


## ADVANCED REVIEW

# The sector coupling concept: A critical review

Jasmine Ramsebner<sup>1</sup>  | Reinhard Haas<sup>1</sup> | Amela Ajanovic<sup>1</sup> | Martin Wietschel<sup>2</sup>

<sup>1</sup>Energy Economics Group, Technische Universität Wien (TU WIEN), Vienna, Austria

<sup>2</sup>Fraunhofer-Institut für System- und Innovationsforschung ISI, Karlsruhe, Germany

## Correspondence

Jasmine Ramsebner, Technische Universität Wien (TU WIEN), Energy Economics Group, Vienna, Austria.  
Email: ramsebner@eeg.tuwien.ac.at

## Abstract

Pursued climate goals require reduced greenhouse gas emissions by substituting fossil fuels with energy from renewable sources in all energy-consuming processes. On a large-scale, this can mainly be achieved through electricity from wind and sun, which are subject to intermittency. To efficiently integrate this variable energy, a coupling of the power sector to the residential, transport, industry, and commercial/trade sector is often promoted, called sector coupling (SC). Nevertheless, our literature review indicates that SC is frequently misinterpreted and its scope varies among available research, from exclusively considering the use of excess renewable electricity to a rather holistic view of integrated energy systems, including excess heat or even biomass sources. The core objective of this article is to provide a thorough understanding of the SC concept through an analysis of its origin and its main purpose, as described in the current literature. We provide a structured categorization of SC, derived from our findings, and critically discuss its remaining challenges as well as its value for renewable energy systems. We find that SC is rooted in the increasing use of variable renewable energy sources, and its main assets are the flexibility it provides for renewable energy systems, decarbonization potential for fossil-fuel-based end-consumption sectors, and consequently, reduced dependency on oil and gas extracting countries. However, the enabling technologies face great challenges in their economic feasibility because of the uncertain future development of competing solutions.

This article is categorized under:

Energy Systems Economics > Economics and Policy

Energy Systems Economics > Systems and Infrastructure

## KEYWORDS

decarbonisation, electrification, hydrogen, power to x (P2X), renewable energy systems, sector coupling, variable renewable energy

**Abbreviations:** a, anno; BEV, battery electric vehicle; BOF, basic oxygen furnace; C, central; C(C)HP, combined (cooling) heat and power; CH<sub>4</sub>, methane; CNG, compressed natural gas; CO<sub>2</sub>, carbon dioxide; COP, coefficient of performance; D, decentralized; DH, district heating; DRI, direct reduced iron; EBs, electric boilers; FCEV, fuel-cell electric vehicle; GHG, greenhouse gas; GW, gigawatts; H<sub>2</sub>, hydrogen; H<sub>2</sub>O, water; HBI, hot briquetted iron; HPs, heat pumps; HRS, hydrogen refueling station; IESs, integrated energy systems; km, kilometers; m<sup>3</sup>, cubic meters; MES, multienergy system; Mt, megatons; MW, megawatts; Nm<sup>3</sup>, normal cubic meter; P2G, power-to-gas; P2H, power-to-heat; P2L, power-to-liquid; P2X, power-to-X; PV, photovoltaics; RESs, renewable energy sources; SC, sector coupling; SES, smart energy system; SI, sector integration; t, tons; TWh, terawatt hours; VRE, variable renewable energy.

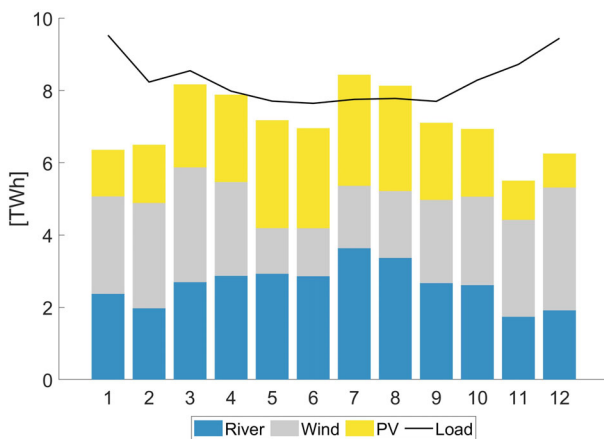
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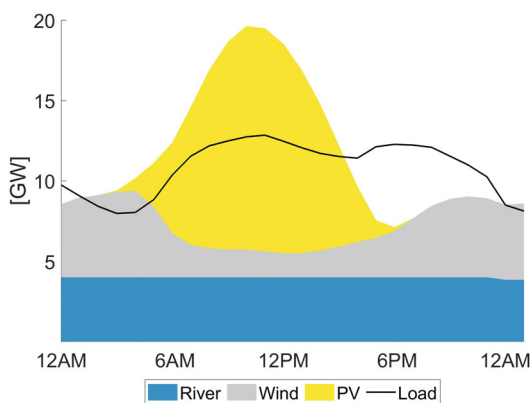
## 1 | INTRODUCTION

The climate goals defined in the EU 2030 Climate and Energy Framework aim at actions and increasing research and development to limit global warming to a maximum of 2°C—ideally even 1.5°C—compared with preindustrial levels (European Commission [EC], 2014). Reducing greenhouse gas (GHG) emissions requires—among other measures such as efficiency improvements and behavioral change—substituting of fossil fuels in all energy-consuming processes with energy from renewable sources. On a large scale, this can mainly be achieved through generating renewable electricity using wind and sun in wind turbines and photovoltaic systems, respectively. However, because natural resources are subject to intermittency and are referred to as variable renewable energy (VRE) sources the increasing variability that these sources add to the electricity system does not only affect the energy system within a day but also throughout the seasons of a year. Consequently, in, for example, continental Europe, excess electricity production can occur frequently, especially during summer, at times of high solar radiation with low demand, or even in combination with high wind availability. In winter, however, this region may experience scarcity of renewable electricity generation with low solar radiation and higher demand. Further, it is assumed that in the course of the decarbonization of heating, electricity demand during winter will rise. In northern countries, the dominance of wind power generation leads to excess electricity generation, especially during winter.

As an example of the seasonal variability of continental Europe, Figure 1 shows the monthly and especially the seasonal variability of renewable power generation in a 2050 scenario for Austria and the respective shares of hydro, wind, and solar power. To achieve a decarbonization of the power sector, long-term seasonal storage such as pumped hydro and compressed air, is required. These capacities, however, are spatially limited, and alternative flexibility methods such as chemical storage in the form of gas will be inevitable. Figure 2 describes VRE generation on an exemplary summer day showing the amount of surplus generation from the sun and wind peaks during low electricity demand, of which not all may be balanced through short-term pumped hydro storage. These changes to the nature of electricity generation add complexity to the management of the energy system.



**FIGURE 1** Monthly electricity generation in a 100% VRE 2050 scenario for Austria  
Source: EEG TU Wien



**FIGURE 2** Exemplary summer day 2050: Surplus VRE electricity generation, Austria  
Source: EEG TU Wien

Questions emerge on how to manage these non-controllable sources, handle excess electricity generation, and use it in an efficient way in terms of economic, ecologic, and social welfare aspects. As a possible solution for seasonal balancing and increased integration of VRE—apart from commonly discussed measures such as grid extension or new electric storage options—VRE power surplus can be used in other end-use sectors, for example, transport, residential heating, or industry. The concept of Sector Coupling (SC) or Sector Integration (SI) represents an approach to substitute fossil fuels with energy from renewable electricity sources in all end-consumption sectors, such as transport, industry, and residential heating/cooling. It supports establishing 100% renewable energy systems, adding flexibility and improved storage and distribution options to the use of renewable electricity (Schaber et al., 2013).

Despite the growing research on SC applications in all end-consumption sectors, the meaning and scope of the SC concept remains to be clarified. The scope and main objectives of SC vary largely throughout literature, and the term is often used inaccurately (Robinius, Otto, Syranidis, et al., 2017). Therefore, the core objective of this article is to analyze the roots of the SC concept and its main purposes, as described in present literature. This requires an understanding of how the sectors are defined within SC, followed by a review of SC definitions and available studies related to SC. In doing so, we provide a brief literature review of specific SC technologies (e.g., P2G or P2H) to support a thorough understanding of the overall concept. Finally, we aim at a critical discussion of its remaining challenges and value for renewable energy systems.

## 2 | METHODOLOGY AND STRUCTURE

The methodology includes a thorough search for definitions of SC, starting with screening the interpretation of the sectors in this context, which is said to vary greatly. This is followed by a review of available research in this field. In our literature review, we consider the overall SC concept and its techno-economic requirements and challenges and do not specifically focus on a detailed review of technological studies, while we add a basic description of enabling technologies and potential SC applications, which we regard as essential to understand its techno-economic aspects.

We first screened publications in online libraries, such as Google Scholar and Science Direct. However, for the definition of SC and the sectors in this context, mainly German literature provided a solid basis that included reports and project results. Looking for available research on SC, the studies had to include the keyword “sector coupling” and focus on the use of renewable electricity. Therefore, fossil fuels, biogas, and biofuels or excess heat were not considered in our interpretation of the concept.

This resulted in the following number of literatures relevant for analysis:

1. Sector definition: 10.
2. SC definition: 14.
3. All results referring to SC on Science Direct: 361.
4. Relevant SC research: 40.

Throughout this article, the authors,

1. Provide a literature review on the definition of sectors and SC.
2. Analyze available research on SC and the most important technologies mentioned with it.
3. Describe enabling technologies required for the realization of transforming power for use in all end-consumption sectors.
4. Investigate the role of SC in integrated, multi-energy systems (MESs).
5. Provide a structured categorization of SC applications for each end-consumption sector, a critical discussion of the findings, future techno-economic challenges, and assets of SC.

Subsequently, the article is structured into a general review of available literature on SC in Section 3. First, an analysis of sectors that are considered in the SC concept, often depending on the nature of research (technical, economical, etc.), is conducted, followed by a review of SC definitions and available research in the field of SC. Section 4 provides an overview of the enabling technologies for SC followed by potential applications in each of the sectors. Once the pathways and enabling technologies are clear, Section 6 discusses the role of SC in future renewable MESs. Finally, Section 7 provides a more critical discussion of the work presented so far, specifically on the definition of the sectors, remaining

challenges, and values of SC. Further, it includes a structured categorization of the current applications and technologies into centralized and decentralized SC using direct or indirect electrification. In Section 8, we provide our conclusions and an outlook on the SC concept.

