Chapter 1

Concept, Definition, Enabling Technologies, and Challenges of Energy Integration in Whole Energy Systems: To Create Integrated Energy Systems

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Status Quo, Challenges and Outlook

The energy crisis and environmental issues have led to the need for integration of energy systems with the aim of efficient use of energy sources to supply different energy demands. For this aim, optimal switching among different conventional and renewable energy sources should be scheduled to enable different energy systems to efficiently meet the energy demands in every sector of the whole energy system. The vector coupling of energy systems is challenging due to technical and economic barriers. Therefore, the first stage is to answer the question that what is the concept and definition of vector coupling of energy systems and related challenges to achieve whole energy systems? and what enabling technologies are required to integrate different energy systems?

1.1 Introduction

Nowadays, vector coupling of energy systems, i.e., integration of different energy systems to achieve comprehensive energy-efficient systems, is ongoing [1]. The energy crisis and air pollution issues [2] and also restraining the uncertainty and intermittency of renewable energy sources in a high penetration [3] are the main reasons for the transition from conventional single-carrier energy systems towards integrated (or coupled) energy systems [4]. Attaining energy sustainability can also be accelerated by the integration of energy systems [5]. Furthermore, the uninterrupted and reliable energy supply is an advantage of integrated energy systems [6]. By vector coupling of energy systems, in addition to improving the energy efficiency, the system flexibility is also improved [7]. This results in a reduction in load interruption in case of failure in the conventional generators [8]. Figure 1.1 illustrates the Sankey diagram of the energy exchange in an integrated energy system.

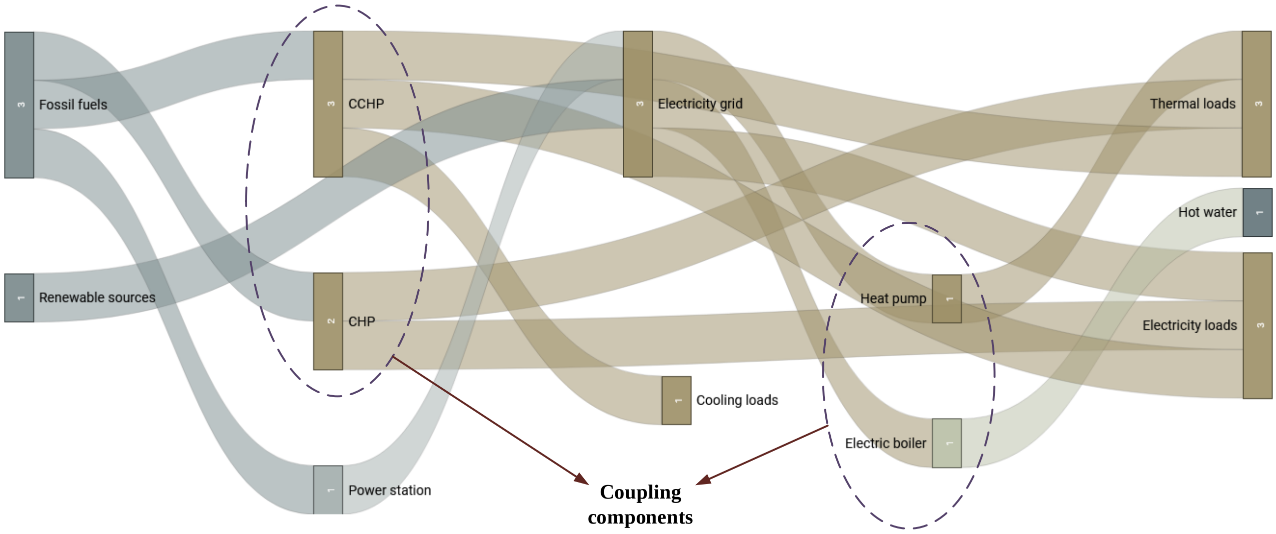

Figure 1.1. Sankey diagram of some components in integrated energy systems

Multi-energy systems are mainly based on synergy among different energy carriers such as electricity, gas, heat, and hydrogen carriers [9]. In such systems, there are degrees of freedom for both the supply and demand sides [10], where the much energy-efficient way to meet the load is optimal scheduling of the energy sources [11]. The vector coupling in energy systems is accomplished with different goals such as improving energy saving, operational costs, reliability, or carbon emission. Due to the above-mentioned advantages, the planning and operation of integrated energy systems instead of single-carrier energy systems have been increasing in recent years [12].

Integration of several multi-carrier energy systems is affordable via coupling technologies such as combined heat and power (CHP) [13], combined cooling, heating and power (CCHP) [14], heat pump [15], electric boiler [16], and gas boiler [17] systems. The characteristics of the coupling points among the multi-energy system for improving the operation and efficiency of the overall system can be studied from the viewpoint of dynamic and static features. In Figure 1.2, a schematic diagram of the energy conversion among gas, electric, and heat networks using coupling components (i.e., energy conversion systems) is presented.

