas network, and 9 % through DH or thermal networks (see Fig. 2). Especially the fossil fuel-based, individual energy sources in heating and transport imply a vast potential for decarbonisation. They will be replaced by electricity in various new applications and increased renewable DH. Fig. 3 shows that the DH share of global heat consumption accounted for 58 % and grid-related heating, including individual gas, for 84 % [9]. The remaining 16 % consisted of other individual heating technologies. In 2015, 94 % of the transport sector were powered by fossil fuels, and its

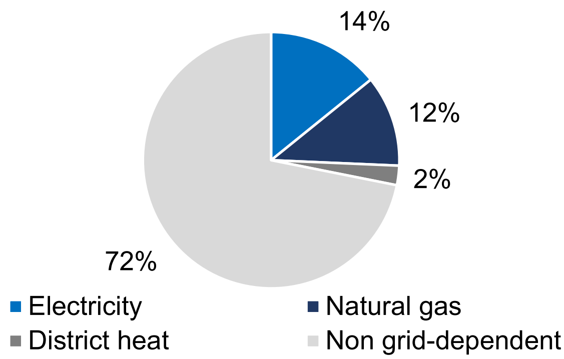

Fig. 1. Distribution between global grid-dependent and individual energy consumption 2015 (Source [7,8]).

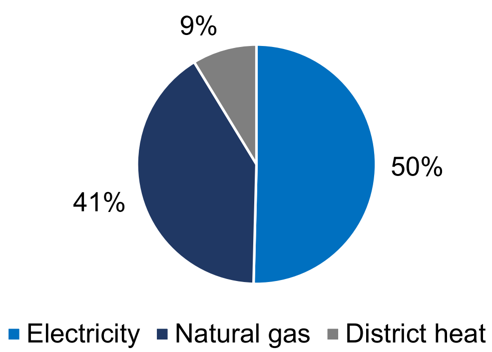

Fig. 2. Distribution between global grid-dependent final energy consumption 2015 (Source [7,8]).

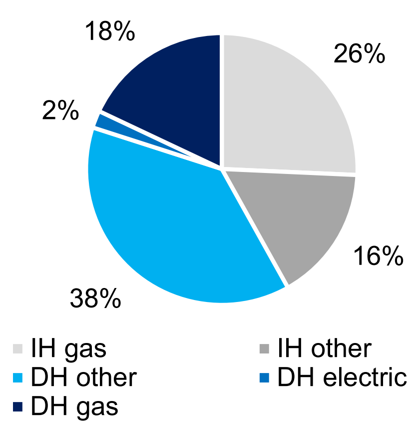

Fig. 3. Distribution between global district heating (DH) and individual heating (IH) 2015 (Source [9]).

grid-related share of electricity will increase from 3 % in 2015 to a substantial amount in 2050 (see Fig. 4).

Supplying more processes with the appropriate form of RESs is a great challenge due to the historically grown infrastructure and market environment. A change in this field requires investments to support the rise of new technologies and new ways of thinking. This section describes the path from historical to modern energy systems and the changing requirements in a renewable energy future.

2.1. *Energy grids: from history to the state of the art*

2.1.1. *Gas grid*

When natural gas first rose from the ground unintendedly and ignited, it was referred to as an 'eternal flame' and considered a religious symbol. The Chinese were the first to recognise natural gas while drilling for brine around 500 BC [10]. The first mention of an actual 'gas grid' in China can be dated back more than 150 years. Not until the mid-nineteenth century did the western world discover how to obtain and excavate natural gas [11]. London was leading Europe around 1812 by setting up the National Light and Heat Company among the first gas enterprises in the western world [12]. The first US gas pipeline was established in 1883, followed by projects, such as the 200-km natural gas pipeline from central Indiana to the city of Chicago in 1891 ([11,13]). Many thousand kilometres were constructed worldwide during the post-war pipeline construction boom until the 1960s. Nevertheless, natural gas had still not been used for electricity generation for a long time [14].

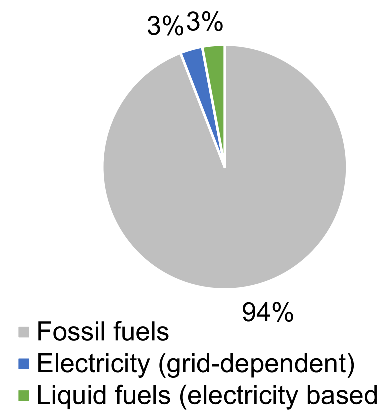

Fig. 4. Distribution between global renewable and fossil fuels and grid-dependent electricity in transport 2015 (Source [9]).

During the twentieth century, petroleum oil and natural gas represented the primary fuels after the golden age of coal (see Fig. 5). The step-wise substitution of oil and coal led to greater diversity in energy supply sources from 1960 onwards. Today, natural gas is regarded as a more environmentally friendly or 'greener' alternative to coal due to its clean-burning characteristics and its suitability for heating and power generation ([13,15]). The US and China are the two major natural gas utilities, accounting for more than half of the global gas generation, followed by the Middle East and Russia [16]. Although gas pipelines still are the common means of transporting natural gas, considering the International Gas Union's report from 2019, LNG had a share in global gas consumption of 10.7 % in 2017, with Qatar leading in export far ahead of Australia, Malaysia, Nigeria and Indonesia. The amount of global LNG increased by 9.8 %–316.5 million tonnes by 2018 [17].

The global gas supply was and still is thriving, with global natural gas production hitting an all-time high of 3.867 billion m^3 in 2018, including natural gas produced for gas-to-liquid transformation [18]. Today, the European gas network spans from Russia to Spain, supplying almost all Western European countries. Approximately 87 % of the European gas consumption is distributed via the gas grid, of which Russia makes up about 40 % and Norway 27 % [18]. About 12 % of European gas consumption is covered by liquefied natural gas (LNG). Despite the fundamental role of gas in the electricity, industry and heating and cooling sector, the strong dependency on few supplying countries and the rising awareness of climate change have led to controversial discussions about gas supply. Global pipeline lengths are difficult to obtain as not all countries disclose statistics on their natural gas networks. According to the CIA World Factbook, the USA owns the most extensive natural gas pipeline system with a total length of roughly 1.6 million km, followed by Russia with 160,000 km and China with 100,000 km. A distance of about 27,000 km is declared for long-distance transmission and distribution. Nevertheless, the lower pressure systems, for which no international database could be identified, substantially increase these numbers, as can be seen in the case of Germany, where the total gas

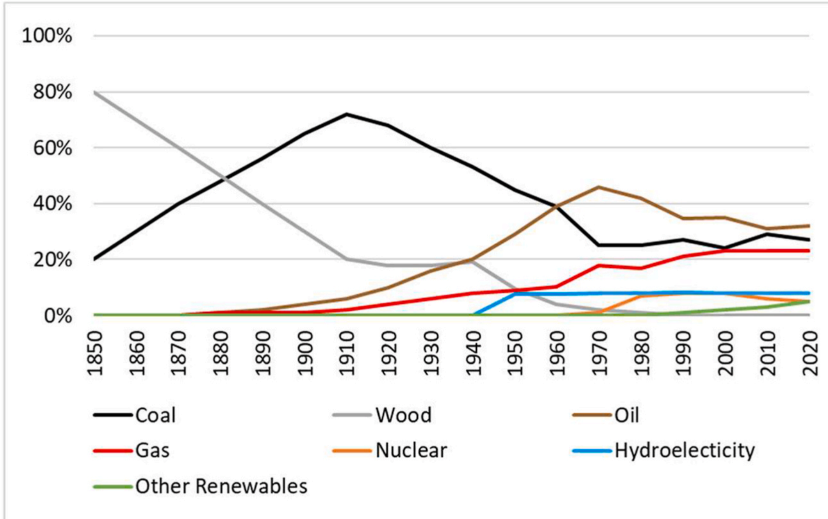

Fig. 5. Global primary energy market shares (Sources [11,18,19]).

network length reaches 0.5 million km ([20,21]).

The favourable storage characteristics of gas also represent a chance for the large-scale integration of VRE in the form of wind and solar PV electricity. The seasonal availability of solar electricity leads to substantial energy supply peaks in summer and shortages in winter. Transformation possibilities from electricity into renewable gas enable seasonal storage and integrate the electricity and gas sectors—an important requirement in renewable energy systems (see Section 3.2). The number and volume of globally existing underground gas storages are displayed in Fig. 6. The largest storage capacities can be found in the USA, where the total design capacity reaches 133 billion m^3 in approximately 400 active underground storages [22].

