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RESEARCH ARTICLE

Saman AMANPOUR, Daniel HUCK, Mark KUPRAT, Harald SCHWARZ

Integrated energy in Germany–A critical look at the development and state of integrated energies in Germany

Abstract In the face of global warming and a scarcity of resources, future energy systems are urged to undergo a major and radical transformation. The recognition of the need to embrace renewable energy technologies and to move toward decarbonization has led to significant changes in the German energy generation, consumption and infrastructure. Ambitious German national plans to decrease carbon dioxide emissions on one side, and the unpredictable and volatile nature of renewable energy sources on the other side have elevated the importance of integrated energies in recent years. The deployment of integrated technologies as a solution to interlink various infrastructures creates opportunities for increasing the reliability of energy systems, minimizing environmental impacts and maximizing the share of renewable resources. This paper discusses the role of integrated energy systems in supporting of sustainable solutions for future energy transitions. Moreover, the reinforcement of this movement with the help of different technologies will be discussed and the development of integrated energy systems in Germany will be reviewed.

Keywords integrated energy, renewable energies, energy transition, power-to-gas, power-to-heat, power-to-mobility, energy storage

1 Introduction

While China has mainly focused on hydro power, renewable energy from wind and photovoltaics in Germany have seen immense growths in both installed capacity and generation, leading to renewable energies accounting for approximately 29% of German electricity consumption in 2016 (188.3 TWh of the 648.4 TWh total). In 2016, 77.4 TWh of electrical energy was generated from wind (compared to 9.5 TWh in 2000) and 38.2 TWh from photovoltaics [1–3]. These major shifts toward renewable energy technologies and away from conventional power sources are necessary in order to meet the goals set by the German Energiewende and stipulated by the Renewable Energy Sources Act (EEG). This multi-facetted energy transition consists of four primary, long-term goals: a reduction of greenhouse gas emissions (GHG) by 80%–95% (compared to 1990) by 2050; a complete phase-out of nuclear power by 2022; an increased reliance on renewable energies for final energy and gross electricity consumption to at least 60% and 80%, respectively, by 2050; and an overall decrease of primary energy and electricity consumption by 50% and 25%, respectively, compared to 2008 [4].

The rising share of electricity from renewable energy sources (RES) continues to aid in the decarbonization of the electricity sector, whereas the role of RES remains relatively minor in the provision of thermal energy. In 2015, thermal energy applications accounted for 55.6% of Germany's final energy consumption, primarily sourced from gas and oil, as opposed to the 5.6% share from electrical applications. Among the economic sectors, the mobility sector, highly dependent on fuels from non-RES, holds the largest share of final energy consumption in Germany, accounting for nearly 30% in 2016 (followed by 28% and 26% by the industrial and household sectors

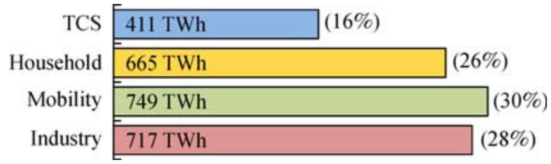

Fig. 1 Final energy consumption by sector, Germany 2016 (data from [1])

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Saman AMANPOUR, Daniel HUCK, Mark KUPRAT, Harald SCHWARZ (✉)
Energy Distribution and High Voltage Engineering, Faculty 3, Brandenburg University of Technology Cottbus-Senftenberg, Cottbus 03013, Germany
E-mail: harald.schwarz@b-tu.de

respectively) [1,3]. Figure 1 illustrates the final energy consumption of different sectors in 2016 in Germany. To meet the ambitious goals of decarbonization and increased use of renewable energies, while also phasing out nuclear power and maintaining competitive markets, accelerated utilization of RES in sectors outside of the electricity sector (namely thermal applications) is necessary.

As the share of energy supply from RES continues to grow, major investments in efficient energy transmission and storage systems will be required in order to maintain stable and reliable energy supply while also considering costs and commitment time lines. Due to the volatility and unpredictability of renewable energy technologies, it is postulated that a major decoupling of energy supply and demand should be pursued, allowing full utilization of RES without challenging available networks. The implementation of integrated energies, as will be discussed by this paper, is a promising approach toward this goal, utilizing and integrating manifold energy carriers, transmission methods and sectors.

