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# Challenges and Opportunities of the Energy Transition and the Added Value of Energy Systems Integration

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## 1.1 Energy Transformation Toward Decarbonization and the Added Value of Energy Systems Integration

The global energy transformation is already in place, and this represents the main reply of humanity to safeguard global climate and maintain sustainable existence on Earth. The first step toward this energy transformation and the international commitment to combating climate change, increasing energy access, and maintaining biodiversity is represented by the Paris Agreement signing at COP 21 with the goal to maintain global warming lower than 2 °C above the pre-industrial levels. Concurrent to the Paris Agreement, countries committed to the United Nations (UN) 17 Sustainable Development Goals (SDGs), representing the plan toward a better world for people and our planet to be achieved by 2030 [1]. Tackling climate change is a transversal goal for almost all SDGs. Although the international commitment is evident, challenges still remain for the successful implementation of the Paris Agreement and climate- and energy-related SDGs, and the gap between aspiration and reality in combating climate change remains significant.

Meeting these ambitious goals requires the commitment beyond the electricity sector, whereas providing decarbonization across different sectors through an integrated approach can represent a valid solution. This is the main idea behind the concept of Integrated Energy Systems that, according to the ETIP SNET Vision 2050 [2], are defined as an integrated infrastructure for all energy carriers, with the electrical system as the backbone. These systems are characterized by a high level of integration among all networks of energy carriers obtained through coupling electrical and gas networks, heating, and cooling, supported by energy storage and conversion processes. Coupling different sectors indicates increasing efforts in a synergic way by coordinating the planning and the operation of energy systems across multiple energy carriers while also achieving a more flexible, reliable, and efficient energy system as a whole.

The main energy trends toward decarbonization are discussed below along with the added value offered by energy systems integration.

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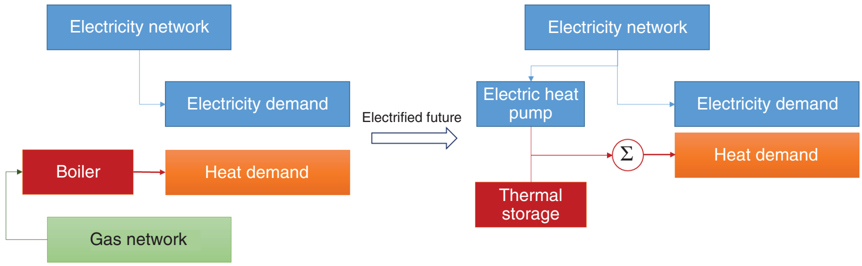


**Figure 1.1** Evolution of the current energy system to an electrified energy system.

**Electrification** is considered a valid cost-effective pathway for decarbonization of final energy consumption. This is mainly due to the fact that several technologies for converting renewable energy into electricity have recently become available at competitive prices such as PV and wind turbines. On the other hand, a large part of $CO_2$ emissions in industries, transport, and buildings is not related to power sector but to end use of fossil fuels. That is why, a large-scale electrification, characterized by the penetration of an electricity carrier produced by renewable technologies in building, transport, and industry sectors, represents a good pathway for decarbonization. According to the International Renewable Energy Agency (IRENA) Renewable Energy Roadmap (REmap) [3], the share of electricity in final energy consumption amounts to 20% today and will reach the percentages of 29%, 38%, and 49% in 2030, 2040, and 2050, respectively.

Figure 1.1 shows the change from the current energy supply system where the electricity demand is typically satisfied by an electricity network and heat demand by gas-fired boilers supplied by a gas network to an electrified energy system, where the electricity network is used to satisfy all energy demands, including heat demand through Power-to-Heat (PtH) technologies. An electrified future poses important questions such as how much additional power network capacity do we need to satisfy all types of energy demands? Or, what happens if there is a contingency in the power system?

A strong electrification scenario creates a number of challenges for the operation of a power system, which in principle would need additional flexibility, reinforcement, and new investments for the transmission and distribution networks.