### 3 | LITERATURE REVIEW ON THE RISE OF THE SECTOR COUPLING CONCEPT

The principles of SC have already been known from the beginning of the 20th century. The first battery electric vehicle (BEV) produced in the United States was demonstrated at the 1892 World's Fair in Chicago, Illinois (Warner, 2015). The developments in Europe, not only in electric bicycles and automobiles but also in public transport, disappeared in the middle of the 20th century. In the United States, BEVs gained early market acceptance despite its short driving range and a speed limit of DC motors of about 32 km/h. Eventually, BEVs were defeated by the internal combustion engine of Henry Ford's low-priced Model T in 1908, introduction of the automatic starter by Charles Kettering in 1911, and the US highway system expansion (Warner, 2015). With a surge of the all-electric American home at the beginning during the 20th century, the residential sector experienced significant electrification using electric stoves, hot plates, washing and ironing machines, dishwashers, electric doorbells, and a vast number of lightening devices (Foy & Schlereth, 1994). Robinius, Otto, Heuser, et al. (2017) found further early applications in energy generation, which applied the basic approach of SC: "Furthermore, while SC has always been practiced, it has hitherto been in the context of fossil fuels such as kerosene, methane, oil or coal, rather than renewable energy sources (RES). For example, a combined heat and power plant that generates electricity would supply excess heat that would otherwise be wasted."

The authors do, however, point out that today the focus is on using renewable electricity in an increasing amount of end-consumption applications with the aim of increasing the share of renewable energy in these sectors (assuming that the electricity supply is or can largely be renewable). This can be realized either through adapting formerly fossil-fuel-based processes for direct electrification with renewable electricity, or indirectly through transformation of electricity into another, more suitable or flexible type of fuel by applying P2X technologies. In this context, SC has become popular in the course of the German energy transition (Schaber et al., 2013).

By investigating the integration of large-scale, variable wind power in future renewable energy systems, we found a first mention of this approach under the term SC in studies by Schaber et al. (2013), Schaber et al. (2013) and later by Richts et al. (2015). In the course of the energy transition, in 2017, several German ministries and international energy agencies developed thorough guidelines and information on SC (BDEW, 2017; BMUB, 2016a; BMWi, 2016; IRENA et al., 2018). Nevertheless, as often as the term "sector coupling" is used in energy policy debates today, it is not used clearly and uniformly (Scorza et al., 2018). One of the first scientific papers to specifically investigate developing a more uniform interpretation of the concept was established by Robinius, Otto, Heuser, et al. (2017). Towards 2018, more peer-reviewed scientific papers were specifically dedicated to SC, such as the work by Buttler and Spliethoff (2018) and Stadler and Sterner (2018), and by 2019, the contributions to the concept were multiplied.

However, future research still needs to define SC uniformly and discuss critically which of its scopes are reasonable for future energy systems (Wietschel et al., 2018). There is still discussion about whether SC only includes renewable electricity or the coupling of conventional electricity generation may be considered as well. Furthermore, the literature does not always agree on the question whether biogas and biofuels, combined (cooling) heat and power (C(C)HP) plants, and the use of excess heat are part of the concept. Additionally, the definition of the sectors that are referred to in SC widely differ throughout the literature depending on the research perspective, which may be technical or economical. The following subsections first provide an analysis of the interpretation of the sectors within SC and then continue with available definitions of SC. Once this basic understanding is established, we conduct a detailed literature review on SC and its common research focus.

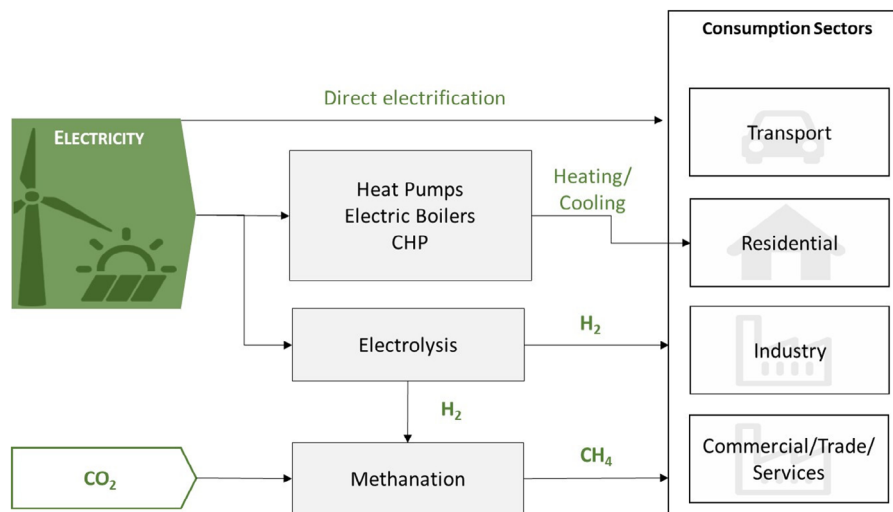
#### 3.1 | Definition of sectors

For definitions of SC, we detect 10 papers mostly represented by reports and project results, one position paper, one dissertation, and only two peer-reviewed papers (see Table 1). Our literature review reveals that the interpretation of the sectors differs widely across the field of SC research. Studies on SC often do not at all address the chosen interpretation

**TABLE 1** Interpretation of sectors in SC

No.	Authors	Interpretation of the sectors in literature	PR
1	(Schaber, 2013)	Power, heat, hydrogen, and natural gas sector	
2	(Schaber et al., 2013)	Power, heat, hydrogen, and natural gas sector	
3	(Quaschnig, 2016)	Power, residential/heat, industry and transport as “sectors” with the distinction between households and heat describing only decentralized/centralized use	
4	(BMUB, 2016b)	Define SC as the use of renewable electricity in the transport, heat, and industrial/services sectors	
5	(BMWi, 2016)	Define SC as the use of renewable electricity in the transport, heat, and industrial/services sectors	
6	(Robinius, Otto, Heuser, et al., 2017)	Refers to the end-consumption sectors common in energy economics: industry, trade and commerce, residential/household, transport	X
7	(BDEW, 2017)	Coupling of power, heat, and mobility as a decarbonization tool and to enable flexible energy use across all end/consumption sectors: industry, residential, trade/services, and transport	
8	(Ausfelder et al., 2017)	Identify that there are various interpretations of the sectors in SC. Their study is based on heat, power, and mobility	
9	(Wietschel et al., 2018)	Differentiates sector, infrastructure, and technology perspective on SC. Defines SC as the use of renewable electricity in the transport, heat, and industrial/services sector but agrees that classical consumption sectors in energy economics are households/residential, commercial/trade/services, industry, and transport	
10	(Richts et al., 2015)	Refers to a coupling of electricity, heat, and transportation	X

Abbreviation: PR, peer-reviewed.

**FIGURE 3** Sector coupling: Pathways from the power to transport, residential, and industry sector

Source: Adapted from Robinius, Otto, Heuser, et al. (2017)

of sectors and dive into the technical specifics very quickly (e.g., producing heat from renewable electricity for space heating).

Depending on the nature of research, and whether it is technical, economical, on a macro or micro level, literature offers a wide spectrum of interpretation concerning the sectors. Robinius, Otto, Heuser, et al. (2017) clearly aim at correcting “inaccurate formulations” of how sectors are described in SC. They claim that heat supply does not constitute a sector but rather an application or an energy carrier or service. Illumination in the household sector is another example. The authors thereby define sectors as industry, trade and commerce, residential/household, and transport, which is common in energy economics. These represent end-consumption sectors and are clearly the source of energy demand. Figure 3 provides a simple overview of how the power sector is linked to the end-consumption sectors, using renewable

electricity from the wind and sun. The figure shows the possibilities for direct or indirect electrification, and the latter can be achieved by applying power-to-heat (P2H) through heat pumps (HPs) —also applicable for cooling— or electric boilers (EBs). Another possibility is power-to-gas (P2G) through electrolysis, which transforms power into hydrogen ( $H_2$ ). With a  $CO_2$  source, it can further be processed to methane ( $CH_4$ ) or also methanol as a liquid fuel (see Section 4). Ausfelder et al. (2017) agreed that sectors in SC are often defined as heat, power, and mobility or even heat, power, and transportation (Richts et al., 2015). Wietschel et al. (2018) specifically defined SC as the application of renewable electricity in the transport, heat, and industry sector according to BMWi (2016) and BMUB (2016a); however, BDEW (2017) interprets SC as the coupling of power, heat, and mobility to supply the end-consumption of the industry, residential, trade/services, and transport sector with renewable energy and emphasizes a coupling of infrastructure as well as energy carriers for a more flexible supply.

Scorza et al. (2018) concluded that most research is based on a rough division into the power sector and the consumption sectors transport, industry, and buildings (see Ausfelder et al., 2017; Dena, 2017), which is largely in line with the approach by Robinius, Otto, Heuser, et al. (2017). A “building” in this case includes the heating demands in residential/households as well as public buildings in services/trade.

DVGW and VDE (2016) pointed out that SC has to be set up following specific goals and needs to fulfill the demand profiles of the residential, industry, and trade/services sectors. Each sector prefers different technologies, and the various coupling elements enable system friendly, ecologic, and macro-economic integration of the energy grids. The European Parliament (2018) addressed different perspectives of SC and clearly differentiated between energy end-use sectors and the energy vectors or carriers electricity, gas, and heat. Although they define end-use SC as the interaction between electricity supply and end-consumption sectors, cross-vector coupling involves the integration of different energy carriers, also known as vectors. In general, they claim that “sector coupling involves the increased integration of energy end-use and supply sectors with one another” (EP, 2018). This strategy may thus improve the efficiency and flexibility of the energy system and add to its reliability. They pointed out that in future renewable energy systems a more integrated approach to energy systems planning is needed. This can occur on the supply side, through a more flexible use of different energy carriers through the transformation of (surplus) electricity, or as cross-vector coupling on the demand side, for example, by using excess heat from power generation or transformation (electrolyzer) or industrial processes for district heating (DH) (EP, 2018). The latter is not the focus of the SC interpretation in this article. Nevertheless, the use of excess heat does substantially contribute to efficiency gains in future renewable energy systems and is specifically investigated by research on multi/smart/integrated energy systems (Lund et al., 2012; Lund, Mathiesen, et al., 2014; Mathiesen et al., 2015). The role of SC in multi-energy systems is discussed in Section 6.

### 3.2 | Definition of sector coupling

Definitions of SC range from considering only the one-way path from the power to another end-consumption sector to including cross-energy-carrier integration even with, for example, excess heat use and biomass energy. The most important interpretations of SC are stated in Table 2, starting with the broadest in scope and terminating with the strictest. Because some references provide a narrower and others a broader interpretation, they may be stated several times. Some authors agree that SC is about linking the power sector to the end-consumption sectors and to fulfill this demand with renewable energy; however, others see it as a general integration of all the energy carriers and the respective infrastructure. Although some papers strongly focus on using surplus energy from VRE to reduce, for example, curtailment needs, other definitions emphasize the decarbonization potential of renewable power in the industry, heat, and transport sector. We discovered more definitions of SC in reports and position papers than in peer-reviewed scientific publications. Further, we detected specific definitions of SC in 14 studies mostly represented by reports and project results, one position paper, one dissertation, and only two peer-reviewed papers.

Ausfelder et al. (2017) attributed a very broad scope to SC with an integrated optimization of the whole energy system by merging the power, mobility, and heat sector. Furthermore, they claimed that in this concept electricity, hydrogen, methane, and even energy produced from biomass as well as geothermal sources are used flexibly in all application forms. However, the authors define the use of power from large-scale VRE in the heat, industry, and transport sector as a core objective of SC. The often cited BMWi (2016) added that using power from VRE helps to promote the energy transition in other than the power sector and claimed the application of “clean” power to reduce the share of fossil fuels in other sectors is called SC.