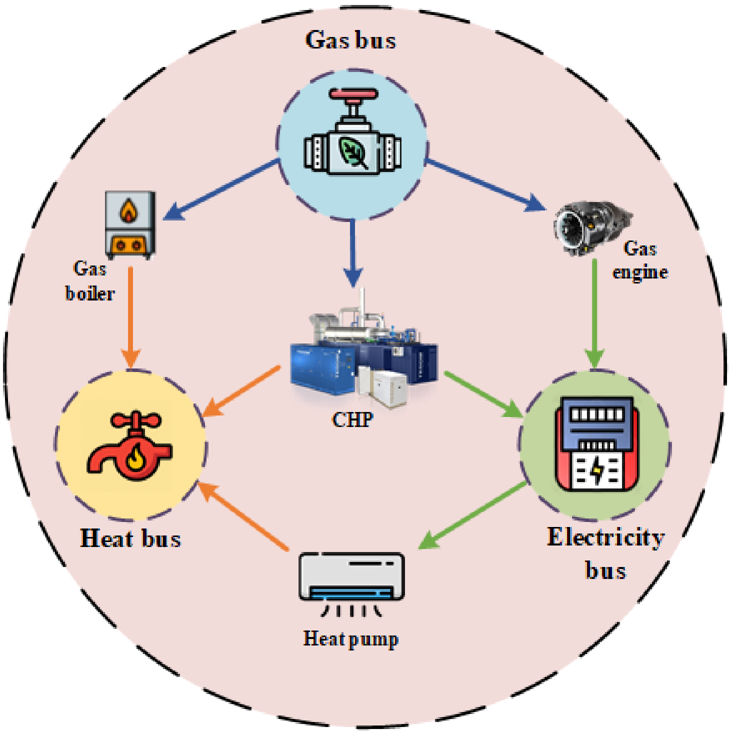

Figure 1.2. The role of energy conversion units in the coupling of energy systems

A key concept for energy integration is the distributed generation concept since a large amount of energy losses has occurred in the generation, transmission, and distribution parts of the electricity systems (respectively generation, distribution, and transmission), which requires “on-site” and “near-site” power generation to overcome [18]. One important type of distributed generation units is renewable energy sources, which are critical to meet energy crisis and decarbonization [19]. Among renewable energy sources, variable renewable sources, including solar photovoltaic and wind turbines, are the most promising ones due to having no operation cost [20]. However, renewable sources are largely dependent on environmental conditions and exhibit intermittent and uncertain behavior [21]. Integrating these generation units can, therefore, compromise the system's security if effective energy management approaches are not used in the case of the high penetration of such renewable energy systems [22]. Energy conversion [23], energy-vector shifting among resources [24], utilizing energy storage systems [25], and demand flexibility [26] are available solutions to meet the surplus energy of variable renewable sources, for a case when the conventional generators are not able to accommodate the uncertainty of variable renewable sources.

There are two major kinds of vector coupling in the energy sector, including end-use sector coupling and cross-sector coupling [7]. Examples for the first one are using a heat pump to electrify the heating system [27] and using CHP units for cogeneration of heat and power [13]. The second vector coupling type is energy integration in main networks, such as the integration of electricity, gas,