In Figure 1.2, the current energy system is compared to an integrated energy system, which is something more than an electrified energy system. In fact, in such system, multiple hybrid energy technologies are managed with high synergy to satisfy the multi-energy demand and services can be provided with the most convenient energy carrier and sector.

If electrification of final consumption is combined with the integration of energy sectors, decarbonization of energy demand would be reached through penetration of renewables in all energy end use sectors while also getting higher flexibility for the whole system by reducing the needs for reinforcing the existing network infrastructures. Moreover, energy systems integration allows increasing efficiency in the energy resources use through exploiting synergies coming from the interplay

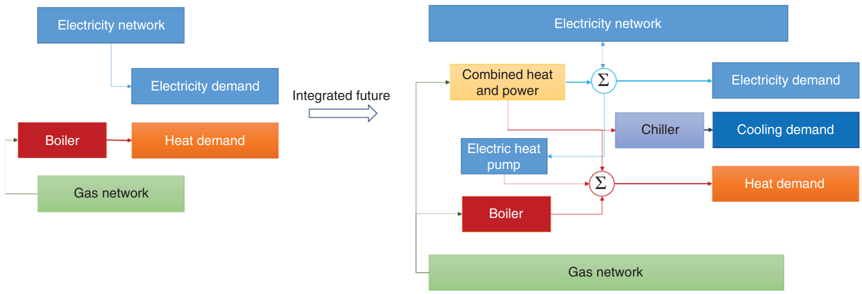


**Figure 1.2** Comparison between the current energy system and an integrated energy system.

of different energy carriers and reduction of renewable energy source (RES) curtailment. In practice, for instance, in the case of excess electricity from RES, it can be converted into gas as hydrogen or synthetic methane through Power-to-Gas (PtG) technologies, stored and/or transported by existing gas infrastructures for immediate or later usage, or re-converted again into electricity when renewable electricity supply is insufficient to satisfy the loads. On the other hand, PtH technologies combined with thermal storage can shift production of thermal energy when renewable electricity is in excess, thereby representing another option for reducing RES curtailment [4].

Also, in the transport sector, electrification can be a successful strategy for decarbonization, while making the system as a whole more flexible. In fact, electric vehicles in Power-to-Mobility (PtM) application represent a valid alternative to traditional cars with internal combustion engines and can provide flexibility to the electricity system through smart charging strategies, for instance, by charging batteries during the period of low demands, thereby flattening out the electricity load profile.

Similarly, heat pumps in PtH application represent a cost-effective and more efficient alternative to conventional gas-fired boilers for heating purposes in buildings and also for reducing primary energy consumption thanks to their high conversion efficiency.

According to REmap [3], the number of electric vehicles worldwide will pass from the current 6 millions to 157, 745, and 1166 millions in 2030, 2040, and 2050, respectively, whereas the number of heat pump installations will pass from the current 20 millions to 155, 259, and 334 million in 2030, 2040, and 2050, respectively. The strong expected electrification of transportation and heating sectors could lead to higher peak loads, thereby requiring higher flexibility to match electricity demand and supply. Again, also in these latter cases, the added value of energy systems integration is given by the possibility to store excess electricity from RES and provide back-up supply to cover peak loads, thereby ensuring balance at all times with clean energy in the equation.

Another major trend in energy landscape is represented by the **large-scale deployment of distributed generation (DG).** In the past years, the power system has been affected by a fundamental revolution as compared to its traditional conception. The deployment of renewable technologies at a local level led to the switch from a "one-way" generation system mainly relying on a few large power plants connected to HV and EHV grids and located far from consumption areas to a "multi-directional" system, whose characterization and management are extremely complex. In the traditional electricity system, the electricity produced in large power plants reaches the users – through the transmission and distribution networks – playing the passive role of energy consumers. On the other hand, the energy model of DG mainly consists of a number of medium–small generation units (from a few tens/hundreds of kilowatts to a few megawatts) usually connected to distribution networks. DG units are usually located close to the loads to satisfy and designed to exploit renewable sources spread throughout the territory and otherwise not usable through traditional large-size generation units.