2 Integrated energy

Integrated energy is the idea of an energy system in which generation sources, consumption sectors and energy carriers are connected to one another so they can be utilized holistically. Excess electricity, rather than being curtailed and remunerated, could be used to meet other industrial demands, such as process heat or the supply of synthetic raw materials. In doing so, excess energy can be used for existing applications, transported and stored for times in which demand would otherwise be higher than supply. In effect, the integration of numerous energy technologies and systems allows energy networks to effectively decouple energy supply from demand, while also coupling various sectors together as a symbiotic, holistic system (Fig. 2).

The integrated energies approach allows energy carriers such as electricity, heat and gas to flow along controlled paths to more efficiently supply the economic sectors: industry, households, mobility as well as trade, commerce, and services (TCS). In addition, the products of such a system can also supply various industrial processes, such as the chemical and paper industries [5,6]. The prevalent technologies by which the integration of energies can be achieved are power-to-gas (PtG), power-to-heat (PtH) and power-to-mobility (PtM).

The interconnection of the technologies and systems within integrated sub-processes is complex and only increases in complexity as they become further integrated into larger holistic systems, as can be seen in Fig. 3. In light of the complexity of such a system, the integration of energies requires precise information and telecommunication technologies (ICT) to consider each sector, economic values, available reserves and the stability of the grid as a whole. Control of such a system remains as one of the largest challenges of implementing the integrated energies approach [7,8].

2.1 Power-to-gas

While electricity is difficult to store in large quantities and over long periods, gasses exhibit favorable features for storage: high capacities, high energy densities and low losses. In the case of PtG processes, electrical energy is used to generate synthetic gases. Hydrogen (H_2) and oxygen (O_2) are produced via electrolysis, whereas methane (CH_4) is produced via methanation [5,8]. The potential applications of PtG are manifold. The synthetic gases can be stored in depleted oil or gas reservoirs, used directly as fuel in the mobility sector, added to the existing natural gas networks, utilized as synthetic raw material or utilized as fuels in thermal power plants [6,9,10]. PtG exhibits great potential for integrated energy systems due to its high versatility and Germany's large potential for gas storage, serving as an energy backbone parallel to the existing electricity networks and as means of meeting long-term energy demands during periods of low electricity generation [8,11].

The technology necessary for electrolysis and methanation is technologically mature and numerous technologies exist. The predominant technologies are alkaline electrolyzer (AEL), polymer electrolyte membrane (PEM) and