As a renewable alternative, biomethane is on the rise in Europe, with plants increasing from 497 in 2016 to 540 in 2017 [26]. The European Biomethane Roadmap suggests that by 2037, a substantial amount of Europe's gas supply will stem from biomethane plants. Multiple steps need to be taken from a technical perspective to transform biogas into biomethane for injection into the gas network. Purification and CO_2 segregation are the most important ones [27]. In a presentation by Scholwin [28], costs are calculated between 1.5 and 3 c/kWh for the entire upgrading process. Another scenario analysis of biomethane upgrading arrives at costs of 46 €/MWh under the most favourable conditions, calling for substantial subsidies for the renewable gas to be competitive with other energy sources [29].

2.1.2. Electricity grid

In August 1891, a three-phase alternating current (AC) was transmitted for the first time across a distance of 175 km from the hydropower plant in Lauffen (Germany) to Frankfurt (Germany) [30]. Before that day, essential milestones paved the way towards the first electric generators. Elkington & Co. In Birmingham most likely assembled the first electrical power plant in the mid-nineteenth century powered by a steam engine [31]. For transmission across long distances, direct current (DC) promoted by business-focused Thomas Edison was less efficient, even though easier to implement, than AC, a technology preferred by Nikola Tesla in the 1880s [32]. Eventually, AC was selected for most transmission cases, while DC mostly remained for short-term electricity transmission [32]. Due to colonisation, the electrification of major cities of a British colony of India took place as early as 1879 [33]. Similar developments have occurred in Africa within the French and British colonies [34]. The British engineer J.D. Bishop lit the first electric arc lamp in China, Shanghai, in 1879, and the first power plant was soon to be installed [35].

After World War II, with the recovery of society and the economy in Europe, between 1945 and 1965, every ten years, electricity consumption doubled [36]. In the second half of the 20th century, the first blackouts and a reliability crisis occurred. Additionally, the global fuel crisis and the nuclear crisis in the 1970s led to a shift of investments towards more efficient natural gas power plants, small electricity utilities and renewables [36]. With the establishment of the People's Republic of China (1949), the country's installed electricity capacity

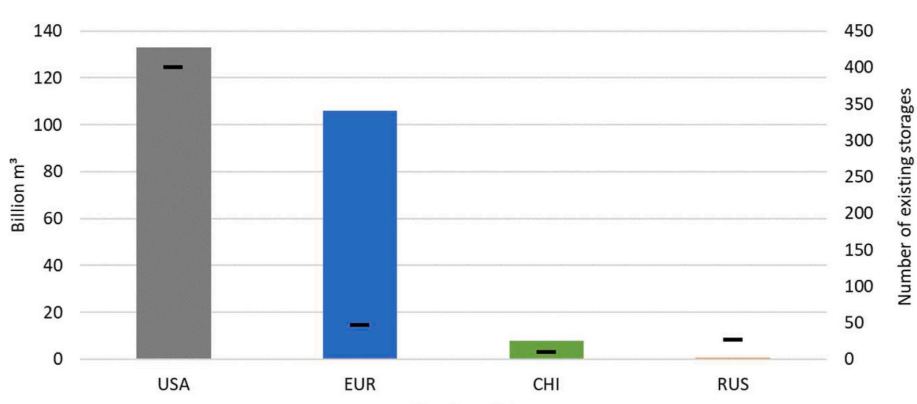

Fig. 6. Underground gas storage in the USA, Europe, China and Russia in 2018 (Sources [22–25]).

developed from 1.85 GW to 50 GW in the 1980s for a population of more than a billion ([37,38]). During the past 100 years, electricity generation was dominated by fossil fuel-based (mainly coal) power stations which hold an 80 % share [35]. Today, globally interconnected electricity networks are under development to establish an appropriate amount of flexibility and the optimal system integration of VRE. The USA electricity network is considered the largest machine globally with more than 7300 power plants, nearly 260,000 km of high-voltage and millions of low-voltage electricity lines and distribution transformers supplying 145 million customers [39]. China nowadays meets 6300 TWh of electricity consumption from 1.3 billion consumers with more than 1700 GW of installed power capacity and accounts for 25 % of global primary energy consumption and more than half of global hard coal consumption [40].

With growing electricity demand, a topic of modern times is the establishment of so-called super grids to connect electricity networks across countries or even a whole continent. During the late twentieth century, continental Europe initiated a trans-European electricity network (ENTSO-E) [41]. Europe's "Long-Term Strategy 2050" claims that electrification of the economy will lead to an increase in electricity consumption by 18 % until 2030 [42]. The electrification of transport, residential heating and cooling and industrial processes are considered the main drivers [42]. In China, the 13th Five-Year Plan, published in 2016, aims to install 2 TW power capacity, representing a 20 % increase [40]. The implementation of 2000-km, ultra-high-voltage 1000 kV lines was required to distribute electricity across the country. In Southeast Asia, ten states established the "Association of Southeast Asian Nations" (ASEAN) network at the beginning of the 21st century [43]. The Asia Super Grid (ASG) concept, with infrastructure at a length of 36,000 km, was presented in September 2011 [44].

Historically, the electricity market primarily focused on short-term profits—investment policies ignored the long-term consequences for society [36]. Competition and a fair balance of demand and supply were expected to be achieved by deregulation. In modern times, this paradigm is more and more challenged by the establishment of distributed energy resources and environmental concerns. At the same time, during the last decades, revolutionary changes in communication systems have offered greater control and monitoring possibilities all over the electricity system. Flexible and effective operation of the electricity network at lower cost are premises of the so-called smart network, which leads to revolutionising the conventional electricity system, as described in Section 2.3.2. A smart grid is an electricity network that manages all connected entities intelligently, from generators to end-users and prosumers (producer and consumer) [45]. It aims at the efficient supply of sustainable, economical and secure electricity. With the ongoing globalisation and increase in global living standards of developing countries, Safiuddin [46] expects an increase in fossil fuel consumption, specifically in transportation and electricity generation. The efficiency of resource- and equipment use, especially in the electricity system, is a major challenge, and understanding the smart grid is essential to facilitate its handling [46]. Furthermore, the application of renewable electricity in more end-consumption sectors and processes needs to be promoted to substitute fossil fuels continuously.

2.1.3. Thermal grid

We define the thermal network or DH as a system that delivers thermal energy (heating and cooling) via pipelines to multiple buildings from an outside source, which often includes excess heat from other processes [48]. Historically heating was the main focus, but hybrid energy networks also need to cover efficient cooling applications [49]. The earliest examples of heating networks were Roman hypocausts, a type of hot-air underfloor heating, often designed to heat several buildings in an area and later adapted to locally available fuels, such as coal in Britain ([49,50]). The first simple form of a heating network using a geothermal heat source was implemented already in the middle ages in 1322 in Chaudes Aigues, southern France, to heat buildings ([49,50]). Sir Martin Trienwald developed a hot-water heating system with copper pipes in his greenhouse in Sweden in 1716, followed by Sir Hugh Plat in 1742, who used steam as a heat source [51]. The first one to realise commercial DH successfully was Birdsill Holly in 1876–1877 with the Holly Steam Combination Company [51]. Supply temperatures of more than 100 °C dominated until the 1970s when lower flow temperatures were introduced [52]. The main objective was to achieve fuel savings and improve comfort by utilizing combined heat and power (CHP) plants and large thermal power plants [52]. Security of supply moved into focus, owing to the two oil crises. Local resources such as coal, biomass and waste were used as fuel supply [53]. The IEA Energy Balance provides data on the global DH supply of end-consumers across all generations since 1973 [54]. However, the database only includes data from the Eastern bloc countries after its collapse in 1990 (see Fig. 7). Although the world's volumes of district cooling supply are much smaller than those of DH supply [8], both applications were established almost in parallel. Already in 1886, the New York Steam Company used absorption chillers with steam as a cooling source—alternatively, cold water could be used [8]. In 1990, a dedicated district cooling enterprise chilled brine to cool Denver through underground pipelines [49].

Global annual DH supply accounted for around 12.2 EJ/a in 2017, 52.5 % of which arose in the building sector and 47.5 % in the industrial sector [54]. Werner [8] estimates that 200 of around 300 PJ of global, annual district cooling supply is consumed in the Middle East. China's DH system is the largest worldwide, with a network of more than 200, 000 km. The Chinese government is currently developing more efficient district energy systems with a higher share of RESs to reduce greenhouse gas emissions [55]. The northern urban heating floor area may experience a growth of 55 % in the upcoming 15 years, eventually consuming 20 billion m^2 [55]. In cities, co-generation represented about 49 % of DH supply with a total of 4092 TWh. Energy consumption in heating and cooling systems is expected to increase due to the country's intensive urbanization—a substantial challenge for the security of energy supply and the environment. China's new urban development strategy considers the expansion of DH also to smaller urban areas, which traditionally used biomass and heat pumps [55]. This network heats approximately 9 billion m^2 of building space—25 % of the US total surface area [55]. In Europe in 2017, about 6000 DH networks were in operation, supplying about 11–12 % of the total heat consumption [56]. Within the EU28 countries, in 2018, 2.03 EJ or 4.6 % of final energy consumption were distributed to end-consumers as thermal energy [57].