The benefits offered by this new energy model are different:

- increase of the efficiency of the electricity system thanks to the reduction of energy transport loss;
- increase of RES penetration levels and more rational use of energy; and
- optimization of the resources at local level and the local production chain.

According to REmap [3], the renewable energy share in power generation will more than double in 2030, reaching the value of 57% as compared to the current percentage of 25%, to arrive at values of 75% and 86% in 2040 and 2050, respectively. Only in the case of PV systems, the REmap cases foresee that the annual solar PV additions will pass from the current value of 109 GW/yr to 360 GW/yr in 2050, and a similar situation is expected for wind source, for which the annual additions are expected to pass from the current value of 109 GW/yr to 240 GW/yr in 2050.

The increasing intermittent renewables penetration in electricity systems is leading to an increase in the reliability and stability problems. The mitigation of uncertainty, which imperils the balance between generation and demand, urges the search of new sources of ancillary services, traditionally provided by bulky synchronous generators. Energy systems integration and in particular the coupling of the electricity and gas sectors reveals promising flexibility solutions for power systems through energy conversion and hydrogen storage. On the other hand, the operation of PtG technologies in periods of excess electricity supply removes the need for curtailment of renewable electricity generation or the need for additional investments in electricity transmission, distribution, or storage infrastructure.

An important aspect closely related to the changes that are affecting the energy sector is the **evolution of the role of the energy consumer**. Historically, the citizen has been a "passive" user, covering the role of the customer using the energy produced at a centralized level to meet the energy needs. Conversely, the scenario that has been taking shape in recent years sees the emergence of a new type of "active" customer who, thanks to digitization, is more informed about the own consumption and energy prices and is more sensitive to the use of "green" energy resources. Through DG units, the end users have the ability to produce and consume their own energy to store it and sell it back to the grid by exploiting the RES available locally; therefore, from simple consumers, they become "prosumers." The direct consequence is the birth of the "self-consumption" concept, where the consumption of energy produced occurs in the same site where it is consumed, both instantaneously and through storage systems, regardless of the subjects covering the role of a producer and a final customer, provided that they operate in the same suitably defined and confined site and regardless of the source that feeds the generation unit.

Another element through which the end user assumes the active role in the changing energy landscape is represented by Demand Response (DR). The United States Department of Energy (DoE) defines DR programs as changes in electricity consumption by end users in response to changes in the price of energy over time or the payment of incentives designed to lead to lower consumption of electricity in periods when the wholesale market price is high or when system reliability problems occur [5].

According to the aforementioned definition, the DR is an active response from consumers based on the price of energy or on the payment of incentives. In DR programs, the consumers are induced to quickly change their electricity consumption when there is a high energy demand or there are low-reserve margins. The reduction/modulation of energy consumption according to market price trends helps to limit the occurrence of energy price peaks. At the same time, DR services represent an important tool for network operators in maintaining a balance between supply and demand and in ensuring the reliability of the system. The end user can, therefore, temporarily vary the power commitment in response to a price signal (deriving from tariffs or directly from the electricity market) or in compliance with agreements made with subjects such as aggregators and network operators.

It is important to underline that local DG units can also be considered as a DR resource as they also allow for a reduction in the withdrawal of energy from the grid without affecting the absorption and load curves of consumers. The classic actions that DR can adopt can be divided into three main categories:

- reduction of demand in the peak periods of the system;
- shifting of demand from peak periods to off-peak periods, obtaining an effect of leveling the peaks and filling the valleys of the load curve (load shifting);
- self-production or use of energy stored, which does not change the internal absorption profile of the user's system but allows to reduce the energy demand from the network.