**TABLE 2** Definitions of SC from broad to narrow scope

No.	Author	Definition of SC	PR
1	(Dena, 2017)	Does not regard SC as a sufficient strategy or approach because of its usually limited scope to one sub-system but prefers a more integrated approach of the whole energy system.	
2	(Ausfelder et al., 2017)	Integrated optimization of the whole energy system merging the power, mobility and heat sector.	
3	(Scorza et al., 2018)	SC may refer to the integration or coupling of all sectors. The central aspect would then cover the substitution of fossil energy carriers including excess heat use and other RES such as biomass and so forth.	
4	(Wietschel et al., 2018)	The ongoing process of replacing fossil energy carriers with largely renewably generated power or other renewable energy carriers and sustainable forms of energy use. This also includes integration among consumption sectors as, for example, using excess heat in new or known cross-sectoral applications.	
5	(BDEW, 2017)	The energy-technical and energy-economic integration of electricity, heat, mobility, and industrial processes, as well as their infrastructures with the aim of decarbonization and simultaneous flexibilization of energy use in industry, households, commerce/trade/services, and transport sector under the premises of economic efficiency, sustainability, and security of supply.	
6	(IRENA et al., 2018)	The concept of SC encompasses co-production, combined use, conversion, and substitution of different energy supply and demand forms—electricity, heat, and fuels.	
7	(Richts et al., 2015)	Coupling electricity, heat, and transportation for decarbonization with technologies based on renewable electricity.	X
8	(BMWi, 2016)	Power from RESs helps to promote the energy transition in other than the power sector. They claim that if this “clean” power is applied to reduce the share of fossil fuels in other sectors, this strategy is called SC.	
9	(Wietschel et al., 2018)	RESs are regarded as replacing fossil fuels in new or the increased use of known applications through either direct use of electricity or a transformation from power into other energy carriers (P2G, P2L, and P2H)	
10	(Scorza et al., 2018)	Use of power in consumption sectors or applications in which it currently has little or no meaning.	
11	Olczak and Piebalgs (2018)	Use of surplus power from renewables and transformation into hydrogen (H <sub>2</sub> ) or methane (CH <sub>4</sub> ), liquid fuels or heat.	
12	(Scorza et al., 2018)	Use of surplus power from VRE in consumption sectors or applications in which it still has little meaning.	
13	(Noussan, 2018)	SC includes different applications that have the common goal of transforming the power excess into other forms of energy, for example, power-to-heat, power-to-liquids or power-to-gas.	X
14	(Schaber, 2013)	SC is regarded an attractive solution for the use of temporary excess electricity from VRE for renewable heat and gas production.	

Abbreviation: PR, peer-reviewed.

BMWi (2016): “With the integration of energy sectors (sector coupling), the power supply meets the demand for energy in households (heat and cooling) and transport (propulsion), as well as in industry and trade, commerce and services (heat, cooling and propulsion).” The strategy leads to the creation of new customers in the power sector and may offer flexibility from the demand side for the inflexible power generation from VRE.

As a primary goal of SC, Wietschel et al. (2018) emphasized the importance of reducing GHG emissions, which puts VRE sources into the spotlight. They regard SC as the ongoing process of replacing fossil energy carriers with renewable electricity or other sustainable forms of energy, which also includes the use of excess heat. The authors further suggest the interaction between classic consumption sectors such as residential, trade/services, industry, and transport through an integration of their infrastructure. BDEW (2017) published 10 theses on SC wherein they defined SC as follows: “The energy-technical and energy-economic integration of electricity, heat, mobility, and industrial processes, as well as their infrastructures with the aim of decarbonization and simultaneous flexibilization of energy use in industry, households, commerce/trade/services, and transport under the premises of economic efficiency, sustainability, and

security of supply.” IRENA et al. (2018) claimed that “the concept of sector coupling encompasses co-production, combined use, conversion, and substitution of different energy supply and demand forms—electricity, heat, and fuels.”

Richts et al. (2015) also interpreted SC as an essential approach to successfully reduce GHG emissions and defined it as an overall integration or coupling of electricity, heat, and transportation using technologies based on renewable electricity. BMWi (2016) regarded SC as a requirement to promote the decarbonization of all sectors effectively and economically. In combination with classic energy efficiency measures and direct generation of heat through other RES (biomass and solar thermal energy), SC supports reducing GHG emissions. Scorza et al. (2018) offered one narrow and one very broad interpretation of SC. In the narrow definition, the use of power in consumption sectors or applications in which it currently has little or no meaning (e.g., the electrification of transport instead of traditional fossil fuels or indirectly via P2G for FCEVs) is included. The definition can be even narrower if only surplus power generation from VRE is considered. Noussan (2018) provided a similarly strict interpretation, “Sector coupling includes different applications that have the common goal of transforming the power excess into other forms of energy, e.g., power-to-heat, power-to-liquids, or power-to-gas.”

In the broader definition Scorza et al. (2018) claimed that SC may refer to integrating or coupling all sectors to increase the flexibility in the operation of the overall energy system. The concept may support the security and economic performance of energy supply. Surplus of VRE generation might result in large-scale curtailment, thereby lowering the value of VRE output and reducing investment attractiveness. To maintain its value, VRE electricity needs to receive new demand from more end-use and supply sectors. Considering SC as a large-scale and economically attractive solution for the use of temporary excess electricity from VRE, Schaber et al. (2013) focused on applying renewable electricity in the heat sector or for generating H<sub>2</sub> through electrolysis.

Olczak and Piebalgs (2018) showed that SC leads to new links between energy carriers and infrastructure by, for example, using surplus power from renewables and transforming it into gas, such as hydrogen (H<sub>2</sub>) or methane (CH<sub>4</sub>), liquid fuels, or heat. Through these technologies, demand from all end-consumption sectors becomes relevant for energy supply from the power sector offering sinks for peak power generation from VRE.

### 3.3 | Available research on sector coupling

Available research on SC ranges from a focus on policies, overall system perspective, to techno-economic aspects, modeling, and specific technological analyses (see Table 3). Between 2014 and 2017, research on SC and its holistic view of end-consumption sectors has been scarce in peer-reviewed journals and rather covered the isolated view of technologies. Relevant literature has been increasing substantially from 2018, and so far in 2020, more peer-reviewed studies on SC have been published than in each of the past 2 years. Papers that focus on a specific sector mainly investigate within the field of residential heating or transport. A small number of publications analyzes SC in the industry or the commercial/trade/services sector. Studies on P2H and P2G technologies are dominant, whereas P2L and direct electrification from VRE are addressed less often. The work considered relevant for this paper mainly focuses on the European area and provides numerous analyses for Germany. Studies without a geographic focus usually represent general, techno-economic research, as for example the state of the art of P2G or P2H or its potential in future energy systems.

There are numerous research available on the techno-economic aspects of SC, such as the use of renewable electricity for heating (Arabzadeh et al., 2020; Bellocchi et al., 2020; Brown et al., 2018; Felten, 2020; Jimenez-Navarro et al., 2020; Richts et al., 2015; Schaber, 2013; Schaber et al., 2013; Schill & Zerrahn, 2020; Stadler & Sterner, 2018; Zhu et al., 2020). Others focus on the transport sector (Arabzadeh et al., 2020; Bellocchi et al., 2020; Brown et al., 2018; Lester et al., 2020; Sterchele et al., 2020) and even the commercial/trade/services sector (Brown et al., 2018; Jimenez-Navarro et al., 2020; Zhu et al., 2020).

Several papers specialize on the enabling technologies for SC without a significant economic perspective, and focus on the transport sector (Robinius, Otto, Heuser, et al., 2017; Schemme et al., 2017), heating in the residential sector (Bloess et al., 2018; Buffa et al., 2019; Witkowski et al., 2020), and industry (Posdziech et al., 2019). Technological papers sometimes do not analyze a specific sector but apply a system perspective or focus on the transformation technologies (Ausfelder et al., 2017; Hidalgo & Martín-Marroquín, 2020; Quaschnig, 2016).

Although policy strategies are still rarely covered in the context of SC, there is work available covering the geographical area of Europe, Germany, and the UK (Cambini et al., 2020; Frank et al., 2020). We assume that the complexity of the whole SC dimension leads to the fact that modeling is not addressed excessively or focuses on one sector in



TABLE 3 Relevant literature on sector coupling

No.	Reference	Focus area										Sector					Technology					Geographical scope
		PR	ECO	TEC	SYS	MOD	POL	T	R	I	C	DE	P2H	P2G	P2L	DE	P2H	P2G	P2L			
																				DE	P2H	
1	(Arabzadeh et al., 2020)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	Helsinki		
2	(Bellocchi et al., 2020)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	Italy		
3	(Cambini et al., 2020)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	Europe		
4	(Felten, 2020)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	Europe, UK		
5	(Frank et al., 2020)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	Europe, UK		
6	(Hidalgo & Martín-Marroquín, 2020)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	Europe, UK		
7	(Jimenez-Navarro et al., 2020)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	Europe		
8	(Lester et al., 2020)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	Denmark, Germany		
9	(Ornetzeder & Sinozic, 2020)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	Austria		
10	(Pavičević et al., 2020)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	Europe		
11	(Roach & Meeus, 2020)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	Europe		
12	(Schill & Zerrahn, 2020)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	Germany		
13	(Sterchele et al., 2020)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	Germany		
14	(Witkowski et al., 2020)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	Germany		
15	(Zhu et al., 2020)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	Europe		
16	(Bernath et al., 2019)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	Germany, Europe		
17	(Bloess, 2019)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	Germany		
18	(Buffa et al., 2019)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	Europe		
19	(Burandt et al., 2019)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	China		
20	(Emonts et al., 2019)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	Germany		
21	(Leitner et al., 2019)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	Germany		
22	(Posdziech et al., 2019)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	Europe		
23	(Thema et al., 2019)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	Germany		
24	(Bloess et al., 2018)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	Europe		
25	(Brown et al., 2018)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	Europe		
26	(Buttler & Spliethoff, 2018)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	Global		
27	(McKenna et al., 2018)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	North-west Germany		
28	(Robinus et al., 2018)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	Germany		
29	(Scorza et al., 2018)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	Germany		

(Continues)

TABLE 3 (Continued)

No.	Reference	Focus area						Sector					Technology					Geographical scope
		PR	ECO	TEC	SYS	MOD	POL	T	R	I	C	DE	P2H	P2G	P2L			
30	(Stadler & Sterner, 2018)	X	X	X								X	X	X		Europe, Germany		
31	(Wietschel et al., 2018)	X	X	X	X											Europe, Germany		
32	(Ausfelder et al., 2017)	X	X	X	X	X										Europe, Germany		
33	(Robinius, Otto, Heuser, et al., 2017)		X	X	X		X					X	X	X		Europe, Germany		
34	(Robinius, Otto, Syranidis, et al., 2017)						X	X				X	X	X		Germany		
35	(Schemme et al., 2017)		X				X							X		Germany		
36	(Quaschnig, 2016)		X	X	X											Europe, Germany		
37	(Iambagi et al., 2015)						X					X				Europe, Germany		
38	(Richits et al., 2015)	X	X	X	X						X	X	X			Europe		
39	(Schaber, 2013)	X	X	X	X	X						X	X	X		Germany		
40	(Schaber et al., 2013)	X	X	X								X	X	X		Germany		

Abbreviations: C, commercial/trade/services; DE, direct electrification; ECO, economics; I, industry; MOD, modeling; P2G, power-to-gas; P2H, power-to-heat; P2L, power-to-liquid; POL, policy; PR, peer-reviewed; R, residential; SYS, systems; T, transport; TEC, technology.

which the majority includes transport and residential heating (Bloess et al., 2018; Burandt et al., 2019; Jambagi et al., 2015; Pavičević et al., 2020; Robinius, Otto, Syranidis, et al., 2017).