Lund et al. [52] identified the transformation to a sustainable energy system as the primary motivation of modern DH. The challenges include integrating (renewable) low-temperature production units, heat pumps and CHP plants into a smart energy system. That requires a change of infrastructure planning from an isolated system view to a more holistic approach. The fifth-generation DH operates at very low temperatures to exploit excess heat and renewable heat sources at low thermal exergy content [58]. The same pipelines can cover the heating and cooling supply for different buildings by reversing the operation of the customer substations, which will enhance the coupling of thermal, electrical and gas networks in a decentralised SES. Buffa et al. [58] detected forty thermal networks that can supply heating and cooling using decentralised heat pumps in Europe: Switzerland (15) and Germany (15), Italy (5), the Netherlands (2), England (1), Belgium (1) and Norway (1). Significant developments for fifth-generation heating networks are advanced control strategies and tariff and price mechanisms that refer to the desired integration of energy system infrastructure and cover thermal and electrical price indicators.

2.2. A review of hybrid energy grids

Geidl et al. [59] explain that current energy infrastructures evolved during the second half of the twentieth century, as described in Section 2.1, and may not be ready for future requirements. The aim for increasing integration of mainly electricity-based RESs in climate

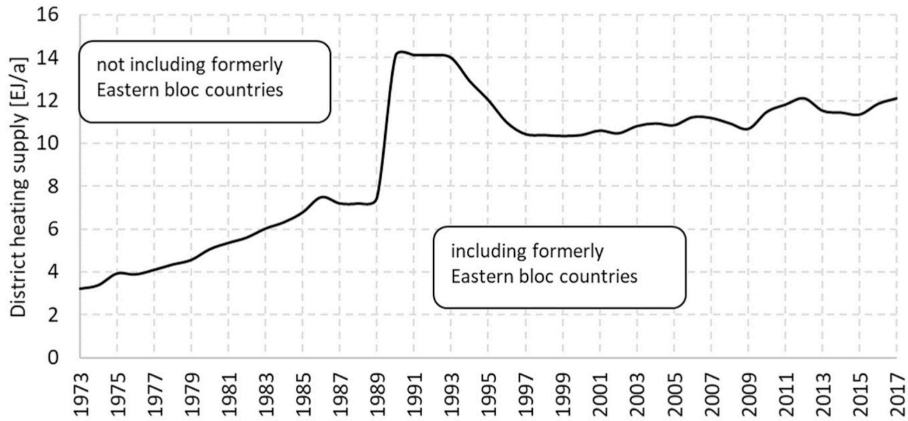

Fig. 7. Global district heating supply from 1973 to 2017 (Source [54]).

mitigation action will finally overload existing transmission systems and demand major changes to the current procedure. Some studies hinder the modelling of an optimal future energy system that includes all types of energy conversion, storage and transport, such as focusing on existing system landscapes and the known view of isolated gas, electricity and thermal energy grids. To analyze future renewable energy systems, Lund et al. [60] investigated SESs, Mancarella [61] focused on MESs, and Wang et al. [62], as well as Marnay and Lai [63], analysed efficient electricity and heat supply in micro-grids. Essential aspects of the transformation into a renewable energy system are the characteristics and the efficiency of renewable energy sources. Novak [64] explains that the amount of exergy in an energy carrier is a valuable measure of energy quality and determines the net energy availability to carry out work. Renewable energy represents pure exergy at zero operational cost. The successful integration of multiple energy carriers can support the handling of VRE and leverage substantial synergies. However, this new, more holistic approach with its new requirements makes it more challenging to use a significant part of existing infrastructure. The question that needs to be answered is, 'How should energy systems look like in 30–50 years to operate more sustainably and maintain economic, ecological and social welfare?'

Hybrid energy systems are gaining importance and are believed to increase renewable energy integration, decrease CO_2 emissions, and improve energy efficiency while offering substantial network flexibility [2]. Even though a broad range of literature on such concepts is available, there is no clearly defined, consistent terminology. Therefore, we screen existing literature for several terms related to renewable, integrated or smart energy systems. Whereas in German literature, the idea is referred to as 'Hybridnetze', directly translated as hybrid grids or systems, the concept is frequently described as integrated-, smart- or multi-energy-systems in English literature. Appelrath et al. [65] defined the hybrid grid as a tool to handle the rising storage needs throughout the current energy transition; see also Ajanovic et al. [66] and Haas et al. [67]. The concept is defined as a multi-energy system in which electricity and other energy carriers are used, stored, delivered, and even transformed into other energy carriers [65]. The authors explain that the transformation of energy has great potential to provide flexibility and stability. A hybrid grid offers alternative use options, which is especially favourable for VRE integration during oversupply situations and makes electricity production and consumption more flexible. A sub-system, which focuses on coupling electricity to other end-consumption sectors and promoting VRE integration, is called sector coupling [68], representing a major part of future integrated and hybrid energy systems ([6,69]). Integration among different energy carriers and their infrastructure offers excellent potential for regional energy supply.

Distributed generation and distribution systems located close to electricity consumers are defined as micro-grids [70]. Marnay and Lai [63] explain that micro-grids—locally controlled distributed energy systems— can customise energy supply to the local requirements. They provide relief to the legacy network, which may operate at a higher power quality and reliability level. The micro-grid resembles one of three pillars of the smart grid, together with improved consumption and supply interaction through advanced monitoring and control technologies and more efficient operation of the superior macro-grid. Holjevac et al. [71] expect a paradigm shift from central generation towards more distributed MESs and small-scale multi-generation systems. They point out that RESs and the demand variability of new end-users, such as electric heating and electric vehicles (EV), add substantial complexity to demand forecasts. Capuder and Mancarella [72] claim that in future energy systems, characterised by more variable and more uncertain production and consumption, a multi-energy micro-grid adds essential flexibility on a decentral and central level.

Moghaddas-Tafreshi et al. [70] described the multiple energy carrier micro-grid (MECM) as an interconnected grid of various energy carriers to use electricity sources in existing infrastructure through energy transformation [70]. Ma et al. [73] associate with a micro-energy grid the ability to coordinate various energy carriers, such as natural gas, electricity, cooling, heat, etc. Chicco and Mancarella [74] presented a detailed analysis of different small-scale, local, multi-generation systems. They described the current challenges concerning distributed energy generation, applying a unified approach called the 'distributed multi-generation paradigm'. Multi-generation systems are characterised by the interaction between co-generation systems, heat pumps and absorption or electric chillers. These approaches achieve the integration of renewable sources by generating various forms of energy, including electricity, heating & cooling, hydrogen and other synthetic fuels. The authors of the described concepts agree that such distributed multi-generation systems may lead to significant advantages, such as improved energy efficiency, less carbon dioxide emissions, and economic growth. Energy security and reliability are enhanced by fulfilling demand flexibly and considering energy prices and environmental aspects.

Whereas the micro-grid concept is focused on small-scale, distributed applications, an MES considers such integration of infrastructure on a larger, centralised scale. Rahmani and Amjady [75] defined it as a coordinated way of using various energy carrier grids in parallel. They suggest using an energy hub to connect the different networks involved and convert these energy carriers according to the demand, as described in Section 2.3.3. According to Skarvelis-Kazakos et al. [76], multiple energy carrier systems offer the possibility of increasing the efficiency, flexibility and sustainability of traditional energy systems. However, Huang et al. [77] claim that the coupling of various energy carriers is characterised by high complexity, so these systems have higher requirements at the stage of planning and optimisation. Mancarella [3] emphasised the great potential associated with optimizing energy carrier and infrastructure integration on the operational and planning level. The overall idea of integrated or MESs was defined by Mancarella [61] as optimal interaction of systems and energy carriers on different levels (for instance, within a district, city or region). Several interactions between electricity, heat, gas and the transport system were highlighted while the challenges caused by the growing diversity of distributed multi-generation of different energy carriers are displayed.

Widl et al. [78] propose a methodology to evaluate multi-carrier energy networks in a structured way to address the increased complexity. Raux-Defossez et al. [2] investigated network services provided by the interactions in MESs and conducted three international case studies in Germany, UK and the US. The authors mainly address the interdependencies between heat and electricity considering CHP, combined heating and cooling systems, and the application of thermal storage to balance heat generation and consumption. Ma et al. [79] addressed planning and energy management strategies for MESs. The authors provide an optimal planning framework and model that is generally applicable to MESs. To prove the benefits of the optimal planning model, the authors compare three types of energy systems: one conventional centralised energy system, a typical combined cooling, heating and power (CCHP) system and an MES designed by the developed planning model. All these studies conclude that by enabling the interaction between sectors, renewables can be integrated more successfully with higher flexibility resulting in much higher system efficiency.