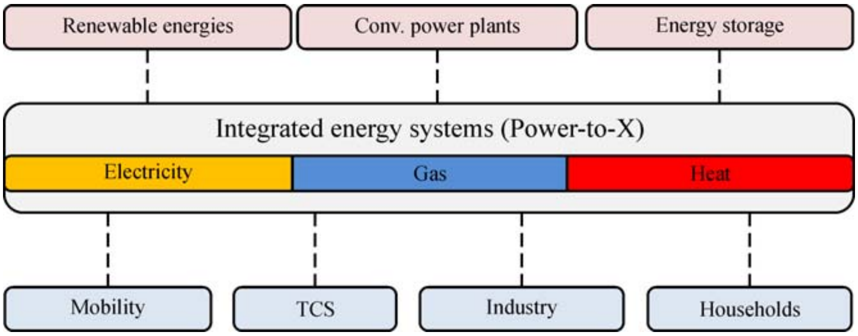

Fig. 2 Concept of integrated energy

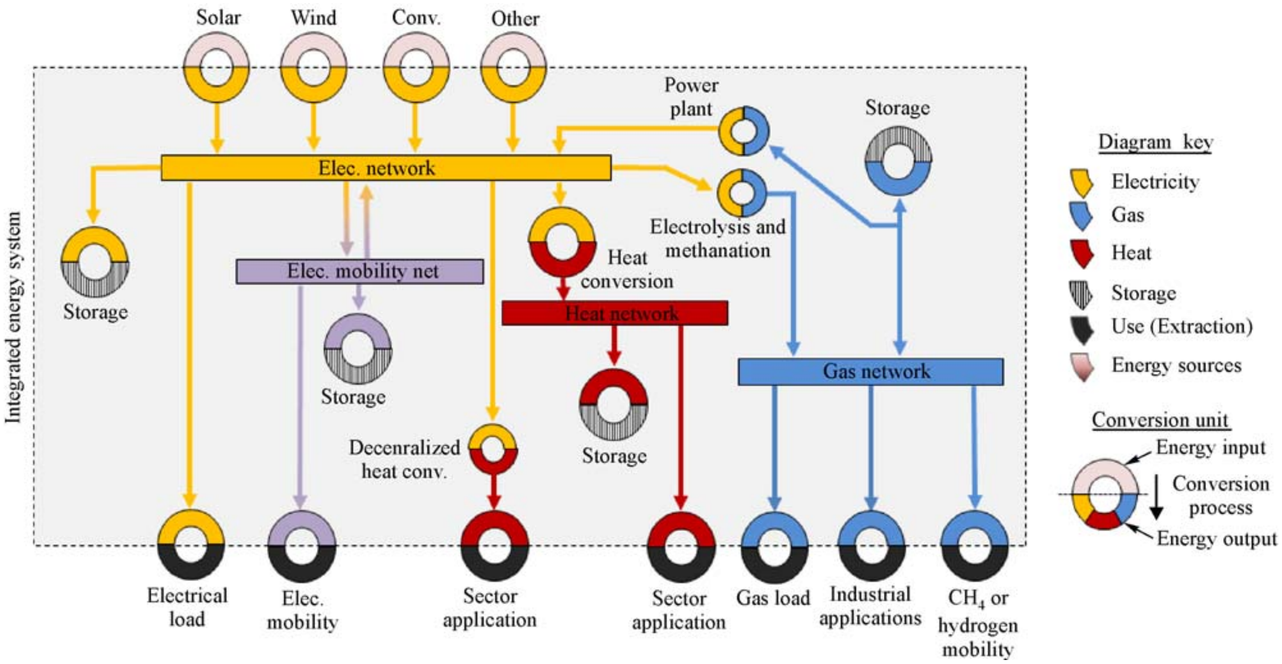

Fig. 3 Integrated energy as a large, holistic system

solid oxide electrolyzer cell (SOEC) systems. Of the PtG technologies, AEL is the most mature and well-understood technology. AEL technology exhibits long lifecycles (30 years) and comparably low costs, enabling large electrolyzer installations, though also limited in efficiency, current density and cold-starting times [12,13]. PEM electrolyzers, on the other hand, allow for higher voltages and current densities while also exhibiting suitable instantaneous performance in response to variations in load [5,14]. SOEC is the youngest electrolysis technology and possesses lower cell voltages for operation. Due to the high-temperature heat demand for cell operation, an additional heat source is required. Therefore, the potential fields of application are limited even though the SOEC technology is characterized by high overall efficiencies. The most significant challenges for SOEC are the fast degradation of the material and the limited long-term operational stability as a result of continuous operation at high temperatures, as well as the requirement of a high-temperature heat source.

To ease the integration of synthetic gases and the long-term storage capability, the electrolysis product, hydrogen, can be transformed into CH_4 via methanation. Classical methanation processes consist of the reaction of CO_2 (or CO) with H_2 over a metal catalyst to produce methane via either biological or catalytic reactors [14].

Currently, the connection to gas and mobility networks are the main applications for PtG. Considering the existence of expansive gas infrastructures linking the various regions of Germany and large storage capacities, PtG is a promising method for matching regional energy supply and demand disparities. Furthermore, PtG processes could help develop valuable synergies between renewable energy technologies and the industry and mobility sectors, facilitating decarbonization efforts. Currently there are about 23 relevant PtG applications in Germany, most of which are embedded in a scientific environment. Some of the plants, such as Mainz (6000 kW), Werlte (6000 kW), and Falkenburg (2000 kW) are in commercial operation and possess industrial power levels [8].

