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Linking the Power and Transport Sectors—Part 1: The Principle of Sector Coupling

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Abstract: The usage of renewable energy sources (RESs) to achieve greenhouse gas (GHG) emission reduction goals requires a holistic transformation across all sectors. Due to the fluctuating nature of RESs, it is necessary to install more wind and photovoltaics (PVs) generation in terms of nominal power than would otherwise be required in order to ensure that the power demand can always be met. In a near fully RES-based energy system, there will be times when there is an inadequate conventional load to meet the overcapacity of RESs, which will lead to demand regularly being exceeded and thereby a surplus. One approach to making productive use of this surplus, which would lead to a holistic transformation of all sectors, is "sector coupling" (SC). This paper describes the general principles behind this concept and develops a working definition intended to be of utility to the international scientific community. Furthermore, a literature review provides an overview of relevant scientific papers on the topic. Due to the challenge of distinguishing between papers with or without SC, the approach adopted here takes the German context as a case study that can be applied to future reviews with an international focus. Finally, to evaluate the potential of SC, an analysis of the linking of the power and transport sectors on a worldwide, EU and German level has been conducted and is outlined here.

Keywords: sector coupling (SC); linking the sectors; power-to-gas; power-to-fuel; power-to-heat; transport sector

1. Introduction

The 2015 21th Conference of the Parties (COP21) conference that culminated in the Paris Agreement to reduce greenhouse gas (GHG) emissions is arguably one of the most significant recent international political developments [1]. Schnellnhuber et al. [2] discuss the possible effects of the Paris Accord on climate change, analyzing the targets it sets out in terms of necessity, feasibility and simplicity, determining it to be an ambitious step towards limiting anthropogenic CO_2 emissions, and therefore towards more environmentally friendly energy supply systems. The agreement is significant for various reasons. One of the most notable is the large number of participating countries, including most of the largest CO_2 polluters. In total, 187 countries agreed to commit, with 175 of them signing the legally binding agreement on 22 April 2016, reaffirming the goal of limiting the global temperature increase to less than 2 °C and striving for a maximum of 1.5 °C, thus setting a record for first-day signatures to an international agreement [3]. Although arresting temperature increase might not seem to be a scientifically concrete objective, it is generally accepted by the environmental science community [2]. An unexpected result of COP21 was, moreover, the inclusion of adaptation directly linked to the level of emissions mitigation while transparency rules were established, meaning that all members will be required to report their status on a regular basis [3]. The agreement constitutes a clear path towards achieving a zero-emission system in the fastest manner possible, especially if we consider the fact that meeting the 2 °C target requires that no new emitting infrastructure will be constructed after 2017, unless either another equivalent emitter is discontinued or a carbon capture technology is applied [4]. There are three major potential pathways for achieving the GHG reduction goals:

(1) Continuing the use of fossil fuels in conjunction with the capture and storage of carbon dioxide.
(2) The usage of nuclear power.
(3) The usage of renewable energy sources (RESs).

Adopting the third pathway of utilizing RESs to achieve the GHG emission goals would require a complete transformation of all sectors. The first two pathways also carry advantages and disadvantages, but are beyond the scope of this paper. Therefore, this paper will focus on one approach that could lead to the transformation of all sectors, namely "sector coupling" (SC), or "integrated energy". The concept of SC has become popular in Germany, in the course of the ongoing "Energiewende" ("energy transition"; see Section 5.3), but it is not always applied correctly in the literature and, furthermore, the principal pathways are sometimes not clearly elaborated; thus, the use of SC in models is often inaccurate. Whereas the approach of SC is likely to be more frequently used, the principle has yet to be clearly defined, and its possible features are yet to be described.

The aim of this paper is therefore to clarify the concept of SC in a general sense (see Section 2) and show in more detail the principal pathways by which the power and transport sectors may be linked (see Section 3). Moreover, Section 4 comprises a literature review. To demonstrate the worldwide potential of coupling these sectors, their respective status will be described in more detail (see Section 5) and current developments will be discussed, along with the prospect for the modeling of SC.

With this contribution, the authors intend to provide basic knowledge for the research community to conduct studies into SC in different countries and use the same terminology to generate comparable results in the future.

2. The Principle of Sector Coupling

To clarify the concept of SC, the general principle behind it will be described. The concept relies on a strong commitment to the afore-noted pathway 3 (increasing usage of RESs as a means of diminishing GHG emissions). Germany, for example, emphasizes this pathway (see Section 5.3). Due to the country's limited potential for hydroelectric power, the main RESs deployed in Germany are wind and photovoltaics (PVs). Given the fluctuating nature of wind and sunlight, it is necessary to install more wind and PVs generation in terms of nominal power than would otherwise be required for the current power demand (conventional demand) to be met. Despite this over-installation, there will still be times (such as during the night and when there is no wind) when there will be a need for consistent power production and distribution similar to that afforded by power plants or storage systems. On the other hand, there will be times when there will not be enough conventional load, and this will lead to the demand being exceeded, and thereby a surplus of power. The uses to which this surplus is put constitute SC. There are different definitions used in Germany, such as that of the German Federal Ministry for Economic Affairs and Energy [5]—for example, the German Technical and Scientific Association for Gas and Water [6] or the German Association of Energy and Water Industries (BDEW) [7]. Herein, the authors will use the definition of SC employed by the BDEW, which defines it as "the energy engineering and energy economy of the connection of electricity, heat, mobility and industrial processes, as well as their infrastructures, with the aim of decarbonization, while simultaneously increasing the flexibility of energy use in the sectors of industry and commercial/trade, households and transport under the premises of profitability, sustainability and security of supply" [7].

It should also be noted that the economic discussion of whether there will be a surplus in future energy systems, or if demand will always be consistent, is beyond the scope of this paper and therefore will not be further discussed. Figure 1 illustrates the principle of SC and was developed on the basis of the description of the concept advanced by the German Federal Ministry for Economic Affairs and Energy [5].