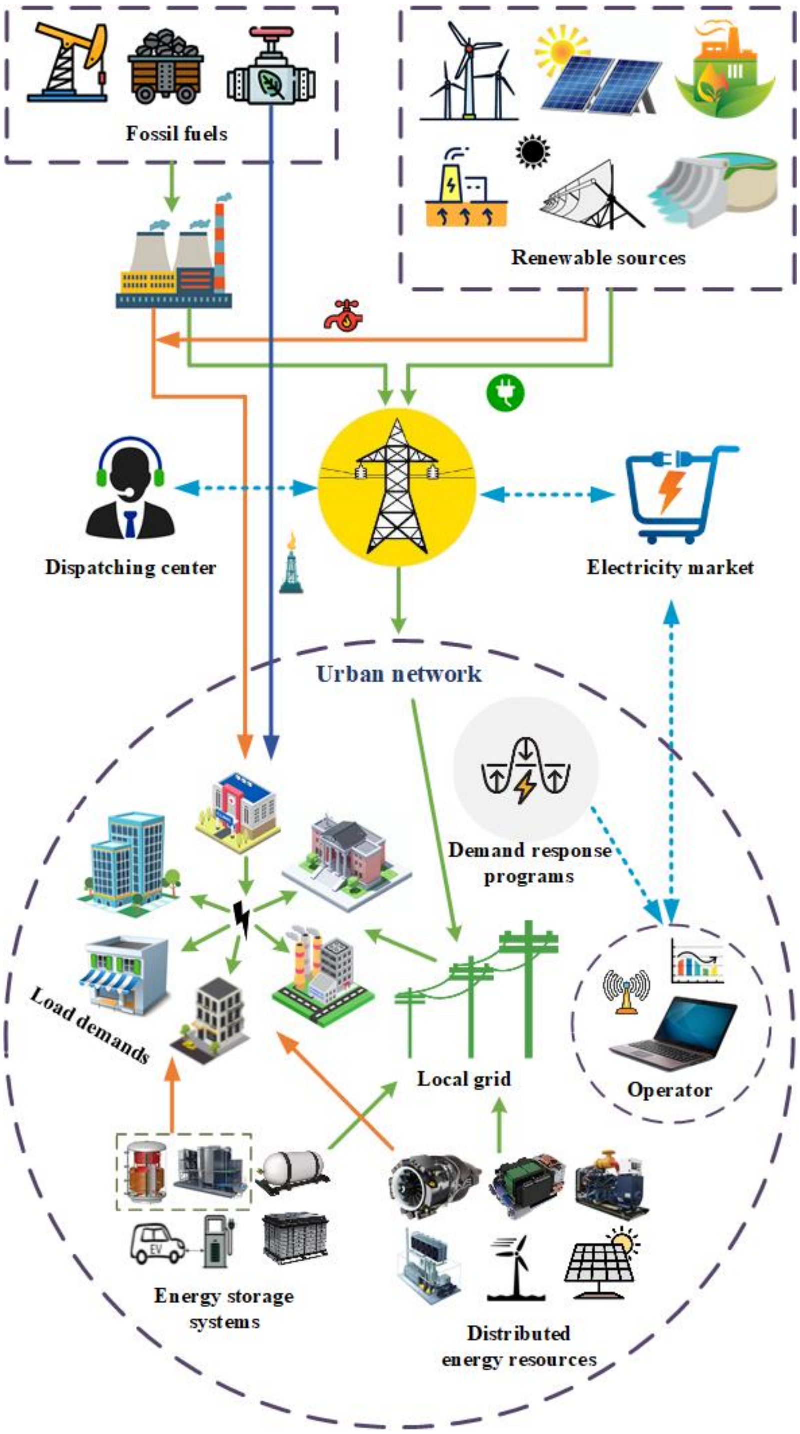

Figure 1.3. Schematic diagram of an integrated energy system

and heat networks. For example, power-gas networks have been attracted a lot of attention in recent years [28]. Vector coupling between supply and demand in renewable-based systems with high penetration [29]and power-to-X technologies [30] are some other approaches of the vector coupling of energy systems. From another point of view, vector-coupling of energy systems are divided into two categories of multi-energy systems and distributed multi-energy systems [31]. Vector coupling of energy systems can be considered for integrating multi-energy systems on every scale, such as individual dwellings, buildings, district, city, region, or country level [32]. A wide number of energy systems and sectors can be integrated to attain the mentioned advantages of vector coupling of energy systems such as residential, commercial, industrial, transportation, agricultural, etc. The increasing penetration level of renewable sources, energy storage systems, and CHP energy units have evolved both supply and demand sides and contribute to the implementation of sector coupling of energy systems [33].

The energy vectors imported from the boundaries of the whole system could be electricity from conventional or renewable sources, natural gas, or waste heat from the industrial processes, etc. [34]. The grid parameters influence on performance and efficiency of integrated energy systems. For instance, the parameters of the electricity, heat, and gas networks [35] and parameters of conversion components (like CHP, heat pump, energy storage systems, and diesel generators). On the other hand, the output of integrated energy systems can be the nodes' voltage, active/reactive power, power losses (for electrical grids), heat power, supply and return temperatures, mass flow rates, and losses (for district heat networks), and nodal pressures, gas flow rates, and losses (for gas networks) [35]. In Figure 1.3, the schematic diagram of an integrated energy system is given.

In integrated systems, in low-demand hours, when the RES's generation is additional, the surplus electrical energy is adopted to generate hydrogen from water, in which the produced hydrogen is taken into account as renewable energy. The surplus energy could be used in transportation, gas grid, and even chemical industry to generate high-temperature thermal energy such as hydrogen usage in the steam reforming process. In addition, hydrogen usage in the aviation and marine sectors is an appropriate choice due to the problems of using electricity. However, more flexible consumption and energy storage systems can also be employed to meet the surplus generation of variable renewable sources (i.e., solar photovoltaic system and wind turbine) [36].

Despite the complexity of integrated multi-energy systems, they have received significant attention in terms of research and practical aspects. There are a lot of cases implemented in practice, such as a Euro project in [37], the University of Parma Campus in Northern Italy [38], the CCHP systems located in eastern Tehran [39], and the decentralized micro-CHP systems in the UK [40]. China's energy policy with social capital supports the construction of integrated multi-energy systems, which are increasingly developing [1]. Furthermore, in [41], the multi-vector energy analysis has been accomplished for interconnected power and gas systems of Great Britain and Ireland, both containing a high penetration level of wind power, whereas the Ireland systems depend on gas import from Great Britain. The analysis has revealed that the hybrid gas and power system of Great Britain is more resilient compared to the Ireland system.

The main keywords of the previous works related to the understudy context associated with the temporal relationship among them are outlined in Figure 1.4. This graph has been created in VOSViewer software using the “Web of Science” research tool.

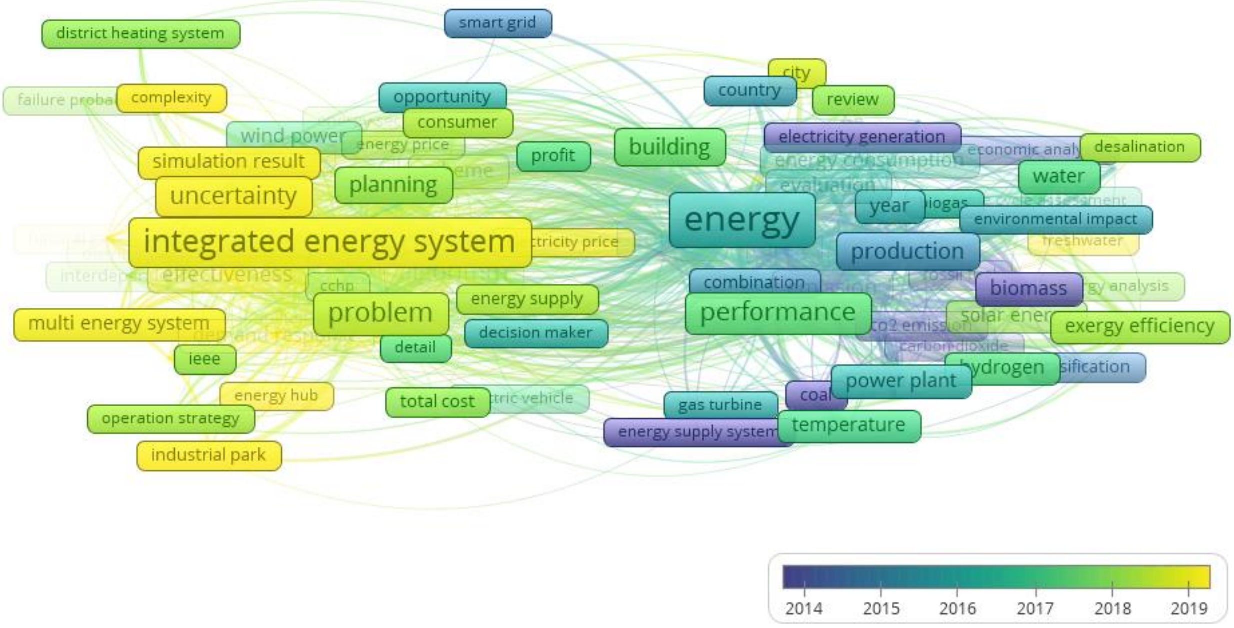

Figure 1.4. The main keywords of the previous works regarding the integrated energy systems

In this chapter, the prerequisites for the integration of energy vectors to create integrated energy systems that is critical to achieve whole energy systems are discussed. For this aim, the vector-coupling definition related to integrating energy systems is given. In addition, the enabling technologies, including energy technologies (coupling and non-coupling energy technologies) and information and communication technology (ICT) are reviewed. The barriers and challenges for coupling energy systems are also discussed in this chapter. Furthermore, the role of demand flexibility in developing such systems is given. Moreover, the decarbonization of energy systems with electrification approaches as a goal for integrating energy systems is described in this study.