Last but not least, the emerging paradigm of energy communities is expected to function as an important tool for engaging end users in renewable generation and low carbon technologies, while also promoting participation in the market of end users that otherwise could not be able to do so.

The added value of energy systems integration in the major trend related to end user engagement and empowerment is mainly given by the possibility to exploit synergies among multiple energy carriers at the local level to increase energy efficiency and RES utilization, as well as to enhance the potential of decarbonization of the energy demand for heating and cooling. For instance, PtH implemented through heat pumps allows to achieve larger flexibility of the energy demand and improve considerably the use of renewables for heating and cooling demands in buildings. Moreover, the high conversion efficiency of this technology can lead to important economic and environmental benefits. The PtH technology coupled with thermal storage could be even more convenient, thanks to the possibility to activate DR services and offer ancillary services to the electric grid. In fact, the excess renewable electrical energy produced could be converted into thermal energy and stored in thermal energy storage, thereby reducing RES curtailment and making the electrical grid more stable to sudden variations of RES. This brings benefits also to network operators through a more efficient use of the existing generation capacity, the reduced need to upgrade the distribution network, the reduction of peak loads, and the more flattened load forms, as well as the reduction of management costs of generation units. In addition to efficient electricity-based (via heat pumps) heating and cooling devices in single houses and small residential buildings, low-carbon district heating and cooling grids can cover the generation and distribution of thermal energy in urban districts. On the other hand, coupling electricity and heating sectors through combined heat and power (CHP) systems would allow to exploit locally the waste heat from power generation processes for thermal purposes in buildings, thereby increasing the efficiency in energy resource use.

## 1.2 European Union as the Global Leader in Energy Transition

The transition of European Union (EU) to net-zero carbon emissions by 2050 is a big challenge but also a great opportunity to modernize the continent's economy and promote growth, employment, technological advancement, and social inclusion.

An effective demonstration of the EU commitment in combating climate change is represented by the **Clean energy for all Europeans package** [6], which is a fundamental measure to lay the foundations for the realization of "a neutral climate economy" by 2050. It contains a set of measures related to energy efficiency, renewable energy, structure of the electricity market, security of electricity supply, and governance rules for the Energy Union. It consists of eight legislative acts that provide for an update of the European energy policy framework aimed at facilitating the energy transition, defining a modern European energy market, promoting and integrating electricity produced from RES, promoting energy efficiency, and strengthen the regulatory framework in which European and national institutions operate.

In more details, the Clean Energy Package introduces significant changes to the structure of the European electricity market by revising and replacing the provisions contained in Regulation 2009/714/EC [7] and in Directive 2009/72/EC [8], currently at the basis of the regulatory framework relating to the internal electricity market of the Union. These changes actually allow for the creation of an electricity market for the Union characterized by more variable and decentralized production, greater interdependence between individual national markets, and higher opportunities for consumers to participate as active players in the market through demand side management, aggregation, self-generation, and the use of storage systems and digitalization. The new directive 2019/944/EU (Energy Market Directive – EMD II) [9] aims to adapt the current regulatory framework to the new market dynamics taking into account the opportunities and challenges related to the decarbonization objective of the energy system and the possible technological developments, in particular those relating to consumer participation and cross-border cooperation. The main objective of EMD II is the construction of an internal market governed by common rules that can guarantee everyone access to the electricity carrier. In relation to consumers, the EMD II provides an important paradigm shift, aimed at qualifying consumers as "active consumers," who can operate directly or in aggregated manner, sell self-produced electricity, as well as participate in flexibility and energy efficiency mechanisms. The directive states that all consumers should be able to benefit from direct participation in the market, in particular by adjusting consumption according to market signals and, in return, by benefiting from lower electricity prices or other incentives. Another important innovation envisaged by the EMD II directive concerns the introduction of the notion of *Citizen Energy Community* or an energy community which will be guaranteed to operate on the market under equal and non-discriminatory conditions compared to other market players, being able to freely cover the roles of end customer, producer, supplier, or manager of distribution systems.