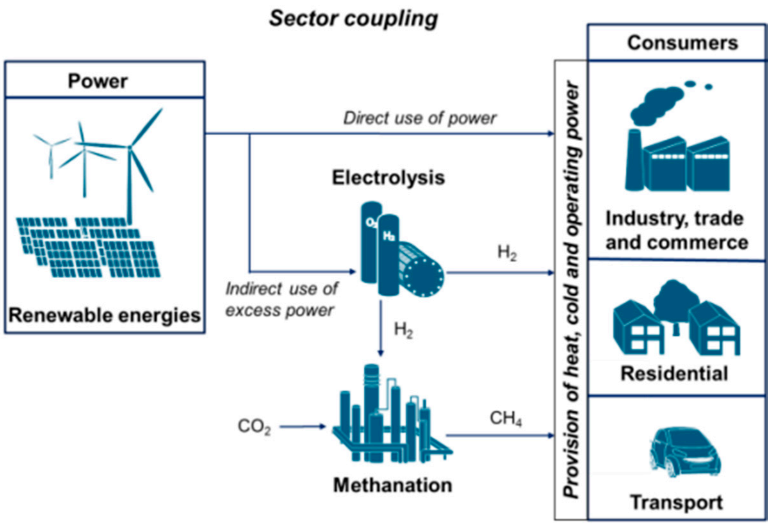

Figure 1. The principle of sector coupling (SC).

First of all, to correctly delineate a sector, inaccurate formulations in the literature must be clarified. For instance, heat supply does not constitute a sector, but rather an application; illumination in the household sector would be another example. The authors thereby define sectors in the context of SC with respect to the definition of the BDEW as the following:

- Industry, trade and commerce
- Residential/household
- Transport

The agriculture sector has not yet been considered in the context of SC, but should also not be ignored.

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 RESs. For example, a combined heat and power plant that generates electricity would supply excess heat that would otherwise be wasted to other industries or the household sector. Correspondingly, a natural gas infrastructure such as a pipeline grid would allow the possibility of using natural gas in the power sector (with natural gas power stations), transport sector (natural gas vehicles), industry sector (hydrogen, methanol or ammonia production) or household sector (heating). Nevertheless, to avoid misconceptions, the concept of SC for our purposes fundamentally relies on RESs and therefore fits the principle outlined in Figure 1.

Figure 2 details a selection of potential SC pathways corresponding to the "power-to-X" principle, where X stands for gas, fuels/chemicals or heat. The use of hydrogen to produce electricity or heat is referred to as "gas-to-power".

Because a detailed description of all possible power-to-X applications is tangential to the purposes of this paper, only the pathways that make it possible to link the power and transport sectors, namely the power-to-gas (P2G) and gas-to-fuel pathways, will be analyzed in greater depth (see Section 3).

Furthermore, the direct use of the electricity surplus in applications such as battery electric vehicles (BEVs) is another possible route.

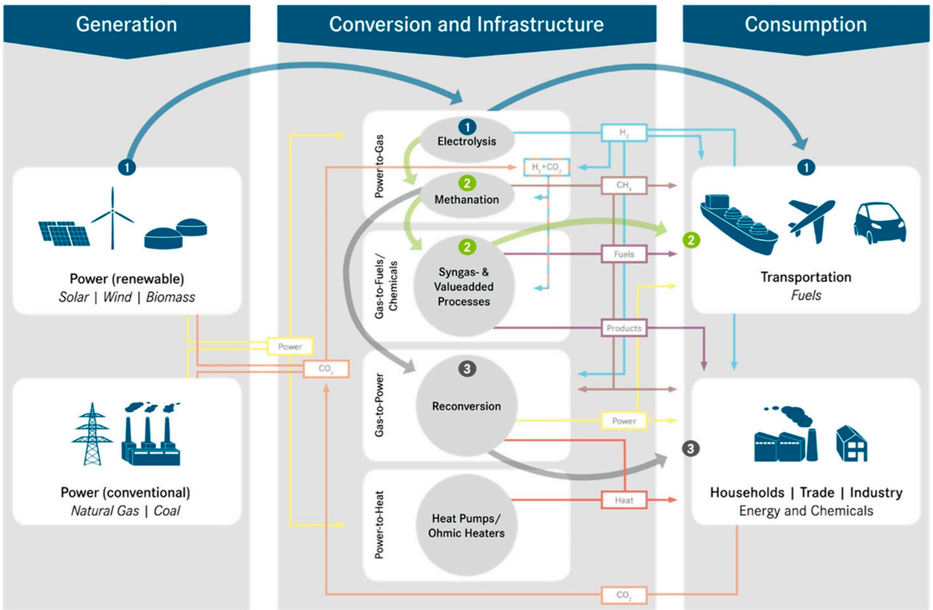

Figure 2. Power-to-X applications.

3. Potential Pathways for Sector Coupling in the Transport Sector

Achieving the promise of reduced GHG emissions across different economic sectors by means of electricity strongly relates to the GHG footprint of the particular quantities of electric energy employed. The historical development of electricity sectors up to today's level was influenced by a great variety of factors, such as feedstock availabilities, technological development, political preferences and market structure. Related to the further evolution of these, in contrast to energy-strategic targets of reducing electricity utilization, total electricity demand is likely to increase. Despite efficiency gains in technologies relating to traditional electricity provision, the use of more applications of electricity arises (rebound effect), such as those described in this paper. An overview of the pathways for cross-sectoral electricity utilization is given in Section 2.

In light of the feed-in fluctuations of wind and solar power, large-scale storage options become indispensable elements of energy provision [8]. While batteries would not be suitable in the long-term for storing large quantities of power in the range of tens of terawatt hours, they could serve as grid-stabilizing components with short response times. Moreover, in the transport sector, batteries could enable the storage of tractive energy for BEVs and hybrid vehicles.

On the other hand, hydrogen may ultimately form the basis of industrial-scale power-to-X routes that efficiently supply the transport, industry and electricity sectors with energy or chemical feedstocks. In order to supply hydrocarbons on the basis of power-to-X, reliable and GHG-neutral CO_2 must be available (also in the long-term).

3.1. Electric Mobility with Battery Electric Vehicles and Fuel Cell Vehicles

BEVs and fuel cell vehicles (FCVs) are seen by many car manufacturers as the most viable options for zero-emission and highly efficient mobility [9]. However, the infrastructural challenges and cost-reduction issues of batteries (for BEVs) and fuel cell systems and H_2 storage (for FCVs) must be resolved.

At present, a variety of BEVs are commercially available. Typical battery capacities are between 14 and 30 kWh, allowing for operational ranges of no more than 250 km [10–25]. Exceptions are the Tesla Models S and X, with operational ranges of 408 and 417 km at battery capacities of 60 and 75 kWh [24,25], respectively. Besides the Tesla Model S and X, the commercially available GM Bolt has a 60 kWh battery. However, manufacturers have announced ranges of more than 500 km (e.g., the Opel Ampera-e [26]) for the next generation of BEVs. Being the most energy-efficient option for motorized transportation, BEVs still lack the operational ranges and fueling times to make them truly comparable to today's capabilities. Furthermore, BEV mass markets are likely to require additional electric network infrastructures, including backup power provisions and distributed storage capacities that may necessitate capital investments that are substantially higher than for the requisite hydrogen infrastructures for FCVs [27].