The chapter is continued as follows: the definition of vector coupling in multi-energy systems is given in Section 1.2. Enabling technologies for coupling energy systems are enumerated in the next section. Section 1.4 discusses the demand-side management programs. The electrification options and their role in the decarbonization of the whole energy system are outlined in Section 1.5. The next section relates to the challenges and barriers for integrating energy systems. Finally, the paper is concluded in Section 1.7.

1.2 Definition

Integration of all the energy carriers has been stated as the definition of the vector coupling of energy systems [42]. In addition, sector coupling has been defined as converting the surplus power to other forms of energy to be used efficiently in high-demand hours or used in other applications such as the industrial sector [43]. This is while the waste or excess heat of power stations or distributed generation units and the waste heat from industrial processes is not generally considered as a vector coupling action in energy systems and only considered as multi-energy systems [42]. Some distinctions between multi-carrier energy systems and integrated energy systems can be found in the literature [42]. Therefore, there is not a widely accepted standard for the vector coupling of energy systems.

In this chapter, the vector coupling of energy systems is defined as follows:

"Vector coupling of energy systems is integration/combination of different fuels (such as fossil fuels, coal, natural gas, hydrogen, biogas, and biomass), different energy systems (such as electricity, gas, hydrogen, and district heat networks), different energy sectors (such as residential, transport, commercial, industrial, and agricultural) or energy systems (such as energy hubs, microgrids, virtual power plants, and building) to coordinate the centralized and distributed energy supply systems (such as power stations, renewable sources, diesel generators, CHP plants, and fuel cells) and energy storage systems (such as battery, thermal, cooling, hydrogen, and compressed air energy storage systems) with every purpose (such as improving the environmental performance, economic operation, energy efficiency, flexibility, and reliability/availability) via suitable coupling technologies (such as CHP, heat pumps, electric and gas boilers, chillers, microturbines, and fuel cell) to supply different energy demands (like electrical, heating, lighting, cooling and every combination of them), by optimal interaction/linkage and switching among energy sources in order to handling a considerable share of renewable sources and better managing sudden failures."

1.3 Enabling Technologies

Vector coupling of the current energy systems will be affordable by respective enabling technologies [42]. These technologies include energy technologies as well as information and communication technology (ICT), which are discussed. These technologies are categorized in Figure 1.5.