Lund et al. [60] state that the application of micro-grids, renewable energy technologies, energy storage and CCHP controlled by information and communication technologies result in modern SESs. Their work aims at creating a scientific basis for the mentioned paradigm shift away from single-system thinking towards an integrated understanding of how to design and implement future sustainable energy systems ([80, 81]). Lund et al. [82] believe that the combination and coordination of smart electricity, thermal and gas networks results in an optimal solution for each individual- and the overall energy system. However, the term SES is also often used synonymously for smart grids or to express a broader application than only within the electricity system [60]. The term has been mentioned from 2009 onwards, with a steep increase between 2014 and 2016. Lund most probably provides the most comprehensive and detailed work on concepts for integrated future energy systems. Yet, this definition of an integrated system does not entirely avoid considering a single-sector perspective and still regards the interaction of the smart electricity, gas and thermal networks.

The work of Wang [83] called the more holistic and integrated approach of future energy systems – 'integrated energy systems (IESs)'; however, it appears that this research focuses on a rather regional scope. They defined an IES as an approach of different small energy systems on a local or regional level, aiming to cover different categories of energy demand by using the energy resources available in the region. The authors point out that this approach represents a hybrid energy system, leading to various research directions, especially in design optimisation during the planning stage. Furthermore, current research and literature concerning energy systems clearly show that the view of single isolated energy networks or vectors—the gas, electricity and thermal networks—is outdated and will not fit a future renewable energy system [83].

2.3. Hybrid energy systems: Applications and enablers

In this section, the approach of hybrid energy systems, the design aspects for maximum efficiency in energy supply and the upcoming challenges are described.

Mancarella [61] characterises an MES from different perspectives of integration:

- Spatial perspective: Representing potential aggregation levels from buildings to districts and regions or countries.
- Multi-service perspective: Focusing on the efficient supply of multiple services or 'outputs' and the combined generation of various types of energy by the optimal integration of energy infrastructure.
- Multi-fuel perspective: Integrating different fuels (natural gas, biomass and RESs) to successfully meet the multi-service demand in an MES for electrical and thermal energy.
- Network perspective: An enabler of multi-energy technologies for the minimisation of system cost at maximum environmental performance.

Connolly et al. [4] saw the innovation in an SES primarily in the phase of transformation or conversion, moving from a simple linear approach—from the primary energy source to conversion and consumption —towards a higher level of interaction. According to Raux-Defossez et al. [2] the availability of technologies and interfaces to the energy system, an appropriate regulatory framework and market design are essential factors for such a system change. Lund et al. [82] described the potential synergies of SESs (see Table 1). In addition, we highlight the sector coupling approaches within the smart energy grid, which aim at an integration of VRE sources.

Basing a vision of hybrid energy systems on the known, historically built environment, however, implies several challenges for successful integration of different energy supply systems [84]:

- Complicated technical, economic and market-related interdependencies between energy systems that are not understood within the so far isolated market frameworks;
- Lack of commercial tools ready to guide the design and operation planning of integrated, interdependent energy supply;
- Still isolated institutional and market structures for energy sectors;
- High operational and management complexity through the integration of multiple energy carrier systems. Without reliable software models and analysis tools, the security of supply is at risk.

Section 3 will discuss these challenges in detail. In the following, we

Table 1
Synergies of smart energy systems [67].

Topic	Description
Excess heat	Excess heat from industry and electricity production can be applied in DH.
Electricity for heating	Sector coupling: The use of electricity for heating enables energy storage as heat, which is more efficient than electricity storage. The potential buffer of heat storage leads to more flexible CHP production and decoupling from consumption. This flexible conversion also offers the potential to balance electricity and electricity grid services, e.g., regulating electricity markets.
Heat pumps	Sector coupling: Heat pumps can provide heating and cooling for district heating/cooling networks.
Biomass conversion to gas	Biomass conversion into gas and liquid fuel requires steam, which may be produced on CHP plants. The resulting low-temperature heat is an efficient source for DH and cooling networks.
Low-temperature heat	This low-temperature heat for the DH network represents an efficient input to Biogas production.
Power-to-gas	Sector coupling: Transforming electricity into gas, such as hydrogen, has the same storage advantage as heat and enables the continued use of existing gas infrastructure in future renewable energy systems. Nevertheless, as already indicated in Section 1, this is currently only considerable within an energy planning perspective, given the lack of appropriate market incentives.
Energy savings	Improved space heating efficiency of buildings through refurbishment enables low-temperature DH. These low temperatures can also be provided more efficiently by industrial surplus heat and CHP.
Power-to-fuel	Sector coupling: EVs may also provide flexibility.

outline several enabling technologies, approaches and proof from existing projects for hybrid grids.

2.3.1. Transformation technologies

Lund et al. [82] described transformation technologies from power to another energy carrier (power-to-x (P2X)) as a critical flexibility option in SESs (e.g. for transportation or heating). Lund et al. [82] claim that the best solution in terms of efficiency is the direct consumption of electricity to avoid transformation losses. However, this cannot cover all the transportation requirements because heavier vehicles are often not suitable to be powered by electric batteries but rather by fuel cells powered by hydrogen. The idea of increasingly using electricity from VRE sources directly or after conversion in new or known approaches within the transport, residential or industry sector is called sector coupling (SC). This approach represents a substantial subsystem in SESs [68]. Satisfying the whole demand for gas and liquid fuel in a renewable energy system cannot be achieved simply by biofuels but requires electricity-based fuels (i.e. P2G through electrolysis).

Lund et al. [82] highlighted the importance of P2X technologies not only in transportation but also in heating as power-to-heat (P2H) [85]. DH systems can integrate volatile wind and PV electricity and establish a balance within the electricity network. Such flexibility helps to avoid curtailment of renewable electricity generation and to achieve renewable shares and efficiency. They suggest a design approach for P2H-based district energy systems. If dynamic emission factors for electricity from the distribution network are applied, which provide information on the local curtailment of wind energy, and the emission intensity of electricity generation, optimal design from a system perspective can be achieved [85]. The result is an emission reduction at a minimal cost. Therefore, a constant emission factor is no longer an option for grid-sourced electricity in dynamic urban energy system models.

P2H in DH is a solution for the integration of renewable resources through the operation of several heat sources and generation options:

- CHP
- Heat from waste-to-energy
- Industrial surplus heat sources
- Geothermal heat
- Large-scale solar thermal heat

Lund et al. [86] further described the role of DH in current and future renewable energy systems. They performed an advanced analysis of the whole national energy system by comparing different residential heating options and evaluating total fuel consumption and CO_2 emissions. The study showed that DH leads to a substantial reduction in fuel use and, consequently, also in CO_2 emissions and cost due to increased efficiency.

2.3.2. The smart way: advanced communication and information systems

Transformation technologies enable the flexible use of electricity, gas and heat in a renewable energy system. Nevertheless, efficient renewable source use can only be guaranteed upon sufficient interconnection between the energy grids and appropriate management tools fed with the relevant data. So-called information and communication technology (ICT) and also the internet of things (IoT) support the storage and processing of vast quantities of data, improve monitoring capabilities, and link a considerable number of technologies, engineers, workers, data and procedures [87]. IoT enables virtual control of many fields in today's life, mainly targeting power system operation, control, and consumption in residential homes, offices or industrial processes [88]. In the energy system, there are various potential applications of IoT (i.e. in energy supply, transmission and distribution, and consumption), which may support energy efficiency, increase the share of renewable energy and reduce the environmental impacts of the energy system. Some components of an IoT platform are the following [87]: sensor devices to collect and transmit data in real-time such as temperature, humidity, light and proximity sensors, wireless communication technologies to connect sensor devices for data transportation, IoT big data computing and analysis for informed decisions, and cloud computing for data processing and storage on the internet. With the help of sensors and communication technologies to collect and distribute real-time data, IoT enables fast processing and optimal decision-making and may also help foresee breakdowns or maintenance needs. IoT, therefore also provides the required data to successfully transform the energy system from a centralised to a distributed, smart and integrated energy system, deploying local, distributed RESs such as solar energy [89]. In this respect, turning distributed energy end-consumers into prosumers can be supported by an IoT platform.