The innovations introduced by the Clean Energy Package in the field of energy produced from renewable sources are aimed at encouraging the use of these resources for the energy transition up to 2030, setting new objectives at the EU level, simplifying the related authorization procedures, providing stability to the financial supports and strengthening consumer rights. The new Directive 2018/2001/EU (Renewable Energy Directive – RED II) [10] on the promotion of the use of energy from renewable sources applies a substantial revision of the regulatory framework provided for in Directive 2009/28/EC [11]. In detail, RED II pays particular attention to the self-consumption of renewable energy, providing that consumers are allowed to become consumers of renewable energy, capable, also, of producing, storing, and selling the electricity generated in excess, both individually and in aggregated form. Another fundamental innovation envisaged by RED II is the introduction of the notion of *Renewable Energy Community*, that is an energy community with the right to produce, consume, store, and sell renewable energy. Furthermore, these communities will be able to exchange, within the same community, the renewable energy they produce and access the electricity market, directly or through aggregation, in a non-discriminatory way.

The provisions on energy efficiency, introduced by the Clean Energy Package, aim to establish new efficiency targets for both the EU and the Member States, introducing new guidelines and expanding consumer rights in the field of heating and cooling metering, for billing and for domestic hot water production. The new Energy Efficiency Directive [12] amends the previous Directive 2012/27/EU [13], modifying the current provisions directly linked to the achievement of the 2030 targets and introducing new rules aimed at extending consumer rights and improving access to smart metering. A further element of the package, in the field of energy efficiency, is Directive 2018/844/EU (new Energy Performance of Buildings Directive – EPBD) [14], which entered into force on 9 July 2018, amending Directive 2010/31/EU on the energy performance of buildings. The new EPBD contains provisions concerning energy efficiency objectives for buildings, energy certification, methods of verification, monitoring and control of energy consumption, and the definition of obligations related to the installation of charging points for electric vehicles. Furthermore, it introduces the definition of the Smart Readiness Indicator (SRI) and a methodology to calculate this indicator to assess the ability of a building or a property unit to adapt its functioning to the needs of the occupier and the network and to improve its energy efficiency and overall performance. The indicator of readiness of buildings to smartness takes into account the characteristics of higher energy saving, comparative analysis, and flexibility, as well as features and capabilities that are improved through more interconnected and smart devices.

Finally, the EU Regulation 2018/1999 on the governance of the Energy Union and Climate Action [15] aims to encourage cooperation between Member States to achieve the EU energy objectives and targets, in particular by strengthening the programming and reporting obligations of individual Member States in the field of energy, climate, and in relation to the implementation of the measures envisaged by the new structure of the Energy Union. The regulation outlines the five dimensions of the Energy Union, namely, (i) decarbonization, (ii) energy efficiency, (iii) energy security, (iv) internal energy market, and (v) research, innovation, and competitiveness, and defines the obligation for each Member State to send to the European Commission a National Integrated Energy and Climate Plan, covering periods of 10 years. The plan must, among other things, contain

- an overview of the procedure followed for defining the plan itself;
- a description of the national objectives and contributions relating to the five dimensions of the Energy Union;
- a description of the policies and measures adopted to achieve the aforementioned objectives;
- a description of the current state of the five dimensions of the Energy Union; and
- an assessment of the impacts of the policies and measures implemented to achieve the aforementioned objectives.

Promoting secure, reliable, competitive, locally produced and sustainable energy is an increasingly central issue on the agenda of the European Council, which in December 2019 announced the European Green Deal [16], a roadmap whose purpose is to make the EU “a fair and prosperous society, with a competitive and resource-efficient modern economy, in which there are no net greenhouse gas emissions in 2050 and economic growth is decoupled from the resources used.”