With respect to FCVs, all major car manufacturers have also developed prototypes and small-series cars. Passenger cars from Toyota and Hyundai, for instance, are already commercially available. Furthermore, Honda began selling its new FCV model in late 2016 [18], while Daimler (Stuttgart, Germany), has announced the release of its Mercedes-Benz GLC F-CELL for the end of 2017 [19]. Typical ranges are, at present, between 400 and 700 km. FCV refueling times are in the range of a few minutes and, thus, are comparable to internal combustion-driven vehicles. On the contrary, the market success of electrified powertrains can hardly be predicted from today's perspective. Contestabile et al. [28] conclude that—with respect to the complexity of stakeholder interests and of car and fuel markets—both BEVs and FCVs are likely to play important roles in the future, alongside plug-in hybrid electric vehicles. Table 1 provides a brief overview of the advantages and challenges facing BEVs and FCVs.

Table 1. Brief overview of the advantages (✓) and challenges (✗) for battery electric vehicles (BEVs) and fuel cell vehicles (FCVs).

BEVs	FCVs
✓ Highest tank-to-wheel efficiency ✓ Zero tailpipe emissions	✓ High tank-to-wheel efficiency (double that of internal combustion engine cars) ✓ Zero tailpipe emissions ✓ Quick refueling possible (<5 min) ✓ Synergy with hydrogen provision to other sectors (industry, re-electrification)
✗ Quick charging (<10 min) of batteries requires new battery and charger concepts ✗ High cost of batteries ✗ High infrastructure cost for the case of large market shares (private and public charging, quick chargers on highways, and grid enhancement) ✗ Unresolved large-scale (seasonal) storage of electricity	✗ Market introduction is more complex ✗ High cost of fuel cell systems ✗ Advanced/low-cost onboard hydrogen storage required

3.2. Power-to-Fuel

On the mobility side, today's passenger car- and truck-based road transport, as well as aviation and maritime shipping, relies heavily on crude oil-derived liquid fuels. A current development target is to identify suitable P2G-based liquid hydrocarbon fuels and related production processes. Available infrastructures and engine technologies could thereby be used in the future. Moreover, such synthetic fuels could be tailored to improve engine efficiency and decrease emission levels. On the downside, also in the long-term, large-scale and low-cost CO_2 sources must be available. In addition, fuel costs will favor hydrogen for direct conversion in fuel cells if full fuel taxes are applied over the long-term [29].

3.3. Power-to-Gas

Related to stationary energy appliances, P2G process chains are currently under consideration. This includes the direct use of hydrogen (P2G-H), for example in the steel production [30] and methane (P2G-M) that is produced from hydrogen and CO_2. Due to the high cost of P2G-M, the major challenge is to achieve cost-competitiveness with natural gas. Examples for economically viable applications in the electricity market are presented by Grueger et al. [31]. Each of these routes leads to the SC of the power and transport sectors and has the possibility of drastically reducing GHG emissions in these sectors.

Whereas this section showed the potential pathways for SC in the transport and power sectors, there remains a need to analyze the current state of the literature in terms of the modeling of SC. Therefore, in Section 4, a review and overview of current literature is presented. Since a worldwide analysis of all models would constitute a scientific paper in itself, the authors present an overview of selected international scientific papers and a more in-depth literature review for the modeling of SC in Germany. The approach adopted here can be applied to future reviews with an international focus.

4. Sector Coupling—Literature Review

The large-scale use of RESs to power parts of or even entire national economies has generated increasing interest in the last decade. There exists a multitude of studies in which the effect of increasing penetrations and potential contributions of RESs has been investigated for economic regions, spanning from isolated islands to whole countries, or even in the global context. The approaches chosen to realize SC are multifaceted and are presented in the following sections. Subsequently, studies that imply SC options for Germany are discussed in more detail to provide a perspective for the modeling of the concept.

4.1. Approaches to Sector Coupling

Studies suggesting SC for economic regions can be placed into certain categories, namely, the investigated region, the coupled sectors, the applied methodology, the type and penetration of renewable technologies in the energy system, and the approaches to handling the intermittent behavior and spatial distribution of the renewables by means of energy transport and storage. The following studies are presented according to the sectors they address, along with a short analysis of how the integration of renewables within these studies is realized.

There are a number of studies in which all, or nearly all, power for the investigated economic region is provided by RESs [32–46]. Therefore, these studies couple all energy-demanding sectors with renewable energy production. Some other studies focus on supplying specific sectors with power from renewables in high penetrations. Case studies in which the power and heat sectors are coupled are listed by Madlener et al. [47], Mason et al. [48], Henning and Palzer [49], Nastasi and Lo Basso [50] and Palzer and Henning [51]. Examples for linking the power and transport sectors in such a way can be found by Robinius [52], Samsatli et al. [53], Garmsiri et al. [54], Rogge et al. [55], Qadrdan et al. [56], Teng et al. [57] and Kim and Moon [58].

In these studies, the intermittent behavior and spatial distribution of RESs is considered, to varying degrees. Studies that analyze renewable potential by comparing the average produced energy to its overall demand do not specifically consider temporal and spatial aspects [38,43,47,58]. Others take the intermittent behavior of renewables into account by including energy storage options, but they do not explicitly consider changes in the energy transport infrastructure. These studies can be subdivided into those that do not consider P2G options for storage [34,44,48,59] and those that do [32,33,35–37,39,42,45,46,49,51,60,61]. In a number of studies, energy transport is considered in addition to energy storage, ranging from an additional markup for transportation costs [40,41,46,49,51] to the detailed modeling of the required energy transport infrastructure [52,53] or, for example, detailed hydrogen supply models [62].

A detailed description of all worldwide SC studies or approaches is not possible within a single paper; rather, the publications highlighted in this subsection should serve as a starting point for further research topics in this field in different countries. Hereinafter, the authors confine their analysis in this paper and in Part 2 [63] to Germany, for numerous reasons. First of all, Germany, after China (258 GW) and the United States (145 GW), has the third-highest installed-RES capacity, at almost 100 GW in 2016, which leads to a pressing need for SC [64]. Furthermore, in the National Climate Action Plan, Germany established concrete CO_2-recuction goals for 2030, which shows the importance of SC (Table 2). In particular, linking the power and transport sectors has a high importance, not only due to the negligible CO_2 reduction from 1990 to 2017 (−1.2%) and still high CO_2-reduction goals for the transport sector by the year 2030 (40% to 42%, compared to 1990), but also due to the importance of the reduction of local transport emissions [65].