According to Masera et al. [90], smartness in an energy system, city, or building can be divided into technical, system and system-of-systems smartness. Technical smartness refers to the capability of a single component to access data from sensors, processing it for predictions or adjustments and transmitting the information to the respective control units. System smartness includes the autonomous operation of defined processes according to their functions and behaviours and interaction with other systems to fulfil economic or ecological goals. System-of-systems goals (such as the transport system within a smart city) refer to integrating several smart systems to achieve an overarching goal.

Energy in domestic homes is used to power lighting, technical devices, refrigerating and “heating, ventilation and air conditioning” (HVAC). The latter usually represents 50 % of total building energy consumption [91]. This part of domestic energy consumption offers substantial opportunities for efficiency improvements, which may be achieved through IoT devices in smart buildings. For example, lighting that is controlled by a motion detector will lead to a significant reduction in energy consumption [87]. Buildings have been developing from primitive, simple, automated to intelligent and eventually smart facilities [92]. While the first automation steps were to use timers and central controls to manage lights or air conditioning automatically, intelligent buildings can adjust these parameters to user needs in real-time, achieving full automation. Finally, smart buildings also collect and process data on the use of the building and enable the analysis of certain parameters at any time. For example, this data can be used for future predictions to react to high numbers of occupants in a public building and to manage the staff accordingly [92]. The optimised use of materials and on-site solar PV systems or geothermal heating systems improves energy efficiency towards zero or plus energy buildings. Furthermore, smart buildings manage plug loads, window shading, human operation and connected distributed energy generation [93]. Smart buildings could reduce primary energy use intensity by 46 % in the US compared to the current US commercial building stock, which consumes 14.6 kWh sq. Ft [94]. Systems integration through ICT could make up almost 50 % of building energy savings [95]. The results of a project on office lighting and energy consumption optimisation are described in detail in Ref. [96].

Smart cities are based on the innovative and sustainable use of the available infrastructure, considering environmental, social and economic aspects [90]. Developments in digital technologies have enabled the application of smart, IoT-based solutions to address challenges in a smart city context [97]. All players in a city, such as smart factories, smart homes, power plants and farms, can be connected and data about their energy consumption stored and analysed. Balancing during times of the day between parties that currently require more and others that demand less energy can achieve minimum system cost and manage the risk of congestion or a blackout [87]. IoT enables the management and control of data in smart cities, from communication and data transmission to intelligent identification, location tracking, monitoring, and emission control [98]. Within smart cities, air pollution and energy losses are mainly caused by the excessive use of fossil-fuel-powered vehicles. IoT technologies in transportation, so-called smart transportation, establish a global management system with real-time data processing for traffic management [87]. Applications of smart transport include congestion control and smart parking systems and enable passengers to select a transportation mode based on least cost, shortest distance and fastest route, thus reducing time, energy, and greenhouse gas emissions [98]. IoT can also have advantages in several phases of the industrial value chain and optimise the production process [87]. Failures may be predicted upfront, consistently screening any changes in machine operation instead of only detecting the failures in the final product. Action can be taken promptly to avoid wasteful production and energy use.

A smart city depends on an appropriate smart grid to integrate renewable energy sources and enable new energy-related value-added services [90]. For Zhang et al. [99], smart grids are characterised by compatibility, flexibility, and efficiency and represent an essential driver of system integration concerning distributed energy, large-scale renewable sources, and demand-side management (DSM) applications. Europe is the greatest investor in smart grids, followed by America and China. Farmanbar et al. [100] emphasised the importance of smart grids in solving the problems of future urbanization in smart cities by using energy sources most efficiently. In their interpretation, a smart grid manages the energy supply and demand of all facilities active within the system, from factories and smart homes towards EVs, all types of power plants and residential and office buildings. The smart grid is commonly interpreted as an extension of the electricity grid from a traditional one-way flow—from electricity generation to the consumer—to a bi-directional flow to integrate distributed energy producers through ICT [80]. Lund et al. [80] made one step further and defined that the smart energy system (SES) links the three smart energy grids to achieve synergies [60]:

- Smart electricity grids: manage the interaction between VRE sources and electricity demand sources that can be operated flexibly, such as heat pumps and EVs.
- Smart thermal grids (DH and cooling): integrate the electricity and heating systems. Thermal storage offers additional flexibility and may recover heat losses in the energy system.
- Smart gas grids: integrate the electricity, heating and transport networks. Gas storage can again add flexibility.

Motlagh et al. [87] claim that ICT technology can control and optimise energy generation, transportation, and distribution and end-consumption in smart grids the most secure. With the help of smart metres, a multi-directional flow of information can be achieved for an efficient energy supply enabling smart (or dynamic) energy tariffs [101]. Furthermore, IoT can actively manage the voltage in transmission networks to reduce losses or help to avoid "non-technical losses" through smart metres [37]. It is not clear if Motlagh et al. [87] referred to electricity networks only in their description. Nevertheless, Lund et al. [80] pointed out that for the future, the perspective needs to be broadened towards the complete energy system and not just the electricity network, following an SES approach. Masera et al. [90] analysed the roles and social impacts of smart grids on smart cities. They highlight that the implementation of smart cities and smart grids needs to be aligned and a cost-benefit analysis carried out in terms of grid management and also the desired ecological and social effects.

2.3.3. The energy hub – building future energy infrastructure from scratch

When it comes to how the energy flow in hybrid systems can be operated flexibly, the energy hub is an innovative concept [59]. Geidl et al. [59] explained that the industry, residential and commercial sectors demand energy in different forms, distributed in various networks that have always been considered isolated. The infrastructures need to be coupled to levy substantial synergies, using converter devices to transform different energy types. According to Geidl et al. [59], the energy hub consumes electricity at the input node and fulfils demand with the required form of energy, such as electricity, heating, cooling and compressed air. It aims at meeting the energy demand by using the provided input and converting it into a suitable energy carrier in an optimised process. Conversion technologies are, for example, CHP, transformers, power-electronic devices, compressors, heat exchangers and other equipment. Industrial plants, large buildings such as airports and shopping malls and isolated systems, e.g. trains and ships, represent existing energy hubs. The energy hub can supply the electricity demand directly from the electricity network or produce it from natural gas. Energy sources may be transformed flexibly by technologies such as gas turbines, gas boilers, electric chillers, P2H via heat pumps and P2G via electrolysis. Electricity, cold and heat are distributed through the power, cooling and heating hub, and the energy flow at each hub will remain balanced at any time. Energy delivery occurs through the electricity, gas and thermal network.

Rahmani and Amjady [75] explain that one example of existing energy converter applications is CHP, producing electricity and heat by natural gas consumption. Fig. 8 shows the CCHP architecture, with a gas turbine that feeds into the electricity and the heating hub. The gas could also be generated from water electrolysis using renewable electricity in a P2G process.

Of course, it has to be kept in mind that every conversion comes with energy loss. With this flexible system, however, the energy hub may control all energy streams economically and ecologically. When it comes to energy transportation in such an interconnected system, substantial challenges arise concerning the infrastructure. In their vision of future energy networks, Geidl et al. [59] neglect the existing infrastructure and build a potential solution from scratch in the form of an interconnector. The 'Vision of Future Energy Networks' project presents a concept for transporting electrical, chemical and thermal energy in one underground device—the interconnector. The main advantage is the possibility of more efficient waste heat recovery by using the gas to store the heat losses generated in the electrical conductor.

3. The future of hybrid grids

In this section, the future vision and potential of hybrid grids are discussed. The first sub-section aims to describe future hybrid grids, followed by an investigation of the role of SC in hybrid energy systems. Finally, an analysis of critical requirements and challenges to successfully integrate energy grids is carried out.

3.1. A vision of future hybrid grids

Electrification through renewable sources is considered a cost-effective way of decarbonising energy consumption. The electrification of currently fossil-fuel-based energy systems will lead to a tighter interaction of these systems with the electricity sector [3]. In some end-consumption sectors, such as passenger transport, direct electrification can be a successful strategy. EVs are an economically feasible way to substitute traditional fossil-fuel-based vehicles. They could ideally be charged flexibly during low overall electricity consumption to prevent additional peak loads, thereby flattening the demand profile [102]. Electric heat pumps could similarly replace fossil-fuel-powered options and, supported by the generally higher fuel efficiency of electric solutions, achieve the decarbonisation of the heat sector [102]. However, in several processes, electricity is not a suitable energy carrier and indirect electrification via a transformation from electricity into heat, gas or liquid fuels is required.