The Green Deal is divided into a series of macro-actions containing strategies for all sectors of the economy, in particular transport, energy, agriculture, construction, and industrial sectors, including new regulatory provisions and investments, to be implemented in the next years till 2050.

The strategy is divided into eight main objectives:

(1) Making the EU climate goals for 2030 and 2050 more ambitious;
(2) Ensure the supply of clean, economical, and safe energy;
(3) Mobilizing industry for a clean and circular economy;
(4) Building and renovating in an energy- and resource-efficient way;
(5) Accelerate the transition to sustainable and smart mobility;
(6) "From producer to consumer": designing a fair, healthy, and respectful food system of the environment;
(7) Preserve and restore ecosystems and biodiversity; and
(8) "Zero pollution" for an environment free of toxic substances.

The first climate action initiatives under the Green Deal include

- a European climate law to incorporate the goal of climate neutrality into EU law to 2050, which in turn has four objectives: (i) establish the long-term direction for achievement of the 2050 climate neutrality goal; (ii) create a monitoring system of progress and take further action if necessary; (iii) provide conditions of predictability to investors and other economic actors; and (iv) ensure that the transition to climate neutrality is irreversible.
- a European climate agreement, aimed at spreading awareness and promoting action, in a first moment focused on four areas (green areas, green transport, green properties, and green skills), while it may subsequently involve other areas of action, such as consumption and sustainable production, soil quality, healthy food and sustainable nutrition, and so on.
- The Climate Target Plan 2030, with which it is intended to further reduce net emission (setting a new reduction target, for 2030, of at least 55% compared to levels of 1990) but also stimulate the creation of green jobs and encourage international partners to be more ambitious in containing global warming by limiting the global temperature rise to 1.5 ° C.
- A new EU strategy on climate adaptation, with the aim to make adaptation smarter, faster, and more systemic and to step up international action on adapting to climate change so that Europe becomes, by 2050, a climate resilient society fully adapted to the inevitable impacts of climatic change.

The EU "Green Deal" and the related European national requirements set precise targets by 2030 including:

- decarbonization of the building stock, transport, industry, and energy systems;
- involvement of consumers and citizen communities in energy systems;
- digitalization as an enabler of the environmental transition and participative energy markets;
- ambitious reductions in transport emissions; and
- reliability, adaptability, and resilience of the integrated energy systems.

The energy transition taking place in EU is also demonstrated by numbers. The EU energy mix, over the past decade of observation (2009–2019), is changed, with a smaller share of solid fossil fuels (whose share falls from 15% to 11.4%) and oil (which increased from 38.1% to 36.4%), mainly in favor of renewable sources, which in 2019 represented 15.3% of primary energy production (+5.2 p.p. compared to 2009). At the same time, the $CO_2$ emissions produced in EU have more or less constantly decreased over the course of the past decade, reaching a level of 2400 Mt in 2019, about 12% less than 10 years earlier.

Energy systems integration is the agenda of EU as a possible route to achieve the ambitious targets set to 2030 and 2050. In the near future until 2030, in EU vision, the share of RES, nuclear energy, and carbon-neutral gases and liquids will increase with high contribution to grid stability and uninterrupted energy supply. New energy carriers are being considered in energy, industrial, and transport applications, such as hydrogen and other carbon- neutral liquids and gases. Additionally, the future energy system will also rely on much better balancing capacities including better interconnections, storage capabilities, DR, low-carbon flexible generation units, and effective energy conversion options (Power-to-X). Particular interest is given to the hydrogen as an energy carrier, which will be mainly used for the following applications:

- Energy carrier for industrial applications;
- μ-CHP systems based on fuel cells for buildings;
- Fuel for mobility;
- Power generation; and
- Energy storage.