2.2 Power-to-heat

PtH serves as a means of coupling the power with the heat sector and can be used to increase thermal energy supply and to provide flexible loads during periods of high electricity generation. PtH and its scale of application differ greatly from the sector of application, the thermal level of demand and the season. Efficient reduction of CO_2 emissions greatly depends on the utilization of RES for thermal applications. In 2015, 94% of energy consumed by households was for thermal applications, with even greater shares in other sectors (74% for industry, 62% for TCS). In the same year, RES played a relatively minor role in thermal demands (14% for households, 11% for TCS and 6% for industry). Between 2008 and 2015, the overall household thermal consumption decreased by 11%, while the share of RES in thermal applications rose by 27% (mostly solar and biomass applications) [1,15].

In the case of centralized PtH applications, large boilers and thermal storage systems can be used to distribute heat to extended areas, whereas decentralized applications generally generate heat on smaller scales via electricity transmission to the point of demand (such as residential heat-pumps) [16]. For high temperature demands, electric boilers and electrode heating boilers can be utilized, producing steam or heat for particular process applications. For low temperature applications, heat pumps offer higher efficiencies [5]. Most PtH technologies are technically mature and are more attractive for investors compared to other PtX technologies, particularly due to their high efficiencies and low investment costs. As a result, it can be seen that relatively many PtH plants are in operation. Furthermore, the application of heat-pumps in the private households is growing year by year [5,17]. Particular examples for large-scale PtH in Germany are the 30 MW facilities of the municipal utilities Kiel and Flensburg and the 50 MW facility in Nuremberg [18].

2.3 Power-to-mobility

The mobility sector, as part of an integrated energy system, is coupled to the super ordinate energy system levels primarily through electricity, natural gas or hydrogen fueled vehicles. In this way, vehicles serve as both storage mechanisms and controllable loads in electricity and gas networks, particularly in consideration of demand response applications [8]. While synthetic gas fueled vehicles primarily serve as a means to reduce CO_2 emissions, battery powered vehicles are able to provide ancillary services such as frequency control and control power. PtM represents a solution to the surplus and intermittency of RES power, working as a flexible load while also working in parallel with PtG systems by utilizing H_2 and CH_4, when applicable. The mobility sector in Germany, with an energy consumption of 749 TWh, accounted for nearly 30% of the total energy consumption in 2016 [1,3].

The share of electric vehicles in Germany, though relatively small (0.73% of all vehicles), continues to see steady growth. In 2016, Germany, with the registration of more than 24500 electric vehicles, gained the 8th rank in the world for the number of new battery-electric and plug-in electric vehicles, resulting in a total of 72300 domestically registered electric vehicles in Germany [19,20]. Developments within the e-mobility sector and evolutions in the charging infrastructures in Germany, by providing more than 6500 public available charging points, shows the importance of e-mobility in sectoral coupling, not only as a solution for energy storage but also as controllable load [21,22].

2.4 Storage capacities

For energy systems with large shares of RES, short- and long-term storage capacities are crucial. Integrated energy systems provide a means to integrate sufficient storage capacities into the system [16]. Considering the electricity grid, it can be said that energy storage capacities are not immediately necessary compared to grid extension measures, as some storage technologies serve more as temporary measures and grid expansion projects are typically seen as long-term solutions. That said, as the generation from RES continues to grow and energy supply becomes more geographically dependent, energy storage capacities become necessary to overcome the volatility and unpredictability of RES [17].

Various technologies are available to serve as energy storage, such as battery storage systems, underground gas reservoirs, capacitors, and flywheels. As of the end of 2017, Germany reported approximately 143 MW of battery storage with an additional 75 MW of rated power for contracted storage, primarily for frequency regulation. The majority of battery storage in Germany uses Lithium-ion cells, but additional technologies, such as flow batteries, lead-acid cells and vanadium Redox Flow systems are also used[1]. The various storage technologies, including battery storage systems, differ not only in their energy storage forms (electricity, thermal, mechanical) but also in their individual overall storage capacity, specific energy, power densities, operational lifetime, response time and efficiency. In addition to these active storage systems, passive storage systems that store and release energy inertly, such as passive heating and cooling, should also be considered [23]. In the context of integrated energy systems, both thermal and gas storage technologies are considered.