Jambagi et al. (2015) and Witkowski et al. (2020) analyzed SC as one tool within integrated MESs. This approach refers to an integration of the electricity, gas, and heating infrastructure and includes the flexible use of possible means of energy generation and storage. Therefore, it also requires SC and its enabling transformation technologies for the use and flexible transformation of renewable energy. Section 6 is specifically dedicated to SC from an integrated/smart energy system perspective.

## 4 | ENABLING TECHNOLOGIES FOR SECTOR COUPLING

SC highly depends on enabling technologies, of which we will take a closer look to establish a thorough understanding of the concept. According to current research, P2X technologies will be inevitable for the decarbonization of various end-use applications, such as the area of industrial process heat, chemical production, international air, or maritime transport. Many of these processes cannot be powered by electricity directly but depend on specific chemical conditions that can only be provided by a material energy source, such as gas and liquid fuel. In other energy-consuming processes, P2X technologies are in competition with direct electrification depending on the socio-economic and infrastructural trade-offs. These, for example, include railway and long-distance truck transport or low temperature heating. For private vehicles, local truck transport, and short-term flexibility within the electricity system, however, P2X transformation technologies are only competitive under certain conditions. Transformation processes from electricity into, for example, gas or fuel ideally are operated at times of excess electricity generation during which electricity prices are low (IRENA et al., 2018). Matthes (2018) pointed out that, if full decarbonization and 100% supply from renewables shall be achieved, not only more powerful battery storage systems but also P2G options for seasonal storage and SI will play a crucial role. These applications require intensive research in the next two decades to become mature technologies.

### 4.1 | Direct electrification

One potential application of SC refers to the direct electrification of processes. Formerly fossil-fuel based applications and technologies may be adapted to be powered by electricity. Some currently directly electrified processes have already used electricity a long time ago. The mid-to long-term goal nowadays, however, has to be the use of renewable electricity. Common examples include transformation from traditional vehicles with combustion engines powered by fossil fuels to BEVs. Although usually direct electrification is not defined as a transformation process similar to P2G, and so forth, Wietschel et al. (2015) defined E-Mobility as power-to-move. Moreover, industrial processes often have large potential for direct electrification, as it is true for steel production that can be transformed using an electric arc furnace instead of a coal fired blast furnace and a basic oxygen furnace (BOF) (see Section 5.3). For smaller-scale residential heating and cooling, direct electrification is also an option (see Section 5.2).

### 4.2 | Power-to-gas/liquids

Not only is the importance of integrating large-scale renewable electricity generation frequently mentioned in literature but also the importance of an integration of the gas sector, because the existing gas infrastructure may already enable large-scale distribution and storage of renewable energy (BMUB, 2016a; DVGW, 2020; DVGW & VDE, 2016). To transform power into gas, water electrolysis is used—an electrochemical process that splits water into  $H_2$  and oxygen ( $O_2$ ) (IEA, 2019). It is an energy carrier with high energy density or energy-to-weight ratio, three times higher than that of gasoline or diesel, and low storage cost (Lewandowska-Bernat & Desideri, 2018; Schiebahn et al., 2015).  $H_2$  is not only a promising alternative for diesel and gasoline in the transport sector but is also used in various industrial applications, such as ammonia synthesis, fertilizer production, glass, and fiber production, and so forth (Lewandowska-Bernat & Desideri, 2018).

Today, three-quarters of  $H_2$  demands are produced from natural gas followed by coal (IEA, 2019). Water electrolysis today accounts for less than 0.1% of dedicated  $H_2$  production globally; however, it is expected to rise substantially with an increasing share of renewable electricity. Electrolyzers currently operate at an efficiency between 60% and 81%,

depending on the technology type and load factor. H<sub>2</sub> may further be processed to methane using renewable H<sub>2</sub> and a CO<sub>2</sub> source and even into liquid, synthetic fuels, with similar characteristics as diesel or gasoline, such as methanol. CO<sub>2</sub> as a required input for methanation may either be produced from organic matter, for example, biomass, from fossil power plants, industrial processes, or captured from the air (Schiebahn et al., 2015). Although hydrogen may be fed into the natural gas grid at a certain share—depending on local technical characteristics—methane can function as a direct substitute.

The liquefaction process is usually defined as P2L (DEA, 2017). However, some authors even specifically name it power-to-fuel (Robinius, Otto, Heuser, et al., 2017; Schemme et al., 2017). Ridjan et al. (2016) reviewed the difference between the terms synthetic fuels and electrofuels, finding that the first does not directly indicate the type of resource or production process used. The authors suggest speaking of electrofuels if a large amount of electricity is included in the production process, as is the case for hydrogen or methanol production via electrolysis. We will refer to electrofuels for gaseous or liquid fuels generated from P2G or P2L.

### 4.3 | Power-to-heat

The transformation of power into heat can be realized using HPs and EBs either on a central level for DH purposes or on a decentralized level directly at the location of consumption. For small applications, even direct electric heating is possible. The flexible generation of heating and cooling from renewable electricity is gaining importance in future renewable energy systems (Bloess et al., 2018). Currently, at least in Denmark, a decrease in taxes on electricity use for these technologies is improving economic performance (Nielsen et al., 2016). HPs are known to be more efficient compared with EBs. HPs transform heat from a low-temperature heat source (e.g., ammonia, air, seawater, or industrial excess heat, etc.) to a higher temperature-level output heat (DEA, 2016) and can also function the other way around for cooling. There are so called “compression HPs”—powered either by electricity or by combustion engines consuming fuel or biogas—and “absorption HPs”—driven by steam, hot water, or flue gas. They can be used in industrial processes, individual space heating/cooling, or DH. Compression HPs achieve a coefficient of performance (COP) or efficiency of 3–5 times the utilized electricity input (DEA, 2016).

EBs, in contrast, are easier to implement from a financial perspective because of lower investment costs and little regulation (Nielsen et al., 2016). They use electricity to generate hot water or steam in a similar way as oil or gas boilers (DEA, 2016). EBs operate at a COP of 1 and are mostly implemented for ancillary services owing to their systemic benefits promoting wind energy utilization and efficient use of heat sources. There are EBs using electrical resistance for 1–2 MW; for example, a common hot water heater or electrode boilers for larger applications of more than a few MW directly connected to the high voltage grid (DEA, 2016).

Considering the technologies described above, various pathways for the use of renewable power or other RES can be considered to achieve a decarbonization of the energy system. Figures 4 and 5 describe the principles of SC from a technological perspective. In Figure 4, the authors call direct electrification of transport using BEVs, power-to-move, which is sometimes even referred to as power-to-mobility or mover-to-transport. Figure 5 outlines the integration of the energy carriers, namely, electricity, gas, and heat as well as their cross-sectorial utilization and energy storage options. Because the original figure focused on the integration of energy carriers, we added the end-consumption sectors, namely, transport, industry, and residential as final demand sources.

## 5 | SECTOR COUPLING APPLICATIONS

### 5.1 | Sector coupling in the transport sector

Traditionally, the transport sector, including road and rail transport, aviation and maritime shipping, is mainly based on crude oil derived liquid fuels (Robinius, Otto, Heuser, et al., 2017). Figure 6 shows the potential pathways of direct and indirect electrification of transport. In the individual passenger transport sector, electrification and decarbonization through SC may, for example, be realized using electricity directly in BEVs or H<sub>2</sub> powered FCEVs (Lund, Mathiesen, et al., 2014).

Direct electrification via BEVs is efficiently applicable in passenger cars. International air and sea freight transport would require much higher battery capacity, which results in too much weight and energy consumption for efficient

Supply sector	Potential application of renewable electricity after transformation		
	Transformation 1 Energy carrier	Transformation 2 For end-use	End Use
Renewable electricity	Power-to-heat	-	Heat pump Electric boiler CHP plant
	Power-to-gas	Gas (H <sub>2</sub> /CH <sub>4</sub> )	Combustion
	Power-to-liquid	1. Gas (H <sub>2</sub> /CH <sub>4</sub> ) 2. Liquefaction	Combustion
	Direct electrification <i>Power-to-move/mobility/transport</i>		<i>Electrolyte</i>
			Space heat Process heat
			Space heat Process heat Industrial products Transport
			Space heat Process heat Industrial products Transport
			Space heat Transport

FIGURE 4 Sector coupling transformation pathways from a technical perspective

Source: Adapted from Wietschel et al. (2018)

FIGURE 5 Power-to-X technologies and cross-sectorial energy storage for sector coupling

Source: Adapted from Stadler and Sterner (2018)

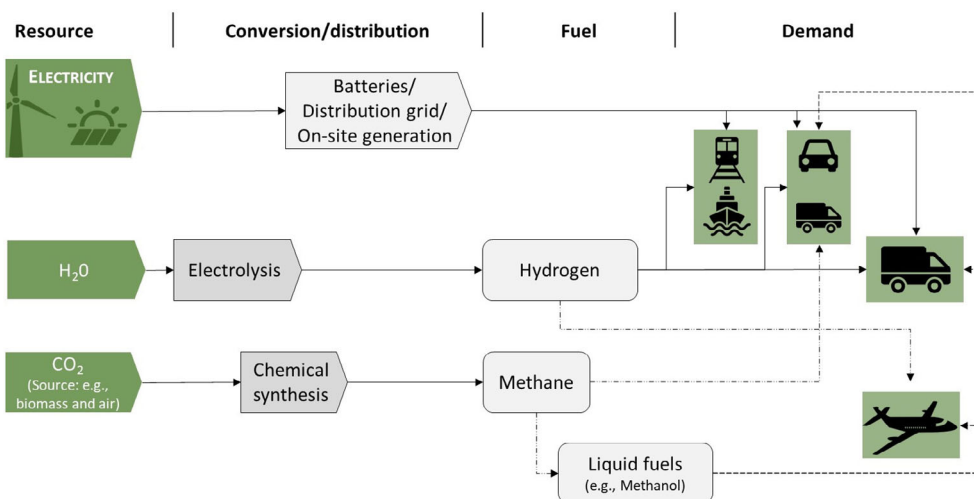
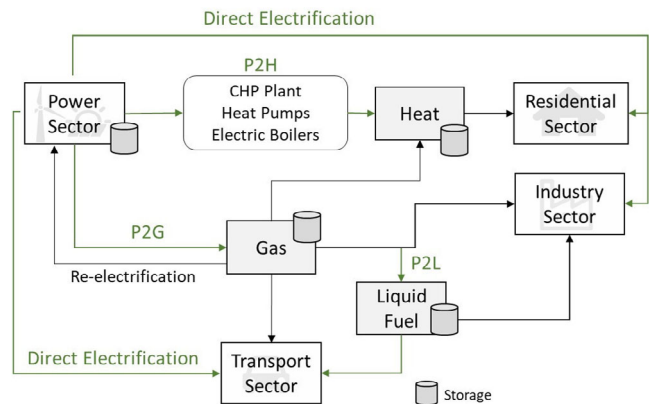