The direct or indirect electrification of known or new processes requires the development of additional cross-sectoral flexibilities to handle VRE feed-in successfully ([103,104]). In hybrid, renewable energy systems with few other flexible sources (e.g. storage hydropower plants), gas-fired power plants represent the main generation-side flexibility, which leads to high capacities required for peak performance. Although electricity generation from natural gas has long been practised, the transformation of renewable electricity into green gas, such as

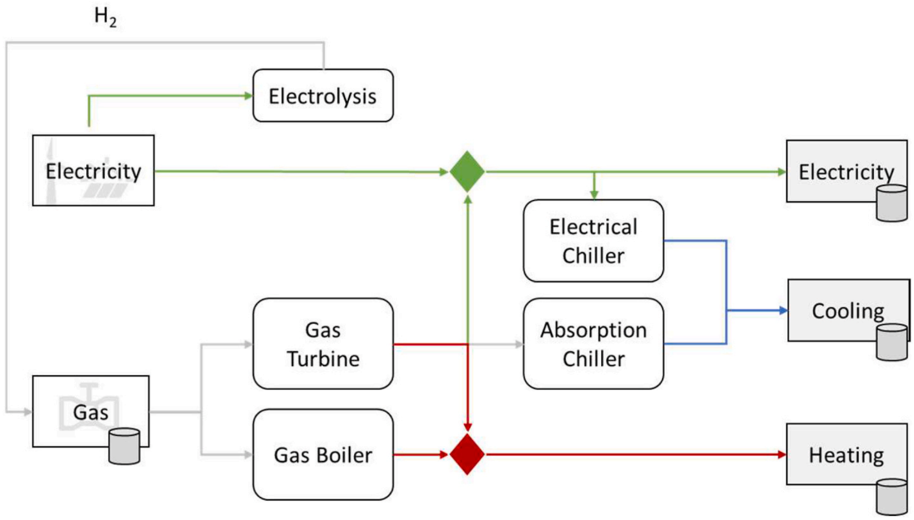

Fig. 8. Architecture of combined cooling, heat and power (adapted from Ref. [73]).

hydrogen or methane, represents a chemical process that is still to be improved. Electricity based gas offers great technical potential for future long-term energy storage [106]. It may be stored as hydrogen, delivered to the end consumer, used in fuel cell electric vehicles (EVs), or re-electrified in a combined cycle gas turbine [105]. Such a transformation provides valuable flexibility but always comes at substantial losses and should be implemented with care [106]. This interconnection of energy carriers increases complexity, thus imposing new challenges for future coordination and business models. Maroufmashat and Fowler [105] also regard the P2G technology as an essential tool for the integration of VRE sources towards the transition to a carbon-free energy system and summarise the value of P2G as follows:

- Hydrogen and methane provide the highest energy storage density of currently available technologies.
- P2G achieves a renewable share in end-consumption petroleum fuels without the need to change vehicle technology or refuelling infrastructure.
- It enables long-term, seasonal storage.
- By integrating biogas generation that provides CO_2 from sequestration, renewable methane, a direct substitute for natural gas, can be produced.
- P2G promotes technology development for decarbonisation in the industry sector, boosting economic growth.

Modern energy systems need to meet a broad set of requirements and provide resilience, reliability, security, affordability, flexibility and sustainability [107]. While historically, as described in section 2.1, energy sectors and grids are considered single-input, single-output systems, a hybrid energy system can flexibly handle multiple inputs (MI) and supply energy services as multiple outputs (MO) [107]. This MI-MO system optimises electricity, heat and chemicals according to market prices. It uses an ICT network as hybrid system demand control (see Fig. 9) to generate environmental and economic benefits [107].

Antoni et al. [106] defined three essential technical steps to successfully integrate renewable energy in urban areas. First, DSM through load shifting can be realised by offering user incentives. Second, the connection of various generation and consumption profiles through appropriate distribution infrastructure is essential. So-called energy clusters could be defined for a better match of generation and consumption. Additionally, spreading the work between urban and rural regions leads to a successful energy transition because both have their specific potential. Finally, the reversible chemical storage of electrical energy offers flexibility to renewable energy systems.

For Connolly et al. [108], the main challenge lies in finding alternatives to the flexibility currently provided by fossil fuel energy and simultaneously offering affordable RESs. They regard SESs as a solution to apply new, renewable forms of flexibility (see Section 2.3.2). Lund et al. [80] described the successful example of the Skagen CHP plant located in the northern part of Denmark. The CHP plant is equipped with

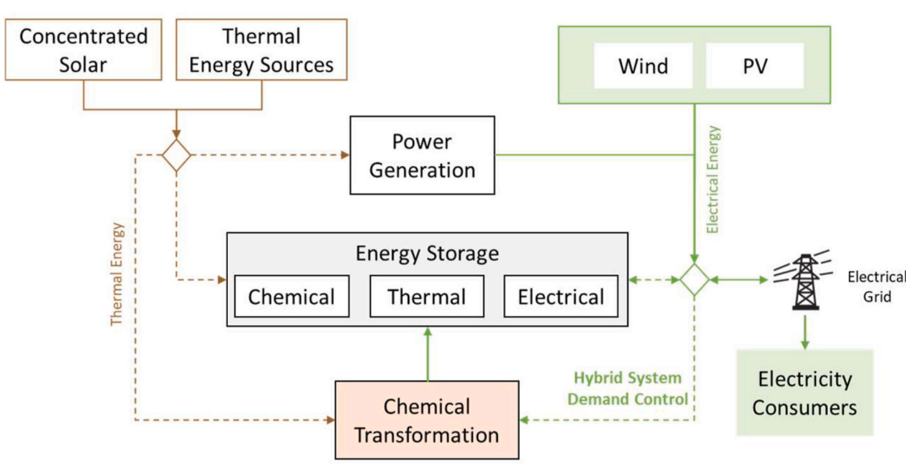

Fig. 9. Integration of the electricity and thermal energy flows in a hybrid energy system (adapted from Ref. [107]).

an incineration boiler and an electric boiler and uses industrial surplus heat to switch between electricity generation and consumption flexibly. It plays an active role in grid stabilisation and regulating power tasks and allows substantial wind inputs in the electricity and heat supply. Raux-Defossez et al. [2] tell the success story of Stanford University's renewable electricity-powered heat recovery system with low-temperature, hot-water distribution. Earlier, Stanford's heating, cooling and electricity supply was powered by a 50 MW natural gas-fired co-generation plant. The new energy system immediately reduced campus emissions by 68 % and water use by 18 %. It integrates the electricity and thermal networks, whereas energy input and output are optimised and managed across these two energy carriers. Moreover, thermal storage and DSM enable electricity load shifting from on-peak to off-peak periods and aid in integrating local VRE generation.

Nevertheless, as Haas 2021 [109] documented, the financing of the grid infrastructure and innovative technologies is an issue, and the economic feasibility is a critical aspect of the further development of hybrid grids. Currently, the efficiency of, e.g. P2G plants is at 75 % with an investment cost of about 6000 €/kW for a flexible electrolyser including grid connection. This cost is expected to decrease to 500 €/kW throughout the next ten years [106]. Assuming a lifetime of 20 years and an efficiency of 80 %, 2000 full-load hours per year would lead to a cost of hydrogen production of 40–50 €/MWh. The price for natural gas currently accounts for 35 €/MWh [106]. An important requirement for the future implementation and maturity of electrolyser technology is its classification as an energy transformer or producer instead of an end-user, freeing its operation from end-consumer taxes and tariffs. In the future, hybrid grids can play a key role in using existing infrastructure for such new applications [106].

Section 2.3.3 described the vision of an energy hub with infrastructure ignoring the historically built characteristics of existing energy grids. However, the cost associated with stranded investments favours existing infrastructure adjustment to the new requirements instead of building everything from scratch. Additionally, the economic framework for the energy system needs a completely new orientation to treat all three energy carriers equally. We suggest integrating energy carriers as virtual energy hubs by an integrated planning approach to overcome the gap between an infrastructure vision and the economic framework. Gas compressor stations, for example, could be operated by natural or green gas from pipelines or directly by electricity [110]. One example is a project in Neusiedl – AT, which shows that the economic feasibility of such an approach can be achieved when using and adjusting existing technologies and infrastructure [111]. The pilot facility connects wind power plants with the local DH network to create an energy hub. The system consists of two air-to-water heat pumps, three thermal storages, two water-to-water heat pumps and a biomass power plant, a gas burner, and a flue gas condenser as a backup system. After covering the DH demand, there is still excess electricity available, which can be transformed into hydrogen to operate public buses. This type of modelling and the flexibilisation of the energy system will form the basis to adjust existing infrastructure and meet the changing requirements.

It becomes clear from the described visions of future hybrid energy systems that the integration of VRE sources plays a key role and determines the degree to which former fossil fuel-based processes and systems may be decarbonised. Potential solutions in this field are often connected to the sector coupling concept, which couples the power sector to other end-consumption sectors transport, industry, residential and trade/services.