In regards to gas storage, Germany already enjoys a large natural gas network system, exceeding 510000 km in total [24], serving not only as a means of gas transportation, but also as a form of storage, particularly for H_2 and CH_4. Furthermore, H_2 can be added to natural gas mixtures up to specific limits, as low as 1%–5% and feasibly up to 17%–20% by volume, dependent upon the network and its particular equipment under consideration [25]. This is an economically favorable option in terms of cost and efficiency, but it is limited by feed-in limitations and potential fatigue complications due to unplanned material exposure to H_2. Since CH_4 is the primary component of natural gas, it usually can be added without limitations but comes along with increased efficiency losses compared to a sole production of H_2.

Beyond network capacities, numerous gas storage options exist, namely cryogenic liquid hydrogen tanks, high-pressure gas storage, metal-hydride vessels and, of particular consideration, underground storages. While storage alternatives, such as high-pressure and cryogenic liquid hydrogen tanks, are potential solutions for smaller, transportable gas storage applications, underground storage remains the safest and most efficient long-term method of storing large quantities of natural gas and H_2

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[1] Global Energy Storage Database, Office of Electricity Delivery & Energy Reliability. https://www.energystorageexchange.org/projects/global_search?q = germany

[14]. Due to the geological structure of Germany, the majority of existing or potential locations for natural gas or H_2 exist primarily in the North, namely in Niedersachsen, Schleswig-Holstein, Mecklenburg-Vorpommern, Nordrhein-Westfalen, Sachsen-Anhalt, Thüringen and north of Hesse, accounting for a potential 8.8×10^9 m^3 of H_2 storage (equivalent to 26.5 TWh) in economically favorable existing gas caverns [26].

As part of PtH processes, thermal storage capacities are necessary for long-term seasonal storage. By the end of 2016, more than 33 MW (thermal) of solar thermal plants with integrated heat storage were reported by the solar district heating group, accounting for a total of 147000 m^3 of hot water storage [27]. Furthermore, the geographic favorability of various areas of Germany possess high-temperature aquifer thermal storage potentials, with more than 12000 MWh of capacity in operation as of 2017 and nearly 175000 MWh of additional capacity planned [28].

3 Perspectives of implementation

The integrated energy approach provides several benefits for an energy system with high shares of RES and is crucial to meet ambitious climate goals, such as Germany's targeted goals. Integrated energy allows for the efficient decoupling of energy supply and demand, as well as the strengthening of energy network flexibility. In addition, the potentially greatest benefit of such a system would be its coupling of the various consumption sectors with the predominant energy supply from RES in the electricity sector. However, the extent to which such a system is able to address the CO_2 reduction commitments of Germany is uncertain due to insufficient data and vague assumptions regarding the technical potentials of RES in the electricity sector and the potentials to transfer the electricity of RES into other energy sectors.

3.1 Balancing feasibility

From the perspective of the feasibility of such a shift in the proportion of energy demand and supply, three major factors must be considered: storage capacity, overall costs and system flexibility. As can be expected for new energy applications, the implementation of such a system comes along with additional investments and operational costs. In the case of PtG, the non-standardized production of electrolyzers leads to high costs, averaging between 1000 and 1500 €/kW (electric) for AEL and 2000–3000 €/kW (electric) for PEM technologies. Considering the cost degression effects due to better and more efficient production techniques, there could be considerable declines in these prices by 2035 [8]. Operational costs being considered, long-term economic feasibility is more dependent upon changes to electricity prices. The cost sensitivity of the major integrated energy technologies (hydrogen/SNG, grid injection, industrial PtH) are highly dependent upon average prices of electricity, with the exception H_2 and CH_4 mobility, which shows more sensitivity to the cost of refueling stations and capital costs. Similarly, the costs of storage capacity and on-demand operations must be considered to support large integrated systems[1].

3.2 Perspectives of overall system efficiency

The concept of integrated energies introduces numerous energy pathways in order to provide a large range of applications, storage options and flexible operations. As is the case for all energy conversions, each conversion in an integrated system results in energy losses and depending upon the technology, the differences in overall efficiency can be significant. In the case of PtG, in which electrical energy is stored via hydrogen or methane, efficiencies range between 50% and nearly 80%, depending upon the technology and compression ratio. If the gas is then reconverted into electricity, the efficiency is shown to be lower, between 30% and 44%. Maximizing overall efficiencies and minimizing the costs of integrated energies is necessary in order for such a complex system to effectively operate [29].