The concept of coupling electricity to other forms of energy has traditionally been referred exclusively to the electrification of sectors such as heating and transport. With the Clean Energy Package, this concept has been expanded in order to include Power-to-X systems that, starting from the electric vector, involve other energy vectors. These applications can provide flexibility to the energy system by managing to meet the demands for thermal energy, fuels, and mobility through PtH, PtG, and PtM technologies, respectively.

First, the market review concerns the rules relating to electric vehicles. Article 33 of the EMD II [9] states that Member States must provide the regulatory framework necessary to facilitate the connection of public and private charging points to the distribution networks. Also, the new EPBD [14] aims to facilitate the introduction of electric mobility by equipping buildings with infrastructure for electric vehicles. Pursuant to Article 8, Member States must provide for measures to simplify the installation of recharging points in new and existing residential and non-residential buildings and provide for the overcoming of any regulatory obstacles.

Second, the RED II [10] provides a first European target for heating and cooling from renewable sources. According to Article 23 of the RED II [10], Member States have the task to increase their percentage of renewable heat by 1.3% every year until 2030. Waste heat and cold can contribute up to 40% to objective, while district heating and cooling will have to contribute with an average annual increase in renewable energies of at least one percentage point.

The long-term vision to 2050 is well defined by ETIP SNET [2], which considers the electrification of European energy systems as the backbone of its societies and markets. In order to achieve a fully carbon-free energy system, it is needed to exploit in the best possible way integration options between electricity and gas networks as well as count on daily or seasonal storage such as hydro, batteries, hot water seasonal storage, and PtG conversion technologies. A key role in the future energy system will also be played by distributed energy resources that according to this vision will be exploited for their full potential, by helping to maximize the resilience of energy supply for electricity and heating and cooling needs. The future integrated energy system will rely on renewable electricity mainly from hydro, solar, wind, geothermal, and renewable heat and cooling from solar, biomass, biogas, and geothermal, renewable gas as biogas and renewable fuels as biofuels.

## 1.3 Pillars for the Transition Toward Integrated Decentralized Energy Systems

This book addresses the topic of integrated decentralized energy systems by focusing the attention on the pillars described below that will play a major role in the transition of the traditional energy systems toward this new energy paradigm.

Power conversion plays a key role in future integrated energy systems, where electricity enables for a switch of energy carriers through **Power-to-X technologies**, which provide energy storage and sector coupling by converting electricity into chemical energy and heat, thereby allowing circularity into the energy system. Power-to-X energy can act as a sink for electricity surpluses by using the available energy in a cost-effective way.

By enabling sector coupling while accelerating carbon neutral transition, **hydrogen as a vector** also plays an essential role in integrated energy systems. With high share of variable renewables, the production of carbon-free energy carriers as hydrogen from renewable electricity covers an important role for the decarbonization of the energy system as a whole. The production of hydrogen can provide significant flexibility to the power system, as well as – most importantly – seasonal storage of renewable electricity by blending hydrogen into natural gas grids. Hydrogen as a vector can be seen as an electricity storage method (Power-to-X-to-Power), which can contribute to the increase of stochastic renewable electricity penetration into the grid, but it also represents a versatile cross-vector medium enabling the deep decarbonization of non-electrified hard-to-abate sectors as renewable fuels, sector integration, and mobility.

In an integrated energy system where the locally available energy resources are used for their full economic potential, **storage in all forms and types** plays a crucial role. Energy storage can provide multiple services to the energy system as a whole by storing the energy produced in excess and delivering it on demand. It can smoothen the variability of RES, making the power system more reliable and flexible. Battery energy storage systems are considered among the best suited technologies for short and mid-term flexibility services, such as frequency regulation, spinning reserve, peak shaving, etc. Long-term storage services including seasonal storage are needed in the presence of high penetration levels of solar and wind energy production, and they are generally supplied by bulk energy storage systems, such as pumped-hydro plants or mechanical storage facilities and electrochemical energy storage. Thermal storage solutions can be used in several industrial applications as well as district heating, PtH applications, etc. Besides, they represent a strong support to heating and cooling electrification. These applications are cornerstone to enhance the energy system circularity, thanks to their characteristics of closing energy cycles without energy waste: storing excess electricity that would, in an open cycle, cause the curtailment of renewables, by converting it to other forms, enables new energy streams bending over the cycle toward useful ends, thus increasing circularity.