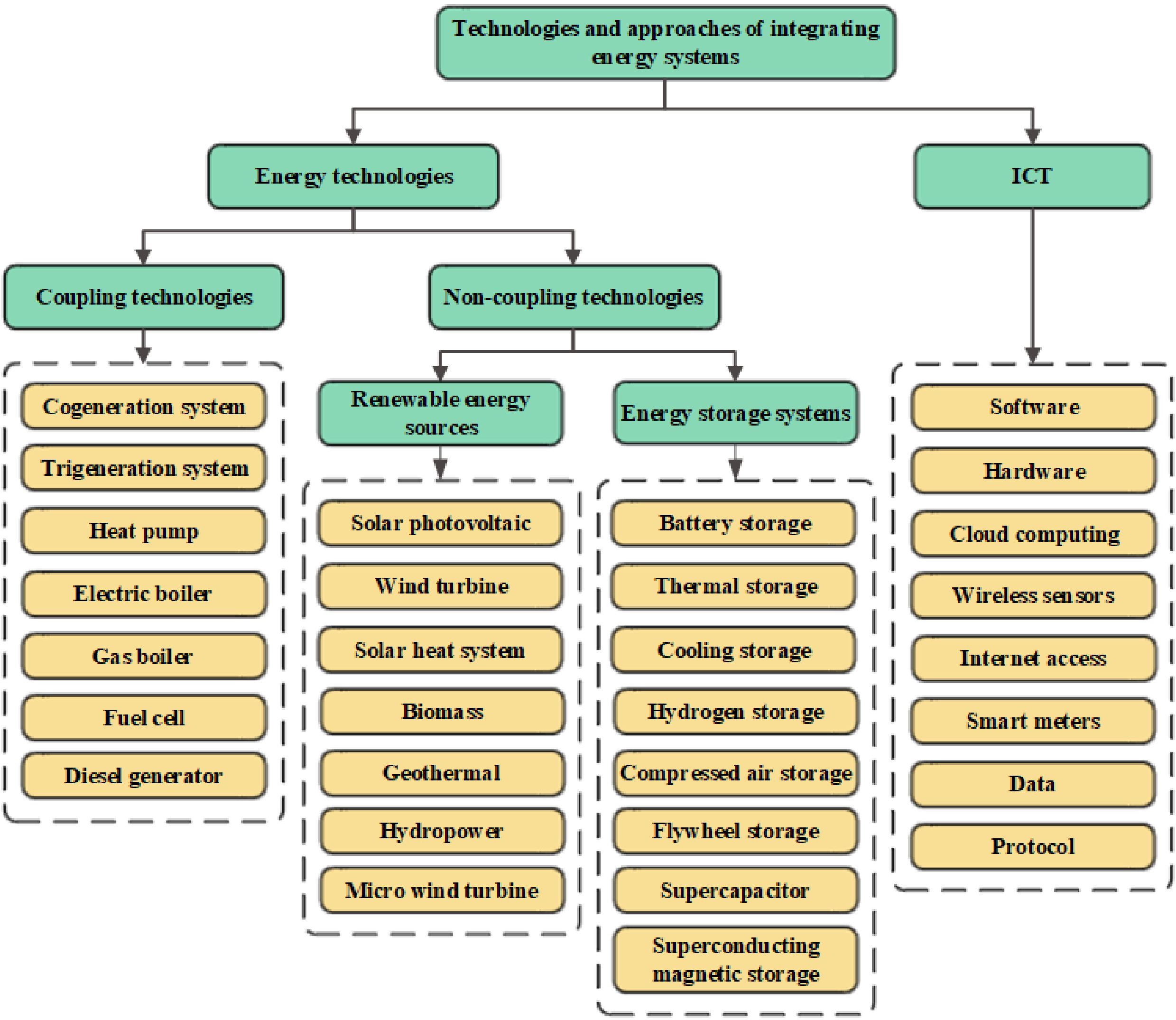

Figure 1.5. Required technologies for integrating energy systems

1.3.1 Energy Technologies

The energy technologies that are required for coupling energy systems are divided into two categories, including coupling elements and non-coupling elements. Coupling components locate in inter-network locations [35]. For instance, the CHP systems are located among gas, electrical, and district heat networks, or electric heat pumps are located among electricity and heat networks [44]. On the other hand, the non-coupling components deal with one type of energy. For instance, the battery storage is located in the electricity network, or thermal storage is situated in the district heat network. In the following, the enabling energy technologies and approaches required for vector coupling of energy systems are discussed.

1.3.1.1 Coupling Energy Technologies (Energy Converting Systems)

The vector coupling of different energy systems needs combination and management of multi-energy together. Coupling components (or conversion systems) relate to different energy carriers to efficiently use the energy sources. The most known conversion systems to couple energy systems are CHP, CCHP, heat pump, boiler, diesel generator, and fuel cell. Among them, CHP plants and heat pumps are seen as the key components for integrating energy systems.

The most noticeable technology for integrated multi-energy systems is the CHP system, which is capable to efficiently generate heat and power, simultaneously [24]. Mainly, CHP systems are gas-fired and coal-fired systems. A CHP system could be a gas turbine with a corresponding efficiency and heat-to-power ratio [35]. The CHP units are mainly integrated with an auxiliary boiler, which the fuel for such boiler is supplied from various sources like electricity. In addition, gas- and hydrogen-based fuel cells are also seen as promising cogeneration systems for the implementation of whole energy systems. Fuel cells are new but non-renewable energy systems that, in addition to environment-friendly generation, can be fueled by hydrogen or different gases, which is another advantage of such generation systems. Cogeneration systems have various advantages contain 30% decarbonization, efficiency over 80%, increasing supply security, 30% saving on energy bills, and loss reduction in both the distribution and transmission levels [45].

CCHP systems or so-called trigeneration systems are another coupling facility to generate cooling, heat, and power, simultaneously. CCHP is mainly a developed form of CHP. Accordingly, CHP systems can be a trigeneration system when they are associated with heat-to-cooling equipment, which are absorption/adsorption machines [46]. By using CHP and CCHP systems, 30–50% energy saving is achieved [47] in comparison to separate production of heat and power, which have about 30% energy efficiency [18]. In other words, using cogeneration and trigeneration systems, 75–80% of the input fuel is converted into useful energy [18]. These systems mainly contain gas engines and gas turbines [47].

Heat pumps (generally means electric heat pumps) is another technology effective on vector coupling of energy systems used to transfer the heat from a colder source (such as the external environment of building or water) to a hotter sink (such as indoor air) for heating aims [48]. Based on their application, the heat pumps are divided into three types contain water-source [49], air-source [50], and ground-source [51] heat pumps. Heat pumps can also operate as chillers for cooling aims. However, chillers can operate in cogeneration mode by producing cooling and heating through using a heat recovery condenser integrated with the chiller. There is also another type of heat pump called gas-fired heat pumps, which are located between gas and heat networks.

Based on the literature [35], a system with CHP systems and heat pumps has the lowest carbon emission, whereas the same system with gas boilers has the highest carbon emission. The most effectiveness of the presence of CHP or heat pump on the total emission depends on the emission of the electricity grid. In addition, a system with heat pumps has the least energy cost, whereas the same system with gas boilers results in the highest energy cost. The most effectiveness of the presence of CHP or heat pump on the total energy cost depends on the energy cost of the electricity grid. By using a combination of technologies such as CHP systems and heat pumps, the balance between techno-economic and carbon emission aspects might be in place.

Boilers as steam-generating systems are other technologies to enable the energy systems to be efficiently integrated [52]. Such conversion systems are responsible for a significant portion of energy use in the world. Heating water or steam is the result of using boilers for heating aims by consuming natural gas, oil, coal, electricity, etc. [53]. The energy efficiency of boilers is about 75–90% [54]. In industrial processes, the generated heat is used by steam turbines to generate electricity.

The microturbine (or so-called micro gas turbine), as another coupling component, is a high-speed and small gas turbine. Such systems generate electricity by consuming different kinds of fuels. The electrical efficiency of a microturbine is about 20–30% and its heat-to-power ratio is about 1.3–2 [55].

1.3.1.2 Non-Coupling Energy Technologies

Non-coupling components play critical roles in coupled energy systems. These components include renewable sources and energy storage systems. As mentioned, increasing the penetration/share of renewable sources is the main reason for integrating energy systems, particularly the variable renewable sources, including solar systems and wind turbines, because of their zero generation cost. However, other renewable sources such as geothermal, biomass, hydro energy, and tidal energy are developing. Apart from grid connection of renewable sources, the surplus power of a decentralized photovoltaic system can directly electrify transport or indirectly supply a heat pump to supply the heating loads. Hydrogen or methane may also be stored by using the surplus electricity of renewable sources or fed into the natural gas network [45].