Table 2. CO_2-reduction goals for each sector through 2030 [66]. tCO_2eq: tons of carbon dioxide equivalent.

Sectors	1990 (tCO_2eq)	2014 (tCO_2eq)	2014 vs. 1990	Goals: 2030 (tCO_2eq)	Goals: 2030 vs. 1990
Energy industries	466	358	−23.2%	175–183	62–61%
Residential	209	119	−43.1%	70–72	67–66%
Transport	162	160	−1.2%	95–98	42–40%
Industry and commerce	283	181	−36%	140–143	51–49%
Agriculture	88	72	−18.2%	58–61	34–31%
Others	39	12	−69%	5	87%
Sum	1248	902	−27.7%	543–562	56–55%

Figure 3 shows the results of different studies of the electricity demand and installed capacity for Germany. It can be seen that studies that were conducted before 2012 in particular (apart from Prognos) estimated a future electricity demand of around 600 TWh. From 2014 on, the studies estimated a much higher installed capacity of RESs, as well as a higher electricity demand, which amounted, in the highest case, to roughly 1300 TWh. This shows that SC, which leads to a higher electricity demand, has a growing importance in the literature surveyed, and therefore it will be analyzed in greater detail.

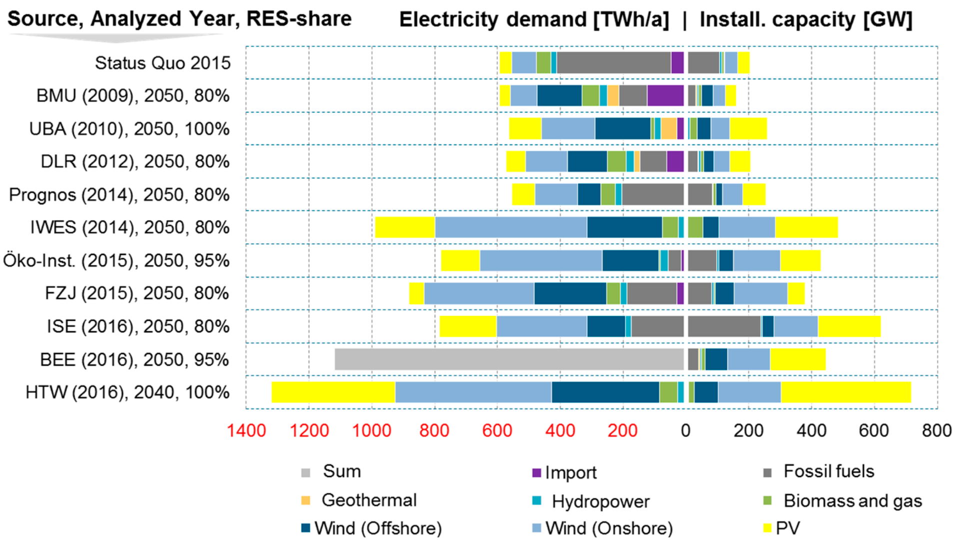

Figure 3. Electricity demand and installed capacities in different energy models for Germany by the years 2040 and 2050 [67].

4.2. Studies on Germany

The expansion of renewable energy technologies and their potential to contribute to electricity generation in Germany has been addressed in numerous German studies, and was summarized and classified in the Fraunhofer IWES and Fraunhofer UMSICHT reports [68], or the report from the Agentur für Erneuerbare Energien e.V. [69]. For 2050, Table 3 shows the results of this classification, with the additional inclusion of a study by Robinius [52,70,71]. Classification in the table is based on the required grid expansion, which was assumed in each study, as well as the strategic development of the power supply system.

Table 3. Classification of targeted German studies on future power supply systems, based on their considered grid expansion (minor to strong) and the strategic development of the power supply system (from Germany to Europe). The table is based on studies reported in the Fraunhofer IWES and Fraunhofer UMSICHT [68].

Strong ← Grid Expansion	→ Minor	
ETG-Task-Force (2012) [72] Fraunhofer ISE (2012) [73] Fraunhofer UMSICHT & Fraunhofer IOSB/AST (2013) [74] SRU (2011) [75] Umweltbundesamt (2010) [76]	Robinius (2016) [52,70,71]	Germany
Agora (2014) [77] DLR et al. (2012) [78] EWI & energynautics (2011) [79] Frontier Economics & swissQuant Group (2013) [80] Jentsch et al. (2014) [81] Prognos AG et al. (2010) [82] ZSW (2014) [83]	EWI & energynautics (2011) [79]	↑ Strategic development of the power supply system ↓
Bussar et al. (2014) [84] Czisch (2005) [85] DENA & IAEW (2012) [86] Droste-Franke (2012) [87] EWI & energynautics (2011) [79] Fraunhofer ISI (2011) [88] Fraunhofer IWES et al. (2014) [89] Pleßmann et al. (2014) [90] Schabram et al. (2013) [91] SRU (2011) [75]	-	Europe

However, the utilization of the excess electricity produced in P2G concepts and accompanying SC options was investigated in some of these studies. On this point, Figure 4 provides further insights, presenting the scenario results for a number of studies listed in Table 3, as well as results from Fraunhofer IWES [92]. These results include electricity generation by renewables and their corresponding excess electricity generation, as well as the amount of excess electricity used for P2G in TWh for Germany in the year 2050. Thereby, electricity generation by renewables is broken down into the contributions from PV and wind turbine installations. Where information was available, the contribution from wind turbines was split into onshore and offshore components.

The studies presented in Figure 4 are subdivided into two categories: In the first, all scenarios in which the electricity generation from renewables is less than 520 TWh are summarized. In the second, this value is above 600 TWh. The subdivision underscores the nature of the scenario. While in the first category, electricity generation only focuses on the power sector, the second also includes additional sectors. Therefore, the scenarios in the second category approach the requirement for an integrated energy system by actually stipulating an energy system transformation, not only the transformation of the German or European power system. Thus, only the scenarios from the second category are of relevance when reviewing existing SC concepts for Germany.