3.3 Role of integrated energies in decarbonization

As of 2016, Germany was a country of 82.5 million inhabitants, each contributing to an annual final energy consumption of 2542 TWh (corresponding to a primary energy consumption of 3736 TWh). In comparison to 2000, today roughly a million more people live in Germany while annual energy production has fallen by more than 260 TWh. Over the same period, the emission of greenhouse gases (GHG) fell from 1043 Mt of CO_2 equivalent to an estimated 906 Mt of CO_2 equivalent, marking a reduction of 27.6% from the emission levels of 1990 [1]. As noted previously, the commitment to reduce GHG emission by 80%–95% by 2050 (as well as the intermittent goals of 2020 and 2035) remains distant, requiring an additional reduction of at least 655 Mt of CO_2 equivalent.

37.2% of the total GHG emissions in Germany (902 Mt of CO_2 equivalent) in 2015 was attributed to the energy sector, followed by 21% from industry and manufacturing, 17.8% from the mobility sector and 9.6% by households directly. As the share of RES generation continues to grow, the share of GHG emitted by the energy sector will steadily decline, leaving more than 550 Mt of CO_2 equivalent

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1) ENEA Consulting. The Potential of Power-to-Gas: Technology review and economic potential assessment. 2016-01-14, http://www.enea-consulting.com/wp-content/uploads/2016/01/ENEA-Consulting-The-potential-of-power-to-gas.pdf

reductions to be achieved in sectors comprised of primarily thermal and mechanical applications, rather than electrical (Fig. 4) [1]. The decarbonization of such sectors remains as one of the greatest challenges in meeting sustainability goals, one in which integrated energy systems would prove advantageous. Via systems like PtG, the mobility sector is presented with an alternative means of energy supply which not only helps to increase the efficiency of installed RES generation capacities, but also helps to decarbonize a sector highly dependent upon fossil fuels.

In order for such an integrated system to successfully decarbonize sectors beyond the electricity sector, vast additional capacities of RES in the electricity sector become necessary in order to provide sufficient excess energy to increasingly support demands in the heat, gas and mobility sector.

In 2015, 4.72 TWh of energy from RES was curtailed, of which 87% (4.10 TWh) was from wind energy [5,30]. In comparison, this curtailment accounted for approximately 2.5% of the total renewable electricity generated. This amount of curtailed excess energy could be enough to produce 8×10^8 m^3 of hydrogen, conservatively calculated using the conversion factors from Table 1. For perspective, this curtailed 4.72 TWh energy is roughly equal to half of the energy consumed in 2015 for household electric space-heating (only 1.4% the total household energy consumption) [1,15].

Imbalances in geographic energy demand and generation, as is the case in the high-generation-low-demand Northern regions of Germany, lead to high infrastructure stresses as excess energy is transported elsewhere, leading to subsequent redispatching to ease loading on transmission infrastructures. In 2016, this resulted in nearly 11500 GWh of redispatched energy [31]. These imbalances in supply and demand also tend to ease electricity prices, even to the point of negative pricing. In 2017, Germany experienced approximately 146 h of negative electricity prices, surpassing the previous record of 126 h from 2015, due to the increased share of wind and solar generation on the market [32].

Integrated energy systems aim to provide the necessary means for all sectors to progress toward a state of decarbonization and this transformation is reliant upon the use of RES such as wind and solar as its backbone. The extent to which these technologies can be implemented is limited, contrary to common perceptions. Land on which solar and wind plants can be permitted, erected and economically operated is finite (hence growth in off-shore wind developments). As per Ref. [33], a theoretical total of 2898 TWh of energy from onshore wind turbines could be feasibly generated in Germany, primarily in the Northern states. As stated previously, the electricity consumption of Germany in 2016 was approximately 648 TWh, which was sufficiently smaller than that of the stated onshore wind

Table 1 Integrated energy, pathway efficiencies [29]