3.2. The role of sector coupling in hybrid grids

SC has often been mentioned in the context of the German energy transition and has been gaining attention elsewhere in Europe [102]. The increasing amount of VRE requires new solutions for long-term, seasonal storage. The decarbonisation goals for the energy system can only be achieved through an increased application of these renewable sources in more end-consumption sectors [68]. The use of electricity in other systems may occur either through direct electrification or indirectly through the transformation of electricity into another, more suitable type of fuel—heat (P2H), gas (P2G) or liquid (P2L)—for an application in the residential, transport and industry sector. As the main part of renewable energy in the future will stem from large-scale VRE from wind and PV, these one-way flows of electricity to any demand purpose with its various technologies represent an important part of hybrid grids. The German BDEW [112] issued a report describing SC as an economic and energetic link between electricity, transport, heating/cooling sectors, industrial systems and infrastructures. It aims at reducing CO_2 emissions and making energy demand more flexible in all these sectors, pursuing cost-effectiveness, sustainability and a very high level of supply security. Fig. 10 shows an example of Austria for hydro and VRE power generation. Electricity generation surplus mainly occurs in summer at high solar radiation, whereas electricity shortage is an issue in winter due to less water and sun availability. Storage (pumped hydro and compressed air) is required to decarbonise the electricity and the whole energy system. However, such capacities are spatially limited, and alternative long-term seasonal flexibility methods (such as chemical storage in the form of renewable gas) will be inevitable.

Apart from the required seasonal balancing, the VRE surplus can be used in other end-consumption sectors: for example, transport, residential or industry ([113,114]). The P2X processes ideally are operated during periods of excess electricity generation when electricity prices are low ([115,116]). Wind electricity may also be used in flexible CHP plants equipped with heat pumps. Hybrid energy grids may provide the required integration of energy grids to promote such SC. A critical review of the sector coupling concept has been conducted by Ramsebner et al. [68]. The changing requirements for energy systems and grids towards CO_2 neutrality impose several challenges associated with technical and economic aspects, market frameworks, regulation and system planning.

3.3. Critical challenges for hybrid energy grids

The interconnectivity of energy supply sources and demand is, at the same time, the value and challenge of hybrid energy systems [107]. A successful implementation requires increased cross-sectoral research and implementation. Linking the relevant energy grids and systems in energy planning often lacks appropriate interfaces, leading to suboptimal decisions. A hybrid energy system depends on a successful linkage of formerly separated infrastructure (see Section 2.3.3), ICT and data-based action and prediction (see Section 2.3.2).

Another critical challenge for hybrid grids in future energy systems is developing appropriate market frameworks for renewable energy integration to become economically feasible. As described in Section 2.3.1, transformation technologies, such as P2G, are necessary but struggling concerning their economic feasibility. Currently, several desired transformation technologies and related investments cannot be realised through the common market framework. The main reasons are the high capital cost and a limited amount of full-load hours achieved by responding to excess electricity generation of the VRE sources paired with the potentially low transformation efficiency. Pilot plants for the initiation of such technologies currently need to be set up within the regulatory framework of natural monopolies, such as grid operators, to follow decarbonisation goals and guarantee the security of supply. One central goal to achieve economic feasibility in renewable energy grids is to maintain the existing natural gas infrastructure and the successful feed-in of renewable gas by minor technical adjustments. However, considering the long-term goal of using green gas, with the technical challenges and risks related to natural gas blending, a separate hydrogen infrastructure appears reasonable in specific cases despite the cost, reducing the long-term prospects of natural gas pipelines.

Estimating primary energy use is essential to conclude on the future role of the energy infrastructure and carriers. Electricity as a primary

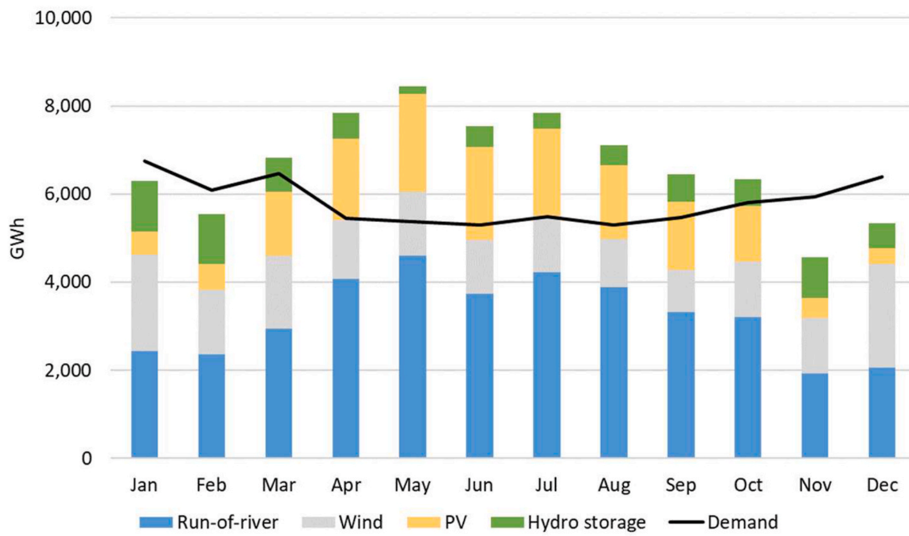

Fig. 10. Monthly generation in a 100% variable renewable energy scenario for Austria.

energy source will be at the heart of future energy systems due to its large-scale renewable energy provision and the transformation options within a hybrid energy system (see other renewables including wind, PV and biofuels in Fig. 11). Therefore, uncertainty on the long-term prospects of the gas and heat grid arises. Due to the complexity and many uncertainties related to the chosen policies and technology cost, however, there is hardly any quantitative study available that provides robust scenarios on the electricity consumption increase in integrated, multi-energy grids according to European or global goals. One of the very few studies investigating the electricity consumption development until 2050 is provided by Ram et al. [117]. The report assumes that electricity generation in Europe, after the transition into 100 % renewable energy, will exceed 4–5 times that of 2015 due to the high electrification rates. However, as stated in the European green deal, European goals communicate at maximum a doubling of electricity consumption until 2050, even with substantial electrification goals. The energy efficiency directive aims at a decrease in overall energy consumption of 41 % by 2050 based on the peaks in 2005 and 2006, driven mainly by the residential sector with improved insulation and building standards ([42,118]).

Globally, IEA estimates a 50 % increase in world energy consumption by 2050, led by solid growth in Asia and mainly driven by the non-OECD countries. The industry is the largest energy-consuming sector on a global level, offering the potential for decarbonisation through hybrid energy systems. Electricity and natural gas consumption increase the most while at the same time renewables are expected to be the leading source of primary energy consumption by 2050, leaving liquid fuels and natural gas behind. Hence, the global picture is quite similar to the European goals regarding the increased importance of electricity and renewable energy generation. These energy efficiency goals will also limit the consumption increase for the energy grids. An effect even amplified by the growing share of so-called prosumers representing decentral generation, which do not rely on the distribution grid infrastructure. These two trends could mean substantial competition to the traditional electricity, gas and thermal grids and reduce their utilisation in the long term. An increasing on-site generation without grid integration, however, also requires storage applications. From an economic system point of view, the vast development of such island solutions is inefficient due to a lack of economies of scale and central management for the socio-economic welfare. An uncontrolled feed-in of distributed

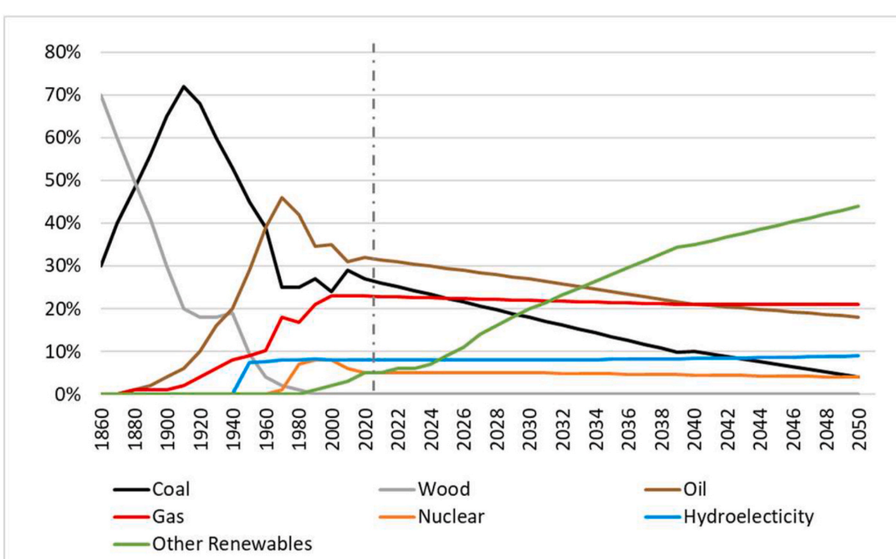

Fig. 11. Prediction of global primary energy consumption (Sources [11,18,19]).