The Fraunhofer ISE study [73], which is represented in Figure 4 in the second category with three different scenarios, points out the possibility of realizing all of Germany's power and heat demand via renewable energies. In the study, electricity storage is taken into account by including pumped hydro storage and batteries, while thermal energy storage is considered through the inclusion of water as a storage medium. The scenarios refer to different degrees of refurbishment for buildings (heat demands of 64.9%, 50% and 40% in reference to the 2010 values for REMax, Medium and SanMax, respectively). A P2G path is integrated as follows: first, hydrogen that was produced by electrolysis during periods of excess electricity generation is transformed into methane; this methane is then stored in already existing caverns for natural gas; finally, during times of positive residual load, the methane is used to produce electricity and heat. Not modeled are the transport sector and fuel-based industry processes. However, the study states that if transport was included (by assuming 50% BEVs and 50% FCVs), an additional yearly electricity demand of 290 TWh would be required.

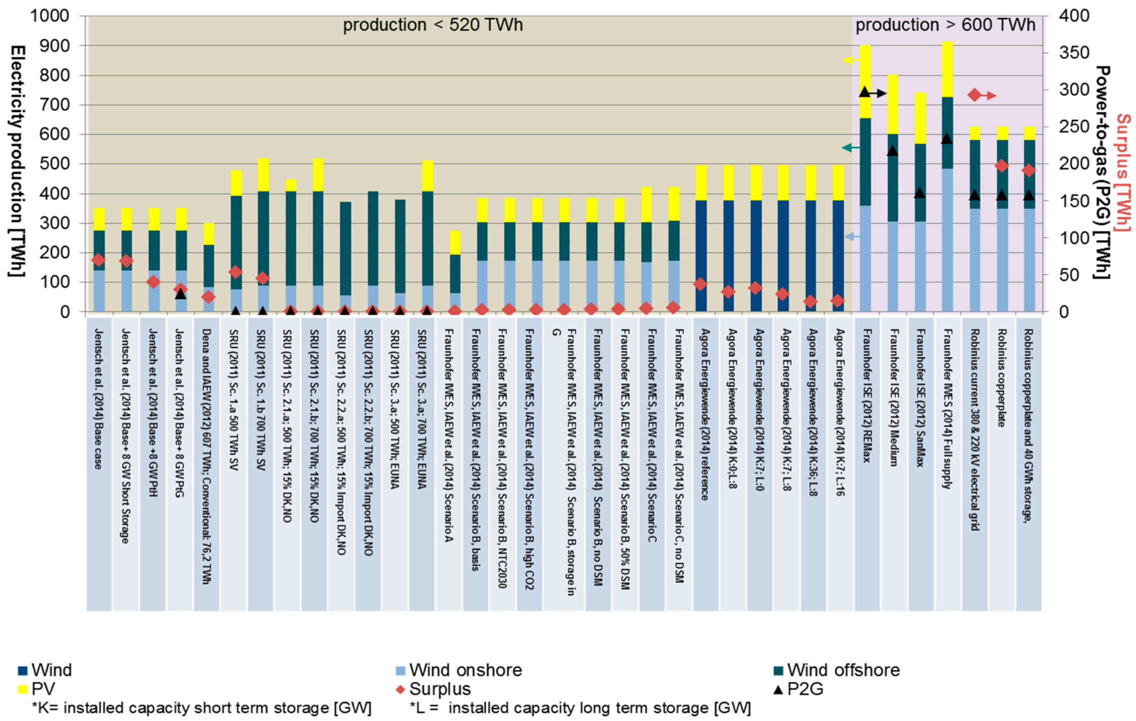

Figure 4. Electricity generation by renewables; corresponding excess electricity generation and the amount of excess electricity used for power-to-gas (P2G) in TWh for Germany in the year 2050, according to the associated study and scenario.

In studies by Robinius [52,70], whose findings are portrayed in Figure 4 in the second category, again with three different scenarios, a power system design with a high penetration of renewables is presented, which is also able to satisfy 75% of the domestic transport sector with hydrogen. The scenarios refer to the modeling of the electrical grid (grid: first scenario; or copper plate: second and third scenarios) and the inclusion of large-scale storage (third scenario). A corresponding P2G path is integrated as follows: first, hydrogen is produced by electrolysis in times of excess electricity generation; the hydrogen is then stored in salt caverns; finally, hydrogen transmission to designated fueling stations is realized via pipelines, where it is then distributed.

The Frauenhofer IWES study [92], on which the second category in Figure 4 is based, with only one scenario, is not included in Table 3 due to its differing methodological approach. In the study, the primary energy demand for Germany in 2050 is first identified. Subsequently, an optimized power plant fleet consisting of only RESs is determined. Thereby, it is assumed that BEVs make up 100% of the domestic transport sector, and that trucks are powered by overhead power lines. P2G is employed to satisfy a residual demand for chemical energy carriers, as well as the remaining positive residual electricity load.

In summary, it can be noted that there already exist a number of studies for Germany that adopt an integrated modeling approach for a future energy system via SC. In these studies, a high penetration of renewables is assumed, consisting mainly of PV installations, as well as on- and off-shore wind turbines. Thereby, the corresponding coupled sectors, as well as the underlying modeling assumptions, vary from study to study.

To obtain an overview of the GHG reduction potential of SC in the power and transport sectors, the current status is described. To see the different potentials regarding different boundary levels, the GHG emissions by sector, electricity production by fuels, and fuel consumption in the transport sector on a worldwide-, European Union (EU)- and Germany-scale are analyzed.

5. Status of the Power and Transport Sectors

The development of power systems around the world has traditionally relied on fossil fuels as a primary source of power. Large thermal stations, usually fueled by coal and occasionally nuclear fuels, are used to cover the base load, while more flexible alternatives based on oil products, natural gas or hydroelectric generation cover the load variations. Although this approach has been cost-efficient and all involved technologies have reached a mature level, the high CO_2 emissions entailed, currently amounting to 42% of total GHGs [93], has driven governments around the world to develop policies that promote more generation from RESs.

5.1. Worldwide

Overall, the energy sector was responsible for 65% of total GHG emissions in 2013 [93], of which 90% consisted of CO_2 [93]. In particular, the electricity and heat sectors were responsible for about 42%, and the transport sector some 23%, of global CO_2 emissions [93]. Therefore, the majority of efforts to limit GHG emissions have focused on the electricity generation sector. Various parameters, including improvements in the energy efficiency of end consumers, have led primary energy consumption to decline in some countries (e.g., Germany and the United States); however, the global trend is increasing. Nevertheless, due to the massive increase in RES-installed capacities, growth in the electricity demand has been decoupled from power sector-related CO_2 emissions [1], which constitute a key factor in the further decarbonization of the power sector.