FIGURE 6 Renewable power use for common modes of transportation

Source: Adapted from Lund, Mathiesen, et al. (2014)

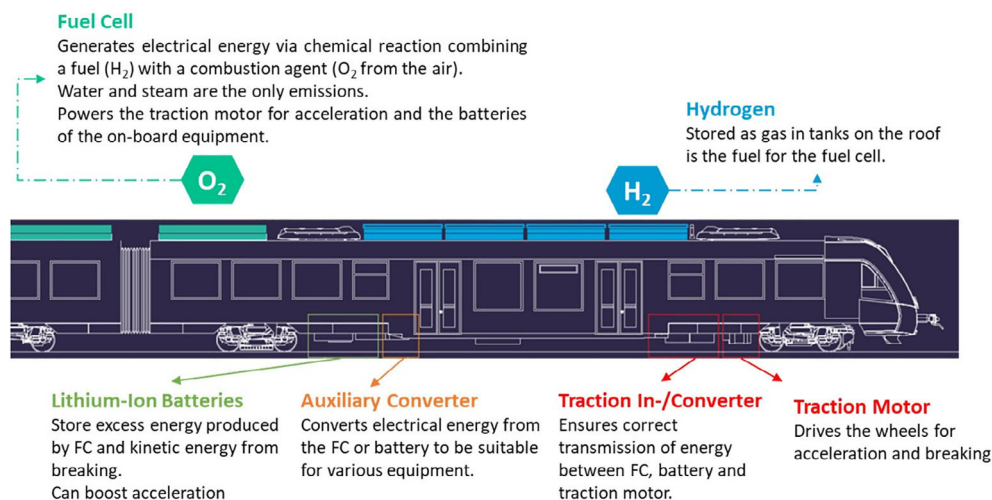
operation. For freight transport by road, BEVs currently enter the market in the smaller but also large truck classes. For the larger weight classes, research is also being conducted on overhead line trucks. H<sub>2</sub> has long been promoted as a potential transport fuel for cars, trucks, and trains (IEA, 2019). There are various application options of renewable gas in different forms, either as H<sub>2</sub>, methane, or blends in conventional internal combustion engines (DEA, 2017). If hydrogen is not produced from fossil fuels but from renewable electricity or biomass, it has a much better climate balance than conventional vehicles (Schemme et al., 2017). FCEVs convert H<sub>2</sub> into electrical energy and represent a dynamic buffer for load-management, using H<sub>2</sub> as a link between the power and the transport sector. While large parts of rail transport are driven by electricity, regions in which no electricity lines are available could use fuel-cell powered trains (Alstom Group, 2020b; Schreiner & Fleischhacker, 2018). The Coradia iLint, the first hydrogen-fuel-cell train of its kind in the world shown in Figure 7, was developed by Alstom (Alstom Group, 2020b). The hydrogen train provides the same performance as traditional regional trains at low noise and zero emissions with up to 140 km/h of speed, and the Coradia iLint has a range of approximately 1000 km—the same as an equivalent-size diesel multiple unit (Alstom Group, 2020b).

Furthermore, in maritime transport, electric shipping is already considered, apart from fuel-cell powered vessels (IRENA, 2015). The use of biofuels is being investigated but it still remains challenging concerning storage on board and the resulting corrosion and bio fouling. Biofuels are not considered as SC in our interpretation and are therefore not included for maritime transport in Figure 6.

Of course, liquid electrofuels with similar specifications as diesel or kerosene are also an option and are, together with H<sub>2</sub>, the only realistic decarbonization approach for maritime and air transport. However, large-scale and low-cost CO<sub>2</sub> sources will be required for production—for example, from biomass—representing a challenge in an increasingly decarbonized energy system (Robinius, Otto, Heuser, et al., 2017). The qualification of an electrofuel as a future transport fuel depends on its technical suitability to be used in existing systems and combustion technologies as well as the economic competitiveness with conventional fuels (Schemme et al., 2017).

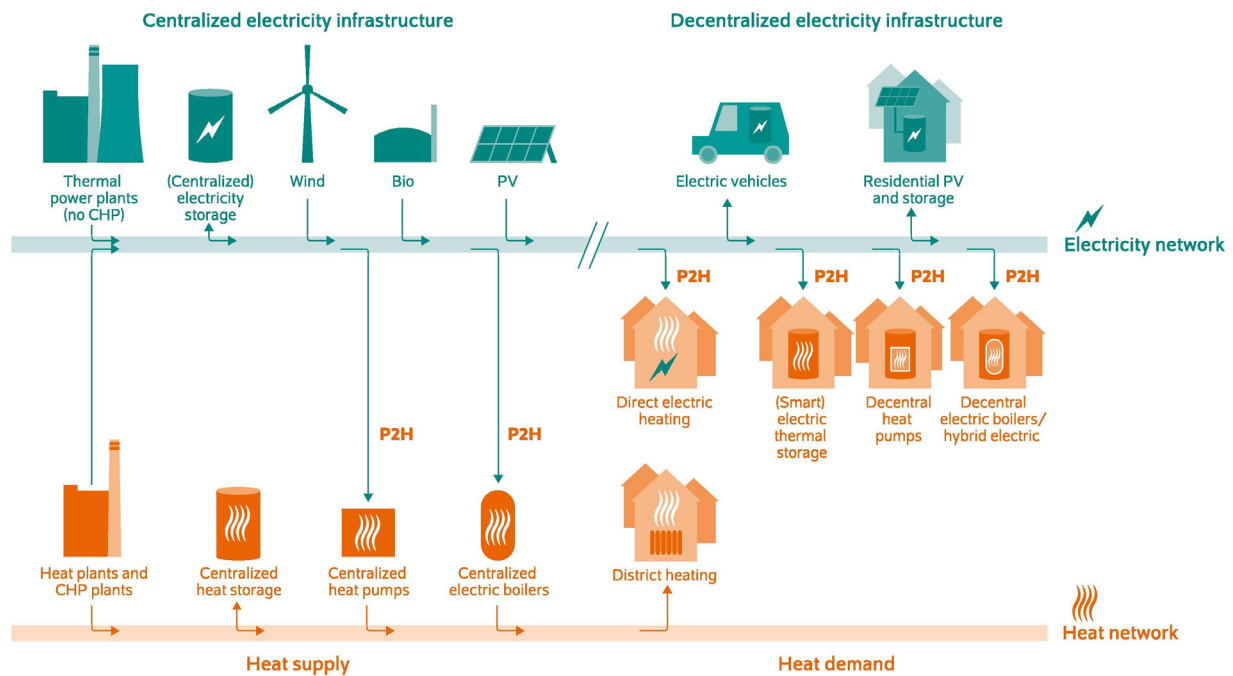
## 5.2 | Sector coupling in the residential sector

Achieving the decarbonization of the residential sector mainly focuses on the area of heating. The transformation of power into heat and cold can either be achieved on a centralized level concerning a spatial or infrastructural perspective close to the power generation plant or on a decentralized level in proximity to the customer location. In Figure 8, Bloess et al. (2018) provided a comprehensive overview of the potential applications using P2H as a technology to provide an alternative to fossil fuel heating. On a decentralized level, direct electric heating, decentralized HPs or EBs can be applied. The decentralized P2H network can also include a private BEV or a rooftop PV system with battery storage to provide flexibility. On a centralized level, renewable electricity may be fed into the central electricity grid and used in centralized HPs or EBs, or fed into the DH system. The authors also include power generation from thermal plants,



**FIGURE 7** Coradia iLint—The world's first hydrogen powered train. Fuel cell (FC)

Source: Adapted from Alstom Group (2020a)



**FIGURE 8** Power-to-heat (P2H) technologies on central and decentralized level (Bloess et al., 2018)

which in the long term may largely be reduced or operated through renewable gas instead of natural gas (Bloess et al., 2018). One important role concerning renewable DH is assigned to existing CHP plants, which may be enhanced through HPs and additional heat storage for an efficient integration of VRE (DEA, 2017).

In general, the literature on heating and cooling in future renewable energy systems largely focus on extended DH and using HPs and EBs. These technologies are far more efficient than green hydrogen, which is produced at an efficiency of about 75%, followed by further efficiency losses in heat production. A decarbonization of existing buildings, which often are equipped with decentralized gas boilers, therefore requires extensive refurbishment. Nevertheless, an increasing amount of processes in other end-consumption sectors (e.g., transport and industry) may be able to use green hydrogen instead of, for example, liquid fuels, and long-term storage is most promising with P2G. Consequently, the gas infrastructure remains an essential asset in future energy systems.

DH has experienced vast development from its first application until now. From coal-powered steam generation in 1880 and CHP plants in the 20th century, it advanced towards heat generation from biomass and large-scale solar systems. Modern DH now focuses on using large-scale renewable electricity (Lund, Mathiesen, et al., 2014). Temperature-levels also decreased substantially compared with the start of DH applications, leading to higher efficiency and parallel operation of district cooling.

DH development is important for MESs to levy synergies between all three types of infrastructure, namely, the electricity, thermal, and gas grid. Such a development may be supported by the more flexible operation of CHP plants, which may be achieved by the following three steps (Mathiesen & Lund, 2009):

1. Active regulation of CHP plants by use of thermal heat storage: The heat generation of CHP stations should not only depend on heat demand but should also adapt to produce less gas powered electricity during high availability of renewables (DEA, 2017). Therefore, heat storage capacity can add flexibility to decouple heat generation from demand (Lund, Werner, et al., 2014).
2. Using EBs and HPs in CHP systems: Enables heat generation from excess renewable electricity (Lund, Werner, et al., 2014). Renewable energy integration is again supported by thermal storage for more flexible generation that is independent of demand.
3. Bypass of turbines: At low electricity prices because of high renewable electricity availability, a bypass for electricity enables a CHP plant to only produce heat from VRE at the efficiency of a heating-only boiler (DEA, 2017).