Energy storage systems are critical facilities for vector coupling of energy systems to increase the degree of freedom in such systems. Using such systems can significantly reduce wind and photovoltaic curtailment and also operation costs [56]. There are different types of energy storage systems for storing energy. Electricity storage has different types such as battery storage, electric vehicles, supercapacitor, flywheel, pumped storage, and compressed air energy storage [57]. The other types of energy storage systems include heat storage, cold water storage, and hydrogen storage tank. There is also another energy storage system called seasonal energy storage systems, which are able to meet the seasonal intermittency of renewable sources. Such systems can play a backup role in the case of system failure. Hybrid energy storage systems have also been focused in recent years. These storage systems are the combination of two or more storage technology to utilize the advantage of different storage technology such as the combination of high-power and high-energy battery storage technologies [58].

1.3.2 Information and Communication Technologies

Information and communication technology (ICT) is another enabling technology for integrating energy systems. ICT is a diverse set of electronic technologies and related approaches used to store, create, manipulate, receive, share, exchange, manage, and transmit information from one place to another by using gadgets such as cell phones, the wireless network, and the internet. Through ICT, the message delivery is accomplished faster, more convenient, and easy to access. ICT tools include software, hardware, services, and communications. Smart meters, controllers, wireless technologies, and the Internet of Things technology are examples of ICT. Internet of Thing technology as a novel ICT form (from 2009s) is a developed form of the radio-frequency identification technology (from 1980s) and the wireless sensor networks (from 1990s) [59]. Although the ICT concept was first born in the 1940s, still there is not a uniform definition for this concept [60].

This technology is essential for linking and coordinating energy systems, especially in the presence of variable renewable energy sources. The optimal switching among energy sources to efficiently save energy consumption considering the comfort level of energy customers is not possible without ICT equipment and related services. This technology provides intelligent monitoring and management systems for energy saving as well as energy efficiency by automation of energy management [61]. The role of ICT is critical in the intelligent management of connecting modern energy networks, in which the coordination of distributed energy resources for enabling collaborative storage and demand response scenarios should be accomplished by this technology for increasing the share of renewable energy resources [62]. The management of grid stability and power quality issues in integrated energy systems are guaranteed by ICT [63]. The ICT contributed to accumulating information from every point of an integrated energy system for demand forecasting, control, protection, and optimal operation of the grid. This technology has increased the requirement for DC power since the equipment of such technology utilized DC power to accomplish related tasks [64]. Energy trading in regional markets is also possible with ICT infrastructures and equipment [65]. Self-healing, energy loss minimization, and emission control are some other applications of ICT in power systems [66]. Through the ICT, the observability of the energy grid is significantly enhanced by real-time monitoring. The ICT has an important role in the automation of load management with switching among energy sources based on the customers behavior. For instance, the comfort requirement in a smart building includes indoor air quality, visual comfort, and thermal comfort [67].

1.4 Importance of Demand-Side Management in Developing Integrated Energy Systems

In addition to using technologies, demand-side management is also effective in developing integrated energy systems [68]. Energy efficiency and demand flexibility as the roles of demand-side management are essential for integrating energy systems. This is because the aim of developing integrated systems is energy conservation as well as enhancing the share of renewable energy sources in supplying the energy demands. Accordingly, the demand-side management concept is divided into energy efficiency and demand response programs. Energy efficiency means using less energy for a typical task and covers several subjects, including the use of new energy-efficient technologies instead of conventional ones, energy saving, and energy transition, whereas demand-side response programs enable the responsive loads to participate in demand flexibility programs. Demand response