PV peaks at noon may also cause challenges for the distribution grid and substantial cost.

Fig. 12 compares the expected global final energy consumption in the transport, electricity, industry and buildings sector in 2050 with 2015. This image allows for conclusions on the grid dependency of the sectors and the development of the energy carriers used. Again, a doubling of demand in the electricity sector is estimated [119].

At first glance, it is striking that electricity from renewables is increasing in all four sectors, while the use of gas is decreasing, most significantly in the buildings sector. In the heating system, gas is substituted by heat pumps, and the energy efficiency of buildings improves. Additionally, district heating based on renewables will come into place, and the overall share of district heating increases towards 2050. Consequently, it could be claimed that the utilisation of the gas infrastructure is decreasing [3]. At the same time, the electricity grid will gain in importance, triggered by large-scale wind and PV feed-in, causing pressure on distribution grid capacities. However, the limitations of the electricity system will promote a transformation into renewable gas for storage and distribution.

Antoni et al. [106] explained that a transition towards renewable energy systems requires substantial investment in infrastructure to provide sufficient renewable energy storage and electricity distribution grid capacity. The gas infrastructure will still be necessary for the short-term stabilisation of the electricity system and is considered to provide flexible distribution and long-term energy storage of green gas, as discussed earlier in Section 3.2. However, the technical requirements of a hydrogen feed-in to the natural gas grid vary regionally and may still require further research to avoid the substantial risk of accidents. The natural gas grid can absorb hydrogen at a limited share only, whereas the technology for methane production, which is less developed, could directly substitute natural gas. The gas grid can distribute different types of renewable gases to decarbonise the energy system [120]. A requirement, however, is the appropriate certification of green gas and carbon pricing of fossil gases.

Gasunie and TenneT emphasise, with a focus on the German and Dutch energy infrastructure, the importance of the electricity and the gas grid, specifically their coordination and integrated planning and operation in the future [121]. International energy demand in 2050 provided by the Netherlands consists of 26 % electricity, 23 % methane, 24 % hydrogen, 12 % liquid fuels and 15 % others. Germany expects to supply 28 % electricity and 29 % methane, only 8 % hydrogen and 10 % liquid fuels. This study agrees that, despite vast electricity storage capacities, only the gas grid will provide seasonal storage for the large amounts of wind and PV power. Additionally, with the H_2 backbone, a European H_2 infrastructure is currently underway to enable the distribution of large-scale renewable gas generation from dedicated wind parks across the continent [122]. The distribution of electricity, gas and heat generated from multiple sources for multiple needs, enabled by conversion and storage technologies, together with the required ICT, create the basis for future hybrid energy systems.

Many research questions on how hybrid systems can be managed successfully remain to be answered. There is still extensive research required in interface technologies to integrate new consumers, such as EVs, heat pumps in historically grown, isolated energy grids and systems, as described in Section 2.1. Concerning the prospects of a hybrid system integration of various types of electric mobility, see Ajanovic et al. [47]. Another concern is that the future energy grid planning for gas and electricity on the national and international levels is still not based on integrated system modelling. It needs to be clarified which energy grids can or shall be connected. The gas and electricity grid usually represent overarching, central infrastructure, while district heating and cooling are rather local systems. Flexibility needs to be defined as a service and integrated into the market framework. Responsibilities and goals must be clear in an integrated system to enable interoperability between the grids, technologies, markets and regulations [65]. But how can these complex interconnections be managed successfully? The connections of the system-of-systems, including the integration of E-Mobility, heat pumps, smart buildings, etc., as mentioned in Section 2.3.2, are a great challenge in hybrid grids [123].

Finally, the growing amount of data gathered in smart cities and smart grids through ICT application may also change demand behaviour in hybrid systems by growing control and awareness. Pfeiffer et al. [124] analysed the acceptable amount of intervention into home energy demand by the management system that optimises system support, self-consumption and self-sufficiency through onsite power generation and additional comfort functions, such as temperature, humidity, air quality and illumination. They find that the users accept DSM of about 1.8 MW in the sample area, revealing higher supply-side profits. Nevertheless, cooperative load behaviour must be rewarded on the electricity market for successful implementation [124].

4. Conclusions

This review outlined the potential and challenges of forming hybrid energy systems from historically grown, individual energy grids. Renewable energy systems need sufficient flexibility to guarantee the security of supply and efficient operation. The integration of large-scale VRE sources requires hybrid energy systems, in which multiple input

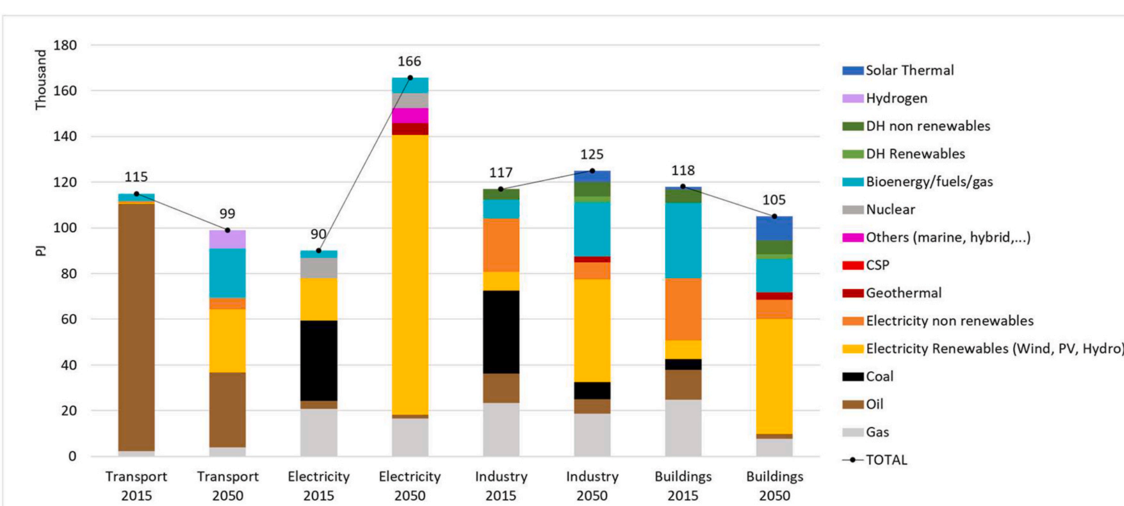

Fig. 12. Global final energy consumption in 2015 compared to 2050 in transport, electricity, industry and buildings (Source [119]).

sources are coordinated to flexibly supply multiple types of demand through electricity, gas, liquids, heat, cold, etc. However, such a paradigm change also implies adjustments in the energy infrastructure, transformation technologies, energy system modelling, data gathering and analysis through ICT, planning and economic frameworks. Uncertainties remain concerning the strong growth of renewable electricity as a primary energy carrier, often substituting gas and grid-related heat demand, which could lead to the conclusion that the gas and heat grid lose importance. The traditional infrastructure will compete with each other and increasingly with distributed power generation and consumption by prosumers. A reversal and reduction of the existing gas grid and the DH network have to be considered. They will, however, remain essential parts of hybrid energy systems. Especially the gas grid provides long-term storage and distribution for the balancing of intermittency and, thus, the successful integration of VRE.

This paper also discussed the vision of an energy hub that uses one pipeline to supply different energy carriers, with the idea to ignore existing infrastructure and design the new system from scratch. Due to the associated investment cost, we claim that such an approach should be realised from the modelling perspective as a virtual hub only. An integrated modelling approach needs to be applied when planning hybrid energy systems based on the relevant data on consumer behaviour and energy supply options. Efficient system operation requires data and clear goals, such as the reduction of carbon emissions. Favourable behaviour of the actors within the system needs to be rewarded monetarily, and CO_2 emissions need to be priced accordingly.

Existing gas and electricity infrastructure can still represent the basis of future hybrid systems if adjusted for the new requirements, e.g. for renewable gas feed-in. Pilot projects already show successful electricity and gas grid connections through P2G plants or integration of wind power plants with DH grids. Nevertheless, linking VRE with new consumers that require high full-load hours at baseload, such as heat pumps, P2G plants or the energy grids, remains a great challenge. Developing hybrid energy systems based on renewables needs support by appropriate technologies, infrastructure financing, integrated system and operation planning based on accurate data and supportive market frameworks. As a result, the desired savings in energy demand and CO_2 emissions can be achieved while maintaining the security of supply and economic feasibility.

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.

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