There is already one successful example of a future energy plant with the Skagen CHP plant located in the northern part of Denmark, which has been in operation for several years (Lund et al., 2012). This CHP plant includes three gas engines

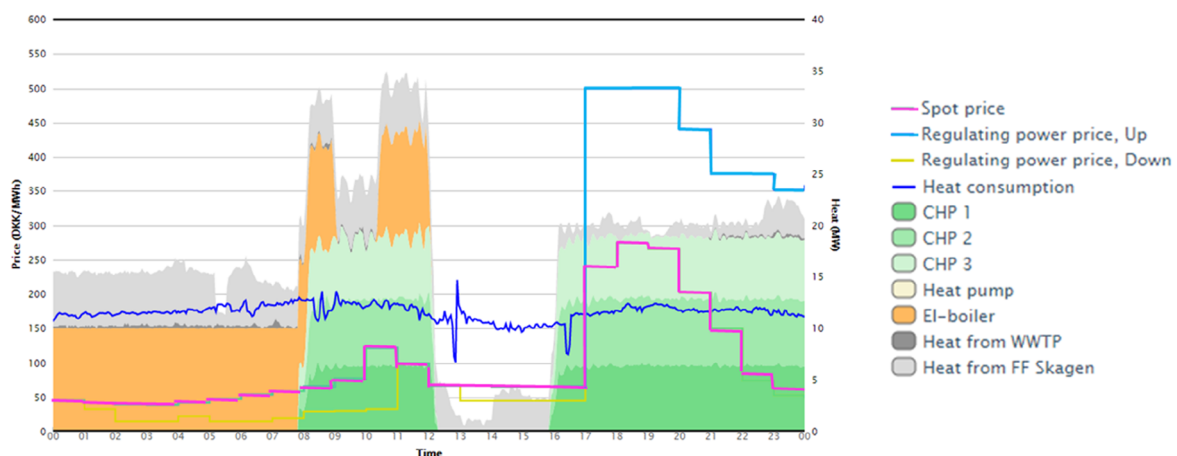
(CHP 1–3) and is supplemented with a waste incineration boiler and an EB, as well as contribution from industrial surplus heat. It plays an active role in the grid stabilization and regulating power tasks and promotes the integration of substantial amounts of wind power in the electricity and heat supply, leading to a decarbonization of these sectors. Heat generation with the EB is conducted at a low spot and regulating power prices, and the CHP plant generates heat at a high spot and regulating power prices (see Figure 9). Additionally, waste heat is used continuously. Thus, with heat generation mostly exceeding heat demand, the thermal storage is built-up on that day. Only recently, Skagen CHP plant has invested in a large-scale HP, which further reduced the use of fossil-fuel heat generation and replaced the EB most of the time because of its high COP.

### 5.3 | Sector coupling in the industrial sector

The industrial sector does require reliable availability of electricity for manufacturing processes and usually uses fossil fuels to power motors or produce H<sub>2</sub> for industrial chemicals. Many of these types of energy consumption may be decarbonized through SC. However, generating fuels that fit into the existing infrastructure and are suitable for common combustion engines or can replace fossil-fuel-based components of chemical products, is a challenge. Thus far, manufacturing has largely been neglected regarding decarbonization action. In the United States, however, the industrial sector is responsible for one-third of the total energy consumption, of which manufacturing activities make up the largest part (Zhong et al., 2017). Onsite renewable energy generation systems would allow the manufacturer to mitigate the disturbances of the utility grid and lead to improved reliability, affordability, resilience, and security of energy supply. Additionally, these decentralized, renewable power systems will decarbonize the industrial sector and reduce the pressure on electricity transmission and distribution systems (Zhong et al., 2017).

Apart from the energy to run machines in manufacturing, the chemical industry has substantial demand for H<sub>2</sub>, which is included in most industrial chemicals, such as ammonia for fertilizer production and methanol for various solvents (IEA, 2019). The chemical sector is responsible for the second largest demand for H<sub>2</sub> for ammonia and the third largest demand for producing methanol at 31 and 12 Mt H<sub>2</sub>/a, respectively. Including further minor applications of H<sub>2</sub>, the chemical sector achieves 40% of total H<sub>2</sub> demand in pure and mixed forms. Until 2030, H<sub>2</sub> demand in chemical production, especially ammonia and methanol, is expected to increase from 44 to 57 Mt/a and remains an important material (IEA, 2019). Furthermore, DRI, a method for producing steel from iron ore represents the fourth-largest single source of H<sub>2</sub> demand today (4 Mt H<sub>2</sub>/a) (IEA, 2019). Steel demand is expected to increase by 6% by 2030. One ton of crude steel results in around 1.4 tons of direct CO<sub>2</sub> emissions. Less CO<sub>2</sub> intense processes are currently being developed and can be divided into the following two categories:

- “CO<sub>2</sub> avoidance” pathways: Through low-carbon sources of energy, usually using H<sub>2</sub>;
- “CO<sub>2</sub> management” pathways: Recovery and management of CO<sub>2</sub> in traditional fossil-fuel-based routes, usually via carbon capture, utilization, and storage.



**FIGURE 9** Flexible operation of Skagen CHP plant, equipped with heat pump and electric boiler on March 18th, 2020 (EMD International, 2020)

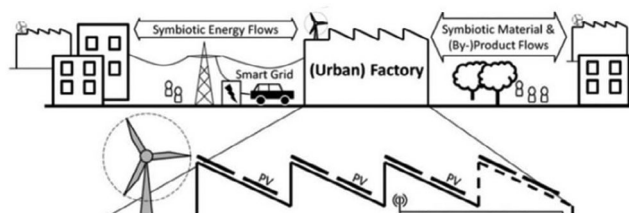


Herrmann et al. (2014) presented their vision of a factory of the future. They pointed out that future manufacturing needs to address all three dimensions of sustainability, namely, economy, ecology, and society. This means that, maintaining or even improving profitability, the environmental impact has to be reduced by aiming at a zero emission concept or even a positive impact on society, improving the quality of air and water, providing renewable energy, and acting as storage for surplus energy. This is the only way to achieve an appropriate degree of sustainability in manufacturing, which preserves resources for future generations. As seen in Figure 10, the factory of the future shall integrate energy flows across industry, households, and urban infrastructure as well as provide renewable power from, for example, a rooftop PV system. This shall enable SC for transport and manufacturing processes or renewable  $H_2$  production (Herrmann et al., 2014). The most famous prototype of such a factory has been realized within an eco-industrial park in Kalundborg, Denmark.

As an exemplary project, voestalpine is striving for a continuous increase in the use of green  $H_2$  in steel production processes, allowing the Group to reduce its  $CO_2$  emissions by over 80% towards 2050. Figure 11 shows this restructured production process in which all the coal input can be replaced by green electricity and hydrogen, and the formerly used coal-powered blast furnace and BOF are eliminated. Such a change in the production process, however, highly depends on the availability of green electricity at commercially realistic prices to stay competitive.

## 6 | THE ROLE OF SECTOR COUPLING IN MULTI-ENERGY SYSTEMS

Thus far, we discussed the SC concept as a measure to integrate renewable electricity into a broad range of applications, enabled by transformation technologies and an adaption of traditional processes. Although SC can be interpreted as a sub-system or even a one-way path from electricity to other end-consumption sectors, there currently is an increased focus on the overall integration of power, heat, industry, and mobility. Lund, Mathiesen, et al. (2014) claimed that the

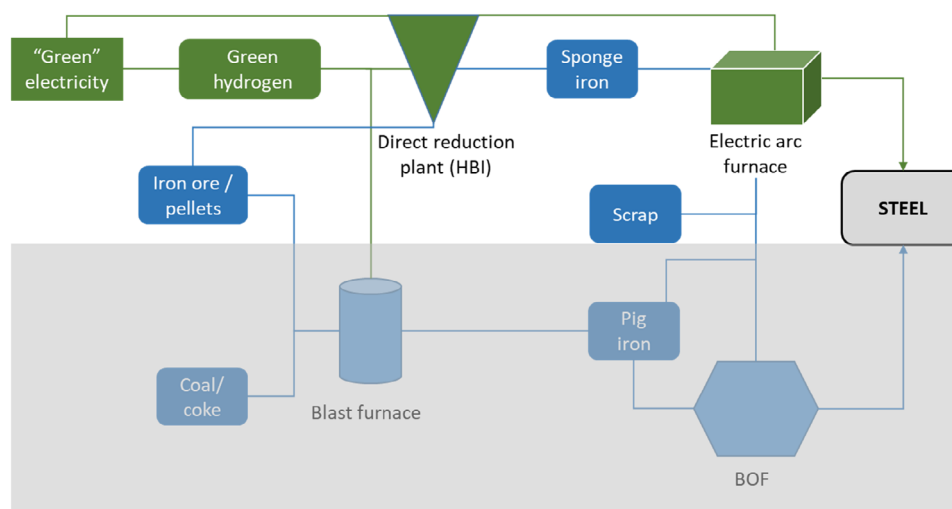


### Sector Coupling Aspect:

- On-site renewable electricity generation
- Use for production processes
- Provision of this electricity to community for BEV charging or households
- Use of renewable electricity on site
- Methanation using surrounding carbon sources from waste and local emissions

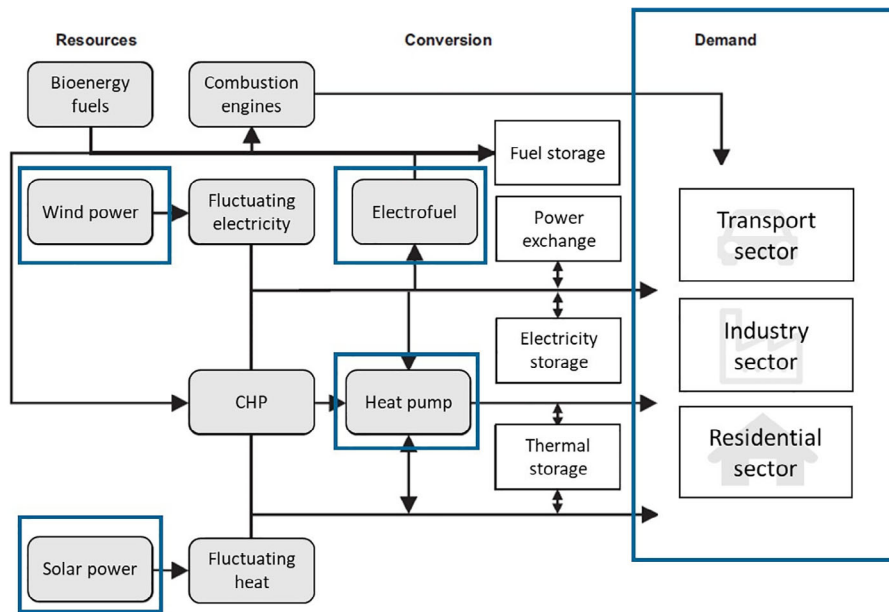
**FIGURE 10** Sector coupling aspects in holistic factories of the future

Source: Adapted from Herrmann et al. (2014)