	Fuel	Efficiency	Conditions
Electricity → gas	Hydrogen	54%–72%	200 bar compression
	Methane (SNG)	49%–64%	
	Hydrogen	57%–73%	80 bar compression (natural gas pipeline)
	Methane (SNG)	50%–64%	
	Hydrogen	64%–77%	without compression
	Methane (SNG)	51%–65%	
Electricity → gas → electricity	Hydrogen	34%–44%	80 bar compression up to 60% back to electricity
	Methane (SNG)	30%–38%	
Electricity → gas → electricity and heat (cogeneration)	Hydrogen	48%–62%	80 bar compression and electricity/heat for 40%/45%
	Methane (SNG)	43%–54%	

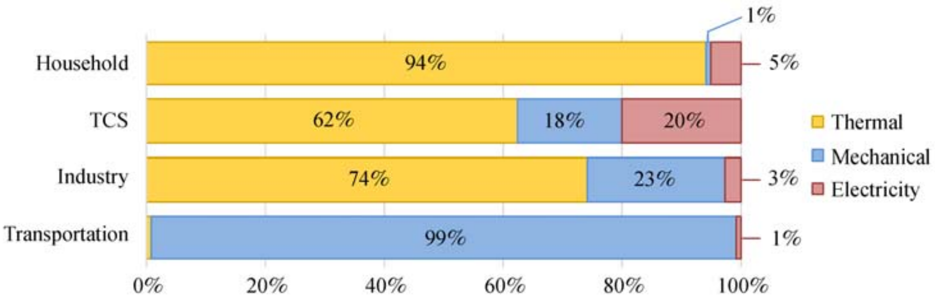

Fig. 4 Final energy use by application and sector, Germany 2015 (data from [1,15])

potential, but the margin diminishes when considering final energy consumption, 2542 TWh [1,15]. Considering actual capacity factors, economic practicalities, seasonal variations and increases in overall energy demand for integrated systems in the future, the feasibility of complete energy reliance on domestic RES is uncertain.

4 Conclusions

Approaching the challenge of effective and efficient utilization of renewable energy technologies is complex, requiring different solutions that can provide flexibility and stability to energy networks. For a sustainable development of renewable energies and moving toward the goals of decarbonization in Germany, special considerations must be given to the aspects of volatility, unpredictability and regionalism of renewable energy technologies. The concept of integrated energy is a promising solution to tackle such challenges, allowing for the integration of various energy carriers, such as electricity, gas and heat. Lack of attention to these crucial aspects and focusing too much on increasing only the installed capacities of renewable energy technologies is not only a threat for a sustainable development in this branch, but also a hazard in the form of excessive stress on each energy sector, leading to an increase in the number of disturbances and decreasing the lifetime of current infrastructures. As it was mentioned before, discrepancy in energy demand and generation due to geographical reasons results in exposure of the current grid infrastructures to a high level of stress. Subsequently, this extra burden must be managed by different measurements like redispatching to relief the grid from incident of a dramatic occasion. From the economical point of view, the necessity of extra grid management measurements in many cases has a negative impact on electricity prices, as it happens very often in Germany.

Though there are currently promising possibilities for energy utilization and for the storage of excess energy, their scale of implementation has remained limited. Nevertheless, the immense scale and complexity of the problems facing future energy generation and consumption demands increasing development toward the implementation of integrated energy.

As the share of electricity generated from RES continues to grow, the energy sector will continually decarbonize, but the decarbonization pathways of other sectors, such as industry and households, is not as clear. For these sectors, strong emphasis on, and development of, carbon-neutral sources of energy for the wide array of thermal and mechanical applications must be pursued. The mobility sector, as the sector with the largest share of final energy consumption, does appear to have market flexibility for such solutions, such as electric or gas fueled vehicles, but the extent to which such a sector transformation can rely on RES generation is not certain. Given the necessity of energy transformations in all sectors beyond electricity generation, such as thermal application and mobility, the concept of integrated energies is the only feasible solution in pursuance of German climate and energy goals. It is yet to be seen how Germany will fair against its goals of 2020, 2035 and 2050, but as more potential solutions are developed, the promise of a holistic decarbonization remains.

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