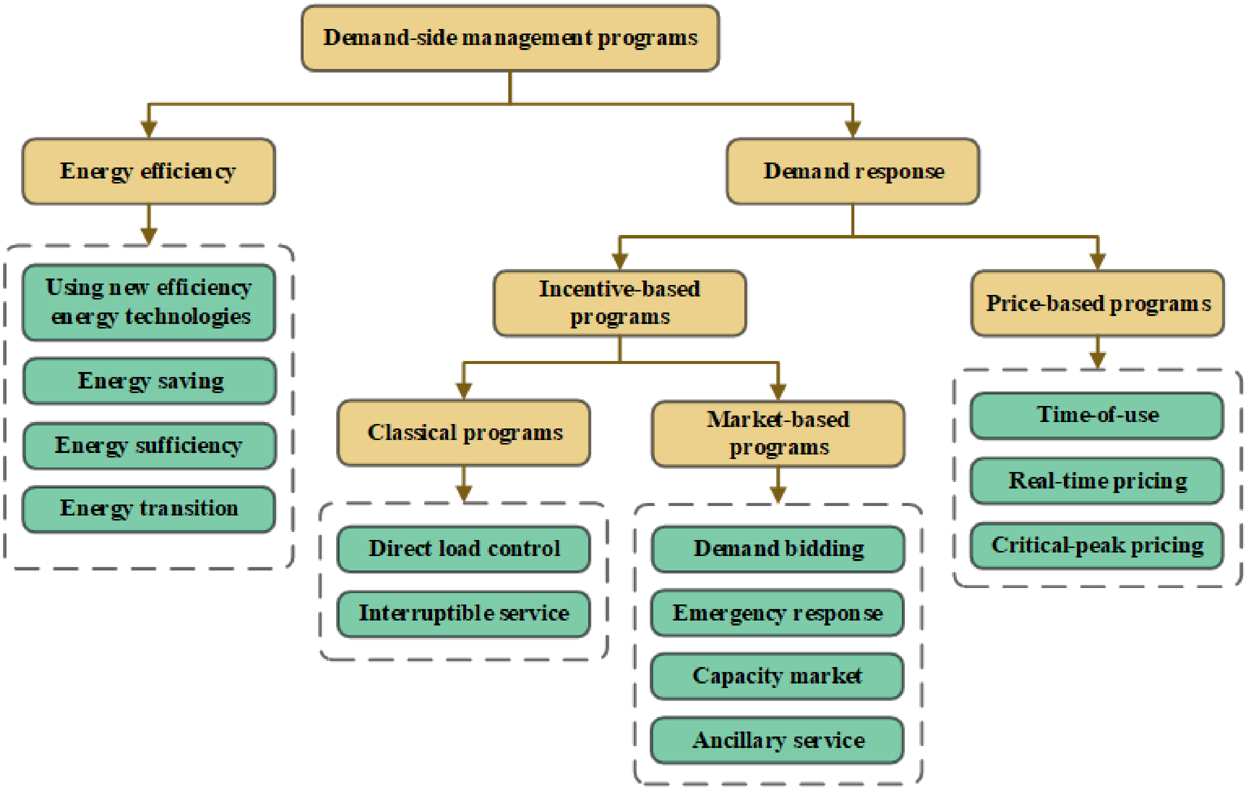

Figure 1.6. Demand-side management approaches and related subcategories

programs in integrated energy systems have been focused on in research studies [26]. For effective implementation of such programs, load forecasting for different load kinds of demands [69] is an indispensable action to manage different load types for optimal participation in demand response programs. However, in the existing research studies regarding load forecasting, a few of them are consistent with integrated energy systems [1]. The demand-side management approaches and related subcategories are listed in Figure 1.6.

1.5 Role of Electrification in Decarbonizing Energy Systems

Coal and oil are responsible for 80% of carbon emission, and therefore, using renewable sources and electrification of the transport sector are the main steps toward decarbonization [19], which as one of the major aims of integrating energy systems [70]. Among the energy sectors, more than two-thirds of all energy is used in cities, whereas urbanization is increasing that accelerates the role of cities in carbonization [71]. Decarbonization is not limited to a specific sector of energy systems and is related to the whole energy system. By efficient use of energy sources, the higher efficiency of integrated energy systems can be achieved, which results in lower fuel use and carbon emission [72]. Like renewable sources, the fuel cell systems generate zero/negligible greenhouse gas emissions and are seen as a clean combined energy system since it enables direct electrification by electrolytes [42]. Energy storage systems are other effective facilities for decarbonization by reducing the peak load to reduce the power generation of the high-emission conventional generators or diesel-based and gas-based distributed generators [73]. Electric heat pumps, electric boilers, solar heat, and geothermal are also effective in decarbonization by heat generation without carbon emission. In such units, the electricity directly converts to thermal energy for space heating or hot water, whereas some other distributed generators such as gas boilers convert fossil fuel to thermal energy by producing carbon

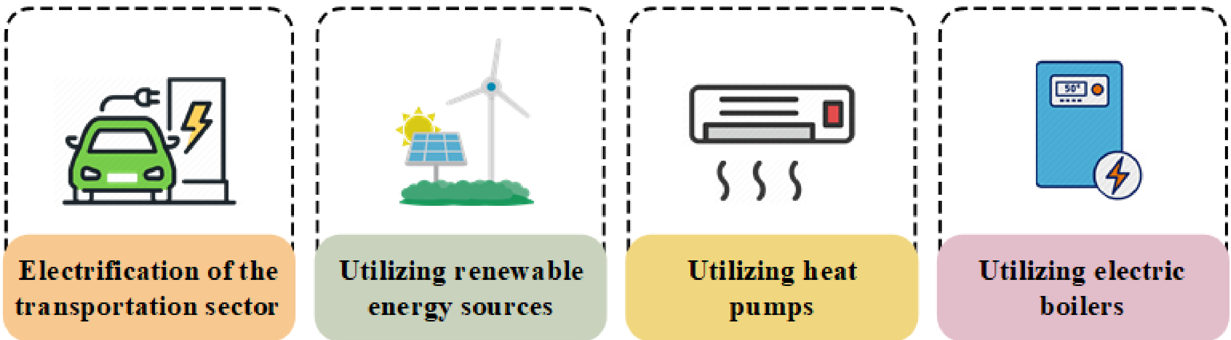

Figure 1.7. Electrification options to decarbonize integrated energy systems

dioxide. Figure 1.7 depicts the main actions for electrification in integrated energy systems [74].

As mentioned, electrification is an action to move toward low-carbon technologies [24]. Electrification needs additional electricity to meet the new electricity demands. The required electricity is mainly supplied via renewable sources, biomass gas, and nuclear facilities. Among energy sectors, the heat, industry, and transport sectors are the most fossil-based sectors [75]. However, electrification of heat and transport is more expected due to their impact on optimizing energy use in low-demand time periods that lead to improvement of the energy efficiency [76]. The electrification for fossil-based heating systems is recognized as an appropriate option to produce low-temperature heat. This is while there is not a commercially feasible option for electrification of high-temperature applications. Electrification for many industries seems difficult as they need high-temperature and high-rate heat processes [77]. Renewable sources, specially biomass-based renewable energy sources are mentioned as the only solution for electrification of some processes in literature [78].

1.6 Challenges and Barriers

Despite the advantages of vector coupling of energy systems, there are a lot of challenges and barriers against the coupling of energy vectors [79]. Optimal design and management of coupled multi-energy systems is a great challenge to move toward such integrated systems [34] [38]. The energy conversion facilities, in addition to coordination with other facilities, should also be coordinated with the transmission and distribution networks of energy networks to establish the balance between the load and supply side [34]. In addition, there is a lack of synergy potential for optimal planning and scheduling of the energy sectors. To overcome this barrier, using an appropriate approach for optimal cooperation between all energy systems and energy sectors is inevitable. The investment strategies may be influenced with time. For instance, long-term gas CHP and boiler investments decrease with increasing strategic behavior, which leads to an increase in gas price 2.6 times more than the case of gas price without strategic behavior [80]. Moreover, the combination of higher gas and CO_2 prices increases power prices and fosters renewable investments [80]. For another challenge, the transition of classical single-carrier systems towards distributed multi-energy systems introduces complex physical and commercial interactions between different energy vectors. Optimal sizing of coupling elements is another challenge for moving toward such systems.