In 2013, the global electricity production totaled about 79,656 PJ. With regard to the contributing fuels, hard coal and lignite accounted for the biggest share, at 39%, followed by natural gas, at 22%. The contribution of RESs, such as hydro power, wind energy and PVs, amounted to 20%, and 22% if biomass was included [94]. Taking into consideration the expansion of RESs, 2015 was remarkable not only because of the COP21 agreement, but also because a new record of RES growth in installed capacities was hit, despite many countervailing factors. Overall, global non-hydro capacities totaled 785 GW, which amounted to 7.6% of the total electricity production in 2015. If hydro power was included, this number grew to 23.7% [95]. These numbers are expected to grow rapidly, especially as the technology for integrating RESs into the system further develops. Currently, the world adds more renewable power capacity than net capacity from all the fossil fuels combined, i.e., 134 GW in RESs excluding large hydro, 22 GW in large hydro, 15 GW in coal-fired plants, and 40 GW in gas-fired plants. Overall, USD $286 billion were invested in RESs, in contrast to $130 billion for fossil fuel generation technologies [96].

Despite the advances in the power sector, other sectors did not follow with a similar pace, and many advances are needed in order to achieve the environmental targets. In 2015, modern RESs contributed 8% to the total heating and cooling demands (primarily biomass), while only 4% did so in the transportation sector, in which liquid biofuels constitute the vast majority [95]. Moreover, future reference case projections [97] show that transportation will remain heavily dependent on liquid fossil fuels, despite the foreseen rapid growth in the share of natural gas, which will merely compensate for the growth in demand in non-OECD (Organisation for Economic Co-operation and Development) countries. However, the number of transport users is still growing in developing countries, although the correlation between gross domestic product (GDP) growth and transport has shown signs of decoupling in the OECD countries [98].

In 2013, petroleum derivatives such as gasoline, diesel and kerosene accounted for over 92% of the total fuel consumption in the global transport sector. Around 65% of the sector's energy consumption is made up by passenger transport; the rest comes from freight transport. With regard to the vehicle type, the vast majority of energy consumption in the transport sector is attributed to cars and light trucks [97]. Therefore, light-duty vehicles will play the most significant role if a transition towards low CO_2 emissions in the transportation sector is to be achieved.

The transportation sector is key to the mitigation of GHG emissions; thus, the Intergovernmental Panel on Climate Change (IPCC) suggests a set of developments that would help reduce the sector's CO_2 footprint [99]. The major paths are avoidance, modal choice, energy intensity and fuel carbon intensity. Figure 5 shows the global GHG emissions by sector in 2013. With avoidance, a reduction in transport activity is sought by cutting or shortening journeys, for example, through internet shopping and the mixed-zoning of cities. Modal choice refers to traveler behavior, where a shift from private to public transportation and cycling is encouraged by corresponding measures in urban planning and the required infrastructure. Enhancing the performance efficiency of vehicles constitutes a means of reducing the fuel consumption and therefore, primary energy requirements and CO_2 emissions. Furthermore, reducing the carbon intensity of the energy carriers used will positively contribute to the independence between energy consumption and GHG emissions. Sustainable technologies such as biofuels, electricity and hydrogen are some of the options RESs can produce; however, they require additional investments in infrastructure.

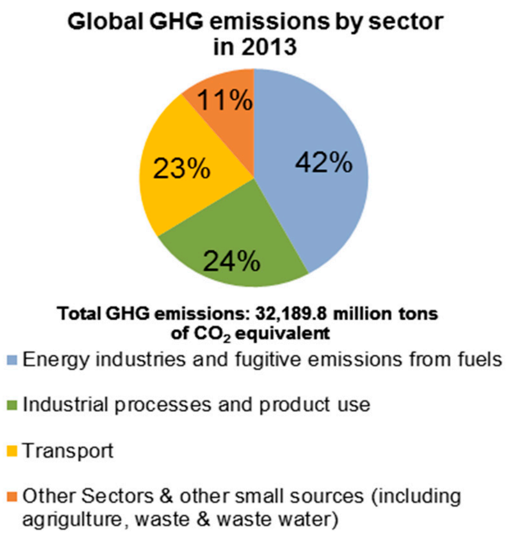

Figure 5. Global GHG emissions by sector in 2013 [93].

Figure 6 shows the global fuel consumption in the transport sector in 2013. The dominance of fossil fuels, such as gasoline, diesel and kerosene, is apparent, with their huge share of 92%, whereas electricity, for example, contributed only about 1% to transport energy consumption.

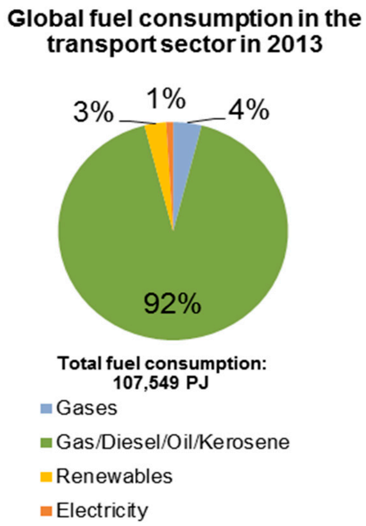

Figure 6. Global fuel consumption in the transport sector in 2013 [100].

5.2. European Union

The EU, a coalition with origins based on common energy strategies, did not have any significant common policy regarding electricity generation from RESs or GHG emissions until the early 2000s and the adoption of the Kyoto Protocol in 1997. The most significant step it took towards a common and greener energy policy was made in 2005 in London, where the development of corresponding legislation was approved by the European Council. This decision was realized two years later with the Action Plan and Treaty of Lisbon, in which the famous 20/20/20 targets for 2020 were set out [101]. These targets constituted the minimum goals to be achieved by 2020 across the entire union, and comprised a 20% share of renewables in energy consumption, a 20% reduction of total energy consumption in comparison to the projections for that year, a 20% reduction in GHG emissions in comparison to 1990 levels, and a 10% share of renewables in the transport sector. Moreover, the main pillars driving the European energy vision were determined in this plan to be sustainability, security of supply, and competitiveness [102].