**Digitalization** is a key enabler for integrated decentralized energy systems by integrating innovative technologies in the electricity system through interoperable, standardized data architectures and related communication for achieving higher levels of efficiency. Digitalization improves the observability of the power system for stable and secure operation in the presence of high shares of RES, enabling advanced planning, operation, protection, control, and automation of the energy systems, through the availability of real-time information that improves system balancing and resilience at all time scales in the case of any unforeseen and sudden event. Information Technologies including semantic data models, Big Data management, and Artificial Intelligence will enable the optimization and automation of processes and support operators' decisions. Through digitalization, it will be possible to facilitate services and achieve full integration of all types of energy systems. Moreover, digitalization is also key to exploit the full potential of active consumers to contribute to the effective integration of RES in the power system. The massive integration of smart meters and Home Energy Management Systems will allow the implementation of new business models and aggregation schemes (e.g. energy communities) that exploit the flexibility of the active consumers.

**Smart mobility** plays an important role in accelerating carbon neutral transition. When supported by higher deployment of RES, it contributes with multiple benefits to the sustainability of the transport system. In fact, electric vehicles are expected to play a primary role in the decentralized energy system and represent a driver for increasing RES integration in the buildings to meet their additional power demand. **Smart grids** also support energy transition through reducing $CO_2$ emissions in a cost-efficient way. By optimizing the asset utilization, they reduce the needs for new investments. Moreover, they enable penetration of renewables and emerging and efficient technologies, thereby allowing minimization of costs and carbon emissions. Another important benefit related to smart grids is the provision of real-time and monitoring control that allows improving stability, resilience, and security of the power system. Last but not least, they enhance the quality of the supplied power through reducing commercial and technical losses.

Efficient energy use in buildings is another constituting factor for integrated energy systems. Moreover, because of the active local energy generation (building-integrated generation) combined with energy efficiency solutions (e.g. insulation and efficient appliances), new buildings in most cases will be **nearly zero-energy and possibly positive-energy buildings**. Employing energy-efficient solutions and renewable energies are critical factors to meet the energy and environmental targets set for the building sector. The first factor can reduce the building's energy consumption, while the second one can reduce the buildings' total energy intensity. Especially, positive energy buildings can be considered advantageous for the decarbonization of the building sector and a promising pathway toward sustainable urban development because of their scalability potential, renewable energy harnessing capacity and high energy efficiency.

Last but not least, **local energy communities** will become increasingly important in the transition toward a low- or even carbon-neutral energy system. Especially in the European context, they represent an emerging paradigm where active consumers and prosumers are engaged and play an active role in aggregated forms through renewable energy communities and citizen energy communities. Moreover, local energy communities can perfectly represent the concept of local integrated energy systems, which, characterized by well-defined boundaries, involve different energy technologies and carriers that can be integrated in order to optimally exploit the synergies coming from this interplay, thereby enhancing energy resources use.

## List of Abbreviations

| | |
|---|---|
| CHP | combined heat and power |
| DG | distributed generation |
| DoE | department of energy |
| DR | demand response |
| EHV | extra high voltage |
| EMD | energy market directive |
| EPBD | energy performance of buildings directive |
| EU | European Union |
| HV | high voltage |
| IRENA | International Renewable Energy Agency |
| PtG | power-to-gas |
| PtH | power-to-heat |
| RED | renewable energy directive |
| REmap | renewable energy roadmap |
| RES | renewable energy sources |
| SDG | sustainable development goals |
| SRI | smart readiness indicator |
| UN | United Nations |

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