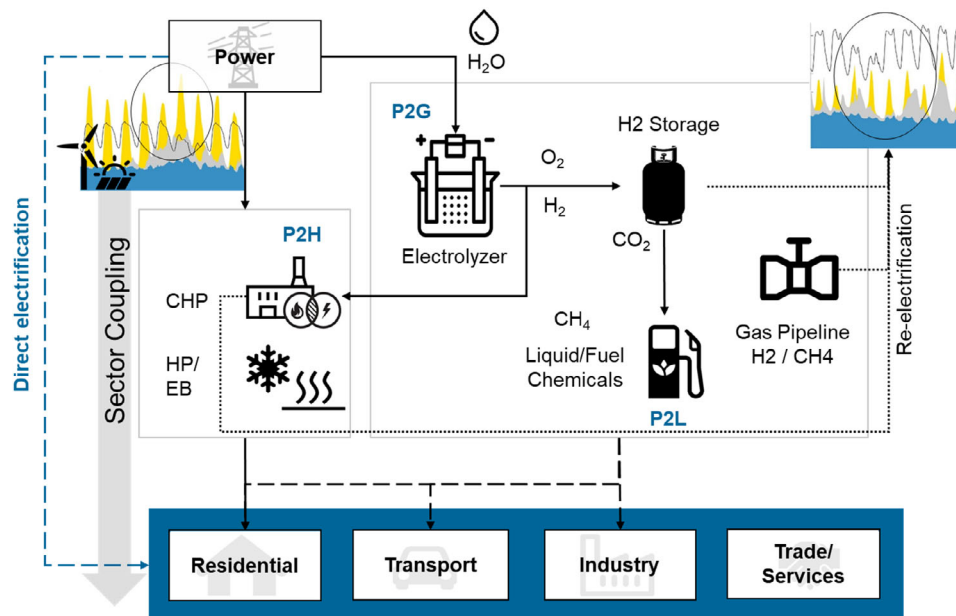
**FIGURE 11** Restructured steel production process powered by renewable energy

Source: Adapted from Voestalpine (2020)



**FIGURE 12** The role of sector coupling in a future smart energy system

Source: Adapted from Connolly et al. (2016)



**FIGURE 13** Comprehensive high-level overview of SC pathways from a technological view

different sub-sectors influence each other, which has to be considered when seeking optimal solutions. These concepts can be found in literature under several terms, such as multi-energy system, integrated energy system, or smart energy system (SES) (Connolly et al., 2016; Lund, Mathiesen, et al., 2014; Witkowski et al., 2020). Such an approach focuses on the intelligent interaction and integration of energy carriers and infrastructure as described by Dena (2017), for the most efficient use and storage of renewable energy. Nevertheless, MESs and efficient VRE integration rely on the basic P2X transformation technologies for renewable electricity. Therefore, SC does not only represent an independent system but can also support fully integrated MESs. Witkowski et al. (2020) specifically analyzed the ability of SC to provide flexibility in the form of renewable heat or gas.

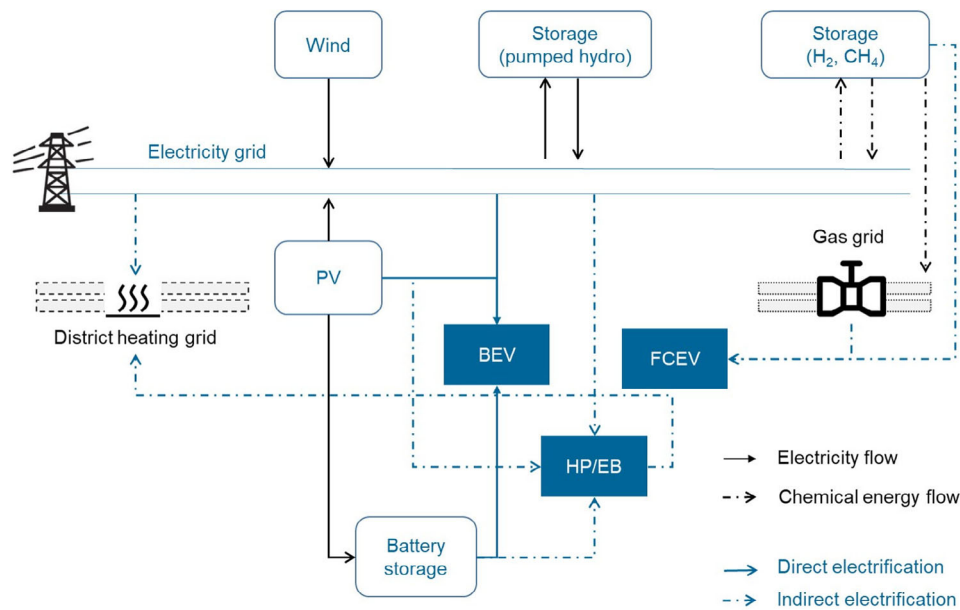
**TABLE 4** Categorization of sector coupling applications into centralized (C)/decentralized (D) transformation (based on scale and proximity to the consumer) and direct/indirect electrification

Sectors and applications	Traditional	Direct electrification		Indirect electrification (P2X)		Alternative options <sup>a</sup>
			C/D		C/D	
Transport						
Cars and small trucks	Gasoline and diesel Natural gas	Batteries	C, D	Hydrogen, methane Liquid electrofuels	C	Biofuels, biogas, trucks: purified biogas
Large trucks	Diesel, natural gas	Overhead lines on highways Batteries	C	Hydrogen, methane Liquid electrofuels	C	Biofuels, trucks: purified biogas
Railway	Electric drive, diesel	Electrification of nonelectrified sections	C	Hydrogen, methane Liquid electrofuels	C	Biodiesel
Air	Turbines (kerosene)	No solutions expected	-	Liquid electrofuels (kerosene) Hydrogen	C	Bio-kerosene
Maritime	Heavy fuel oil, diesel LNG	No solutions expected	-	Hydrogen, methane, liquid electrofuels (diesel/kerosene)	C	Biodiesel, purified biogas
Residential/industry/trade: Low temperature heat for households, industry and trade/services						
Low temperature heat	Oil or gas heating, DH	Heat pumps Resistance heating	C, D	Hydrogen/methane	C, D	Biomass, biogas
Industry						
Industrial process heat	Gas engine, steam	Electrode boiler, induction heating, plasma process, resistance heating	D	Liquid electrofuels	C	Biomass, biogas
Iron (primary route)	Coke	Not applicable	-	Hydrogen	C	Biomass, biogas
Refinery	H <sub>2</sub> (side product and from natural gas)	Not applicable	-	Hydrogen	C	Biomass, biogas
Chemicals		Not applicable	-	Hydrogen, liquid electrofuels	C	Biomass, biogas

Source: Adapted from Ausfelder and Dura (2018).

Abbreviations: C, centralized; D, decentralized.

<sup>a</sup>Not depending on electricity input.



**FIGURE 14** Direct and indirect electrification of transport and heating, heat pump (HP), electric boiler (EB), battery electric vehicle (BEV), fuel-cell electric vehicle (FCEV), photovoltaic (PV)

Lund, Mathiesen, et al. (2014) defined such an integrated energy system enhanced by new technologies and infrastructure as smart energy systems. The “smart” in SESs, however, does not specifically indicate a large amount of intelligent technologies but implies a radical shift in the understanding of energy system infrastructure. SESs are considered an option to efficiently use a larger share of VRE sources in future energy systems by using new types of flexibility and integrating the infrastructure of smart or bi-directional electricity, smart gas, and smart thermal grids (Lund, Mathiesen, et al., 2014). The smart electricity grid provides a connection between flexible electricity demand of HPs and EBVs and the VRE sources. The smart thermal grid enables the integration of electricity and heating and cooling and provides flexibility through thermal energy storage. Finally, the smart gas grid connects electricity, heating and cooling, and transport by considering renewable gas generation through electrolysis (Lund et al., 2017). Obviously, the modeling of such MESs for a time in the future is characterized by high complexity.

Figure 12 shows that the input and conversion processes related to SC, which are marked in blue, are at the heart of such a multi-energy system or SES. They initiate electricity use and transformation into any suitable energy carrier for more flexibility. The transport, residential, and industry sector have demand for mobility, electricity, and heating and cooling. The SC concept therefore is one essential part of the future 100% renewable energy systems.

## 7 | DISCUSSION OF FINDINGS

We now provide a summary and critical discussion of the literature review conducted in this article in Section 3. First, we outline a suggested interpretation of the sectors in SC, followed by a structured categorization of the SC concept from our findings in Sections 3.2 and 3.3. Finally, we discuss the remaining challenges of SC technologies as well as its value for future renewable energy systems.

### 7.1 | Definition of sectors

Our work proves that the interpretation of SC is multiplied and that the understanding of the concept already varies with the definition of the sectors. The differences in the sector definitions originate from research perspectives and depend on the field of application, either engineering or energy economics. Although Wietschel et al. (2018) used a technical approach in defining the sectors as transport, heat, and industry, Robinius, Otto, Heuser, et al. (2017) referred

to sectors as transport, residential/household, industry, and trade/commerce. The latter is common in energy economics, while heat or gas do not represent a sector but an energy carrier or service. BDEW (2017), however, regarded SC as the coupling of power, heat, and mobility to supply the end-consumption sectors, namely, industry, residential, trade/services, and transport with renewable energy and used two approaches on the sector definition. Further, BMWi (2016) mentioned SC as the coupling of the heating sector, and spoke of a coupling of the residential sector, not specifically following one approach.

A requirement for future renewable energy systems is the determination of new demand sources for renewable electricity by substituting fossil energy. The final goal is fulfilling the demand of end-consumption in industry, transport and residential homes, while the processes in these end-consumption sectors can be adapted to be powered by another form of energy carrier. A definition as end-consumption sectors as in Robinius, Otto, Heuser, et al. (2017), hence provides a technology-neutral approach and allows for a broader range of solutions, independently of the energy carrier applied (electricity, gas, or heat). To avoid thinking in the existing infrastructure and trying to establish a totally new design of future energy systems, and specifically supply, represents one important paradigm shift that is attempted through the energy hub by Geidl et al. (2007). We therefore suggest using the sector definition common in energy economics for techno-economic research on SC. More specifically, in technological research, it is obvious that the perspective may focus on the transformation of power into a specific energy carrier. This would largely meet the approach by EP (2018), differentiating so called end-use SC and an integration of energy carriers as a cross-vector coupling, which is explained in Section 3.1.

## 7.2 | Sector coupling: Categorization from an own perspective

As indicated in our introduction, SC lacks a consistent definition and is often interpreted misleadingly. Drawing conclusions from our literature review in Section 3, we now aim at a comprehensive overview of the potential pathways of SC and the enabling transformation technologies in Figure 13, followed by a detailed categorization as per sector in Table 4. Renewable electricity may be used directly or through transformation into heating (P2H) or cooling, gas (P2G), or liquid (P2L) in the end-consumption sectors, namely, residential, transport, industry, and commercial/trade/services. We strongly suggest avoiding additional terms, such as power-to-move or power-to-fuel, which imply all potential technologies for fuel generation or movement, and are not specific enough. While the first term simply summarizes all types of an electrification of transport, the latter summarizes different fuels and should be categorized more specifically as P2G or P2L to follow the known structure. Excess electricity may also be used in flexible CHP plants equipped with HPs as described in Section 5.2. The re-electrification of  $H_2$  in times of little availability of renewable electricity sources—for efficiency matters preferably via CHP plants—or via gas turbines, is possible, nevertheless only at substantial efficiency losses.