Besides the 2020 targets, the EU has recently adopted new commitments for climate and energy for the year 2030 [103], as well as setting long-term targets for 2050. The 2030 goals follow from those for the year 2020, and set domestic GHG emissions to a minimum reduction of 40%, the share of the gross final renewable energy consumption to a minimum of 27%, and an indicative minimum improvement in energy efficiency of 27% [104]. These legislative frameworks move in the direction set by the EU energy roadmap for 2050 [105], where the long-term vision for environmental policy is defined at a minimum 60% emissions reduction, in comparison to the 1990 level, by 2040 and 80% by 2050. The key findings of the various scenarios that were tested in this roadmap show that there is no energy technology that will dominate the future system that will require, in all cases, a minimum 55% share of renewables in electricity generation, almost double the share of electricity in total consumption and the broad use of electricity storage and carbon capture technologies [102].

Despite the legal validity of the agreements, the major diversity of the EU necessitates different approaches to implementing the environmental strategies; therefore, every nation is accountable for developing its individual pathways and regulations (National Renewable Energy Action Plans). Overall, the electricity strategies are the most diverse, whereas the transport sectors, for example, are mainly supported by quota obligations, investment grants and fiscal measures (e.g., tax incentives) [106]. In conjunction with the actions of individual members, however, enhancing interconnections amongst the EU's regions and different sectors, thus creating a single European energy market, constitutes one of the top priorities towards achieving the 2050 goals.

The targets may be criticized for their environmental effectiveness; nevertheless, the EU is constantly progressing in order to meet the aims on time. In 2013, the overall share of renewables and hydro power in the energy consumption mix for electricity production in the EU was 24%, including biomass. Figure 7 shows the electricity generation mix for the EU in 2013, with a total electricity production of about 11,774 PJ that year.

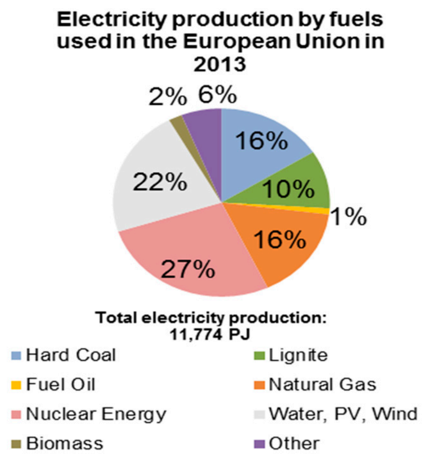

Figure 7. Electricity production in the European Union (EU) in 2013 by fuels used [107].

When it comes to total GHG emissions in the EU, the respective national energy industries and fugitive emissions from fuels were responsible for around 29% of emissions, whereas the transport sector contributed 19% to the total, equivalent to some 4600 million tons of CO_2. Within the transport sector, about 82% of energy is used by road vehicles, accounting for three-quarters of GHG emissions [108,109].

The most significant step towards promoting emission reductions was the white paper on transport published by the European Commission [105], in which emission targets were set for all modes thereof, including aviation, shipping and road, to a 20% reduction by 2030 on 2008 levels and a 60% reduction against 1990 levels. Moreover, the white paper promoted a shift from road (both passenger and freight) mobility to rail, as well as CO_2-free city mobility, by 2030. Following on from these directives, corresponding legislation to reduce the emission levels was put in place by the EU [105].

Despite the significant improvements in motor efficiencies, however, the emission targets for 2050 will be difficult to achieve unless emission-free fuels are introduced as soon as possible. As Figure 8 shows, in 2013, 91% of mobility fuels were oil-dependent, with the major types being diesel, gasoline and jet fuel. Electricity, a form of energy on which high hopes are pinned for the future, only constituted about 1% of the converted energy in the EU transport sector. The rest was contributed by natural gas—which, on the one hand, shows a better hydrogen/carbon ratio than oil derivatives, but still belongs to the fossil fuel category—and renewables, especially biofuels made from energy crops [110].

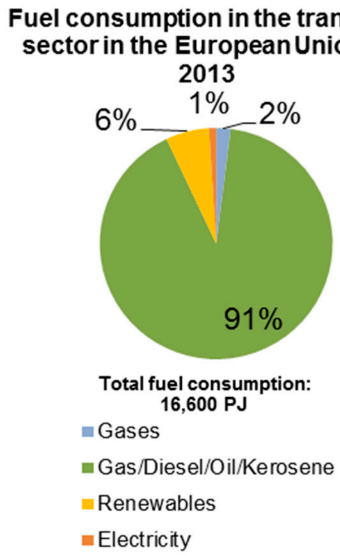

Figure 8. Fuel consumption in the transport sector of the EU in 2013 [110].

5.3. Germany

Germany set voluntary goals within the scope of the Energiewende. This roughly translates as "energy transition" and describes the systemic embrace of renewable energy technologies and energy efficiency, which the German Federal Government has actively promoted. After the catastrophe of Fukushima, the term Energiewende also came to encompass the substitution of nuclear energy, which could be formally adduced to the attainment of the 2 °C target. All in all, the Energiewende takes into consideration the following four main objectives: the phasing out of nuclear energy by 2022, the continual expansion of RESs, an increase in energy efficiency, and climate protection through the reduction of GHG emissions. As shown in Figure 9, the GHG emission goals are quantified up to 2050.

Whereas the sectors of industry and households could respectively affect a GHG reduction of 34% and 21% from 1990 to 2013, the sectors of power generation and mobility could only contribute 15% and 3%, respectively, in practice (compare Figure 10).

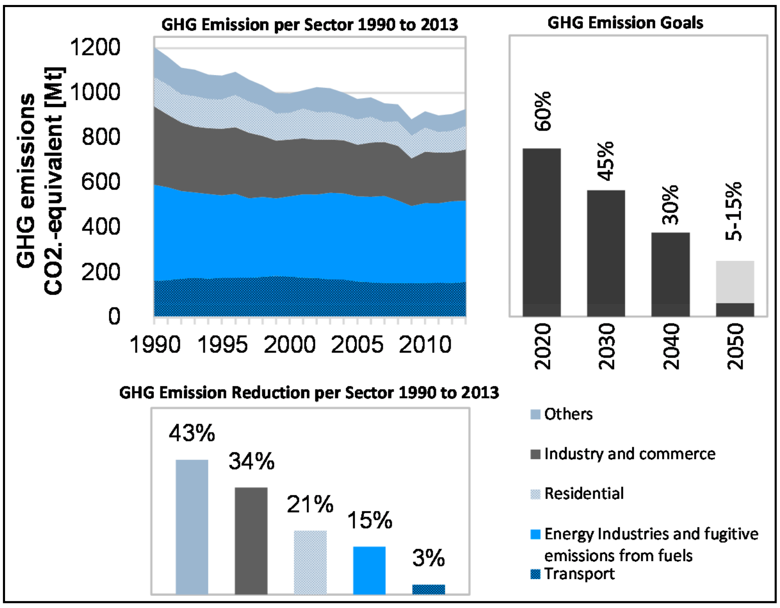

Figure 9. GHG emissions and reductions per sector (1990–2013) and the goals in Germany [111].