Integrating energy systems leads to complex systems, in which the planning and scheduling problem of such systems needs specific approaches [19]. Available computer tools to simulate and analyze the integrated multi-energy systems combined with renewable sources have been discussed in [81]. Most of the available tools that can be used for individual energy systems are not capable of being used for integrated energy systems [35]. To solve the resulted model in such systems, agent-based models or model coupling are required [82]. A lot of approaches for optimal management and operation of integrated energy systems have been introduced in the literature [83]. Load flow in integrated energy systems requires hybrid load flow methods. It has been stated in the previous studies that no systematic framework has, so far, been developed for techno-economic analysis of complex and distributed coupled energy systems [84]. For every integrated energy system, a coordinated scheduling model is required to optimally use all the components for demands supply [45]. Temporal and spatial resolutions are the major specific challenges for modeling the energy infrastructure [82], which need a fundamental understanding of the modeling, dynamics, and interdependency among the systems [45].

One other barrier is the need to further innovation in technologies. For instance, a combination of renewable sources with energy storage systems is not still competitive with other existing solutions due to the high price of battery energy storage systems. For another sample, converting electricity in low-demand hours into hydrogen and methane as usable gases will be 20% more expensive compared to fossil-based fuels in 2050. Therefore, the cost-efficiency of transforming power to other forms of energy such as hydrogen is important for developing integrated energy systems. Since the existing technologies vary in each region, a comprehensive study regarding the understudy region is required before the energy integration.

Energy is produced, stored, and transported over distances in one of the three basic forms containing thermal, electric, and chemical. For instance, the energy in the form of natural gas is transmitted to be used in power stations to generate electricity or use in buildings to generate heat by boilers or gas-based CHP systems [34]. The case of Denmark shows that district heating and the gas network have much more capacity than the electricity grid, both in terms of distribution and storage [34], but this capacity is not available elsewhere. Reinforcement and extension of energy networks may be required for vector coupling of energy systems. Development of distributed generation systems and electrification of heating systems influence line flows in electricity systems. In addition, there is a need for investment in heat networks, which have not been developed compared to gas and electricity grids. District heating systems are uncompetitive with existing decentralized heating systems. However, it is expected that the building space heating demand is 20% lower in 2050 compared to 2016, due to improvement in building energy efficiency measures in the future [19]. Although electricity networks are more developed compared to the other energy networks, grid expansion to maximize the usage of renewable sources' generation is an alternative for developing integrated systems. The authors in [85] have revealed that the second solution only costs 30% of an electrolyzer having the same capacity. However, the hydrogen can be sold without re-electrification in a competitive environment and transmission expansion can also be economically beneficial. For the most efficient way for the supply of demand in integrated energy systems, the best network topology/configuration should be adopted. The energy losses and cost of such networks are effective factors in the adoption and construction of multi-energy-based network configuration [86]. A new concept of transmission network has been introduced for integrated energy systems as combined transmission or interconnector concept with the aim of transmitting electrical, thermal, and chemical energy in one underground device [87]. This layout seems to be a hollow conductor with the capability of carrying gas inside. The advantage of using this layout is efficiency improvement by storing the heat generated by conductors in the carried gas. The efficiency of such transmission lines is increased when the stored heat in the gas is used at the end of the link [88]. The integration of energy systems may lead to congestion in the capacity of the individual energy systems. For instance, using the CHP units increased the used capacity of gas networks in Germany [89]. However, distributed generation units in integrated energy systems can solve the congestion according to their location in the network.

Another barrier in integrating the energy systems is regarding the market condition, which can restrict the development of technologies with small scales such as electric-to-gas technologies like hydrogen generation from surplus electricity. For another example, low-scale biomass in distributed areas is not expected to be exploited. Another challenge is the possibility that low electricity prices may lead to direct electrification instead of power-to-gas and power-to-heat transformations in low-price time intervals [42].

Uncertainty is another challenge in such systems. The uncertainty sources may be load demand, generation of renewable energy sources, fuel (or energy) price, etc. One important uncertainty source is the power generation of variable renewable sources. The transformation mechanisms are associated with uncertainty in the long term. For instance, global warming can change the demand from heating to cooling. To overcome this challenge, using low-temperature district heat systems can enable the system for cogeneration of heating and cooling [42]. Another challenge for integrated energy systems is that a threatening factor to one energy system may endanger the security of all the integrated energy systems by rising mismatch issues between demand and supply sides.

The current limitation in using ICT equipment and approaches is another challenge of developing integrated energy systems. A limited number of companies currently exist that have restricted this development. However, nowadays, new emerging and promising ICT approaches such as the Internet of Things technology are increasingly developing [90].

1.7 Conclusions

In this chapter, the integration of the energy systems, which is ongoing with the aim of improving energy efficiency, climate protection, and also enhancing reliability in supplying energy demands, was discussed. Firstly, the concept and definition of vector coupling in whole energy systems was discussed. In addition, the coupling technologies, including energy (coupling and non-coupling energy technologies) and the information and communication technology (ICT), were enumerated in this chapter. Furthermore, the challenges and barriers related to integrated energy systems and available solutions to overcome them were explained. Demand-side management and decarbonization as the main steps towards energy integration were also outlined. The conducted study showed that there is still a need for a lot of actions to couple the energy systems in order to achieve the whole energy system.

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