To provide a better understanding of direct and indirect electrification, Figure 14 describes examples mainly focusing on transport and heating and shows the flow of electricity, which is used for direct electrification and the chemical energy flow, for example,  $H_2$  for indirect electrification. Apart from grid dependent electricity use, a decentralized PV system can directly electrify transport using a BEV, or indirectly electrify heat using a decentralized HP.  $H_2$  or methane may also be stored long term in chemical storage or fed into the natural gas grid.

Table 4 provides a structured categorization of SC applications for each sector as direct and indirect electrification, and centralized (C) and decentralized (D) SC. The categorization is conducted based on the proximity to the consumer and the scale of generation or conversion. SC can be conducted on a large scale, centralized level or on a smaller-scale decentralized level, with the transformation or use taking place closer to the end-customer. For example, while large-scale P2H from the electricity grid via central EBs is regarded as central SC with indirect electrification, the use of such decentralized EBs or HPs is defined as decentralized SC (Bloess et al., 2018).

One matter often discussed is whether the consideration of further renewable or waste energy sources, such as biofuels and excess heat, are part of the SC concept. We refer to Section 3, in which we outlined that the new rise of SC was triggered by the increasing share of VRE electricity generation along with the energy transition. Based on this observation and supporting statements in various literature, we claim that SC mainly has its origin in the efficient integration of VRE (BMW, 2016; Robinius, Otto, Heuser, et al., 2017; Schaber et al., 2013; Scorza et al., 2018). Consequently, we do not consider renewable energy that does not include electricity as a main input, such as waste heat, or biofuels, as the main aspect of the SC concept but of MESS, but state it as alternative options in our summary in Table 4. Even if we agree that, for example, the use of excess heat from power generation or industrial processes is

essential to increase energy system efficiency, we suggest addressing it within the area of MESs and regard it as out of scope in SC (Lund, Mathiesen, et al., 2014; Ma et al., 2018; Mancarella, 2014; Marnay & Lai, 2012).

### 7.3 | The challenges and value of sector coupling

It is evident, that an increasing share of electricity from VRE sources requires an energy system with more flexible consumption, distribution, and storage. In contrast, VRE sources represent a great chance for the decarbonization of the end-consumptions sectors and are essential to reach climate goals. IRENA (2018) considered P2G as a most promising transformation technology that enables SC in various ways. Thanks to the large capacity of gas pipelines in Europe, even low blending shares of H<sub>2</sub> would lead to the absorption of substantial quantities of VRE. Green gas may replace fossil fuels in many end-use applications while fully utilizing existing infrastructure. Olczak and Piebalgs (2018) are convinced that SC will exploit the rising share of electricity by distributing and storing it after a transformation into H<sub>2</sub> and synthetic methane.

While P2G seems promising for various end-consumption sectors and as a large-scale storage technology, we would emphasize the importance of all potential transformation technologies together. The development of transformation technologies faces various uncertainties, such as electricity prices and competition through transmission grid expansion. However, its economic feasibility remains challenging with a small amount of full load hours, if considered to operate only at times of excess electricity generation. Within the existing market environment, low electricity prices may promote direct electrification instead of P2G or P2H, whenever possible.

Brown et al. (2018) detected SC and transmission grid expansion to be competing concepts with respect to the integration of renewable energy. In their study, many scenarios favor the expansion of transmission network capacity, specifically in the North and Baltic seas. They also found that direct electrification of individual transport is more efficient, without the losses of P2G and P2L (Brown et al., 2018). However, P2G is considered beneficial in renewable energy systems to provide flexibility and long-term storage. We interpret these results as a suggestion to implement both transmission network expansion and SC for the efficient integration of renewable energy.

Robinius et al. (2018) specifically compared the cost efficiency of P2G and transmission grid expansion and concluded that investment into the latter is currently more cost effective. Achieving a certain amount of flexibility through transmission network expansion only costs 30% of the same capacity implementation of an electrolyzer; however, they do not consider an income from selling the hydrogen at a competitive price. Hörsch and Brown (2017), in contrast, argued against a substantial cost benefit of transmission grid expansion compared with P2X technologies. They concluded that an almost fully renewable energy system without any grid expansion is only about 20% more expensive. They assumed the cost benefit to be even smaller, if investment in line volume was included to avoid rejection of a growing amount of new lines by the public. Robinius et al. (2018) later acknowledged that their results highly depended on the regional situation and scenario assumptions. Decreasing capital investment cost and an expected decrease in electricity wholesale prices may eventually support the economic feasibility of P2G at least for seasonal storage (Robinius et al., 2018). This argument stands against the likely trend of using low-cost renewable electricity directly if possible, which again reduces the need for P2G.

Other transformation technologies also face uncertainties in the long term. For example, the importance of P2H may change along with the consequences of global warming, whereas, simultaneously, requirements for cooling may increase. This uncertainty asks for an appropriate design of DH using lower temperatures that allow efficient heating and cooling in the same network.

Despite all these risks, some arguments do justify the continuous investment into SC technologies and appropriate infrastructure. First, with the path towards CO<sub>2</sub> neutrality having been decided in Europe, direct or indirect use of large-scale renewable electricity remains a requirement in many cases. Flexible transformation between energy carriers provides a basis for efficient management of renewable energy systems. This can be realized partly within the SC concept. Second, Novak (2017) explained the value of energy carriers based on the amount of exergy, which is defined as the net energy provided. Renewable energy is pure exergy with zero operative cost. Therefore, it needs to be used most efficiently without being wasted. Third, because of the increasing share of electricity generation from wind and PV, the demand for seasonal renewable storage, for example, in the form of H<sub>2</sub> is growing. These arguments clearly only make sense if the input electricity for SC is produced from renewable sources and does not include gray electricity from coal, oil, or gas. Nevertheless, to develop the required technologies in the long term, hybrid solutions may be necessary before a sufficient capacity of VRE is available. Another important aspect is the political risk related to the dependency

on oil and gas extracting countries. In history, severe crises have been caused from a lack of alternatives through national energy provision, such as the oil crisis in 1973. SC represents an option to fulfill former fossil based fuel demand with renewable hydrogen, methane, and liquid electrofuels.

Because the electricity market does not currently provide the incentives to install P2G capacities, a possible solution is the initiation within the regulatory framework of national TSOs and DSOs. With the capital investment largely being refunded to these regulated institutions, they could install electrolyzer capacity at a low cost and auction it to power plant operators for feed-in of their excess VRE generation. The renewable hydrogen may be stored or support the decarbonization of the end-consumption sectors (Robinius et al., 2018). Such projects have already been initiated with an aim to develop the technology towards maturity, establish economic feasibility, and guarantee security of supply. One example is the hydrogen valley in the northern Netherlands in which emission-free hydrogen will become cost-competitive throughout the upcoming decade (Foresight Climate and Energy, 2019). Generation scale is the measure to reduce the cost, thereby achieving energy expertise and using the available pipeline infrastructure. The project aims at generating 3–4 GW of wind energy for hydrogen production until 2030, which could be extended to 10 GW up to 2040. 800,000 tons of green hydrogen could avoid 7 megatons CO<sub>2</sub> emissions in 2040 (Foresight Climate and Energy, 2019).

## 8 | CONCLUSION

The basic idea to couple different sectors and energy carriers has already been applied previously, for the electrification of transport and residential homes and by coupling conventional, thermal power plants for efficiency gains. During the past decade, the SC approach arose newly to handle the increasing share of VRE power generation, implemented for the purpose of climate protection.

Definitions of SC in available literature range from exclusively using excess renewable electricity in other end-consumption sectors to even including cross-energy-carrier integration with the use of excess heat and biomass energy. From our literature review, we conclude that the concept is rooted in the increasing share of VRE in the overall energy system (see Section 3). We therefore suggest considering SC as a concept to promote the integration of large-scale renewable electricity by increasing its direct use or indirect application through transformation into a suitable energy carrier, such as heat, gas, and liquids. Consequently, we do not consider renewable energy, which does not include electricity as a main input, such as waste heat or biofuels, as a main aspect of the SC concept but rather of MESs. SC as a sub-system may thus allow for more specific analysis of technologies for power transformation with slightly less complexity than fully integrated energy systems. SC can be applied on a centralized level with large-scale electricity generation and transformation or on a decentralized level closer to the location consumption. In this analysis, we provided a thorough categorization for all end-consumption sectors in Section 7.2. With respect to the sectors that are considered in SC, we find the approach that is common in energy economics (transport, residential, industry, and trade/services) suitable for analyses regarding the techno-economic and system perspective, because these represent the final demand (see Section 7.1). For specific technological research such as P2G, however, a focus on the energy carriers—such as electricity, heat, and gas—may of course be useful.

Apart from already highly developed renewable energy systems, as in the Northern European countries such as Norway, the economic feasibility of P2H and especially of P2G and P2L continues to include uncertainty in many regions of the world. The developments also depend on hardly predictable future global demand and supply situations and climate change roadmaps. P2G faces substantial competition from transmission grid expansion and direct electrification with only minimal efficiency losses (see Section 7.3). There are various trade-offs to consider and a prediction of system-wide effects is extremely challenging. After all, direct electrification is not possible for all processes, and the transport sector will rely on electrofuels for larger vehicles. Furthermore, a certain amount of P2G will be required to enable the efficient management of renewable energy systems. Currently, P2G projects are initiated within the regulatory environment of TSOs and DSOs, which have an interest in long-term security of supply in renewable energy systems and receive refunds for the capital investment cost. Obviously, the SC concept in light of the energy transition can only fulfill its aim with a sufficient amount of renewable energy capacity installed. Additionally, we believe that market and price coupling of commodities such as electricity, heat, methane, hydrogen, and others is a very important aspect for the development of SC from the technological and economic perspective. Such an adjusted market structure enables an increase of choices between fuels and more flexible substitution of energy carriers. This will guarantee higher price stability and lower price risks owing to greater interdependencies.

SC and its enabling technologies still face challenges in the long-term future; however, the path towards renewable energy systems is certain, and the climate goals need to be met. The use of large-scale renewable electricity in a growing amount of applications will be required and can partly be realized with SC. Nevertheless, the research gap in system-wide effects of SC and the competition between different technologies and solutions needs to be closed in the near future.

## CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

## AUTHOR CONTRIBUTIONS

**Jasmine Ramsebner:** Conceptualization; data curation; formal analysis; investigation; methodology; resources; visualization; writing-original draft. **Reinhard Haas:** Conceptualization; supervision; writing-review and editing. **Amela Ajanovic:** Writing-review and editing. **Martin Wietschel:** Visualization; writing-review and editing.

## ORCID

Jasmine Ramsebner  <https://orcid.org/0000-0002-4154-8131>

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