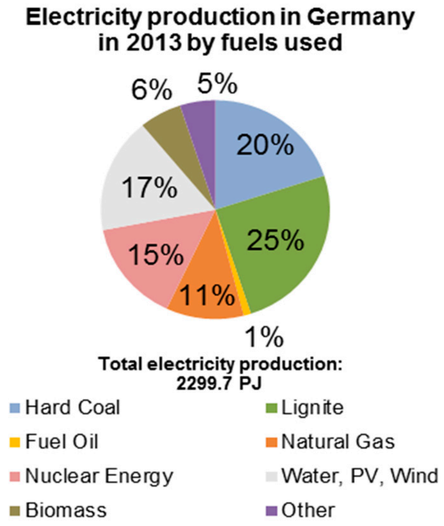

Figure 10. Electricity production in Germany by fuel in 2013 [107].

In 2013, electricity production in Germany amounted to about 2300 PJ [107]. The allocation of energy sources used to produce electricity is shown in Figure 10. Amounting to 45% in total, almost half of the electricity was produced using coal products. Despite the fact that Germany has announced the phasing out of nuclear energy, 15% of its electricity was produced by nuclear power plants. Together with biomass and hydro power, renewable energies make up a share of 23%. The remaining electricity is produced with natural gas, oil derivatives and other sources.

The large share of coal-fired plants contributes to 40% of the GHG emissions in Germany, emanating from the energy industry and fugitive emissions from fuels (Figure 11) [112]. Roughly 17% of the 2013 GHG emissions originated in the transport sector. Approximately the same amount was contributed by industrial processes and product use.

With regard to the transport sector, fuel consumption is, at 94%, dominated by oil derivatives. The remaining 6% of power used in the transport sector comes from renewable sources such as biomass, electricity and renewable gases [113].

Analysis of the worldwide, EU and German cases reveals the potential of SC, especially in the power and transport sectors.

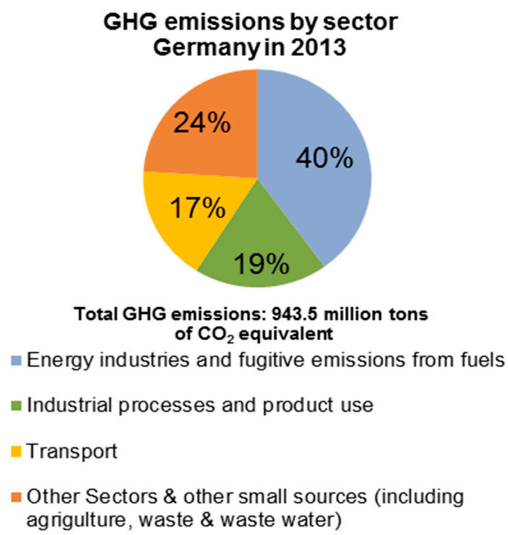

Figure 11. GHG emissions in Germany by sector in 2013 [112].

6. Summary and Conclusions

To illuminate the concept of SC, a delineation of sectors and a definition of SC was outlined, in recognition of the fact that the term is often inaccurately used in the literature. Furthermore, a scheme of potential pathways that consist of power-to-X approaches for SC was shown and described (see Section 2).

To address the potential pathways of SC in the power and transport sectors, a detailed analysis of the electric mobility pathways with BEVs and FCVs, power-to-fuel and P2G was conducted (see Section 3). All potential pathways have their advantages and challenges, and therefore, each has its own particular potential in each context. Therefore, all pathways must be considered in terms of modeling a future energy system, so as to identify the optimal solution for each country.

The literature already contains a lot of studies that consider SC, but oftentimes, at least on the international level, the term SC is not used. Since a detailed analysis of worldwide SC approaches is beyond the scope of this paper, only the most important were noted and roughly described, in order to give researchers a starting point if they would like to analyze these studies in greater detail. Nevertheless, Germany was selected to be analyzed in greater detail for several reasons, one of which was the high share of RESs in the country and the increasing studies that analyze SC in detail. These differ in terms of the intermittent behavior and spatial distribution of renewables, which is important for seeing the location of potential technologies in a country for SC, or to determine the available surplus for SC. Summarizing the modeling of the intermittent behavior of the RESs or spatial resolution differs from case to case. In particular, models that try to conduct studies at the European level are often inaccurate, due to computational limitations (see Section 4).

Whereas this paper shows and analyzes the international and national studies on SC, especially for Germany, Part 2 [63] will show the results of a SC model that connects the power and transport sectors in great detail in Germany.

The analysis of the worldwide, EU and German cases shows that there is still a long way to go towards achieving the COP21 goals. This work introduces the concept of coupling the power and transport sectors in order to reduce GHG emissions. At all scales, conventional electricity production (hard coal, lignite, fuel oil, natural gas and nuclear energy) accounts for roughly three-quarters (worldwide: 77%; EU: 70%; and Germany: 72%) of the total. Moreover, the share of fuel consumption by gas/diesel/oil and kerosene amounts to roughly 90% at all scales (worldwide: 92%; EU: 91%; Germany: 94%). While conventional electricity production and fuel consumption of gas/diesel/oil and kerosene account for roughly the same ratios of total electricity production and fuel consumption, respectively, the emissions of the energy industries and fugitive emissions from fuels and the transport sector differ to a greater degree, due to, for example, the different share of nuclear energy or the efficiency of the processes. At the worldwide scale, the total contribution of the energy industries and fugitive emissions from fuels and the transport sector is 65%, while at the EU level, it is 48%, and on the German level, it is 57%—detailed: worldwide: 42% (energy industries and fugitive emissions from fuels) and 23% (transport); EU: 29% (energy industries and fugitive emissions from fuels) and 19% (transport); and Germany: 40% (energy industries and fugitive emissions from fuels) and 17% (transport)—(see Section 5). Therefore, the potential of SC for the power and transport sectors is not adequate for achieving the COP21 goals.

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