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Perspective

Sector Coupling and Migration towards Carbon-Neutral Power Systems

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Abstract: There is increasing interest in migrating to a carbon-neutral power system that relies on renewable energy due to concerns about greenhouse gas emissions, energy shortages, and global warming. However, the increasing share of renewable energy has added volatility and uncertainty to power system operations. Introducing new devices and using flexible resources may help solve the problem, but expanding the domain of the problem can be another solution. Sector coupling, which integrates production, consumption, conversion, and storage by connecting various energy domains, could potentially meet the needs of each energy sector. It can also reduce the generation of surplus energy and unnecessary carbon emissions. As a result, sector coupling, an integrated energy system, increases the acceptance of renewable energy in the traditional power system and makes it carbon neutral. However, difficulties in large-scale integration, low conversion efficiency and economic feasibility remain obstacles. This perspective paper discusses the background, definition, and components of sector coupling, as well as its functions and examples in rendering power systems carbon-neutral. The current limitations and outlook of sector coupling are also examined.

Keywords: sector coupling; renewable energy; electricity; hydrogen; heat; gas

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Citation: Son, M.; Kim, M.; Kim, H. Sector Coupling and Migration towards Carbon-Neutral Power Systems. *Energies* **2023**, *16*, 1897. https://doi.org/10.3390/en16041897

Academic Editor: Dimitrios Katsaprakakis

Received: 11 January 2023
Revised: 7 February 2023
Accepted: 7 February 2023
Published: 14 February 2023

1. Introduction

Climate change is not an anomaly unique to certain countries, but a common problem shared by all countries. In the past 60 years, land and oceans have absorbed approximately 56% of carbon dioxide emissions from human activities, leading to a rise in surface temperatures of 0.84–1.10 °C above pre-industrial levels [1]. To limit the global temperature increase to less than 1.5 °C by 2100, net carbon dioxide emissions must be reduced by 45% by 2030 [2]. However, achieving these goals poses a challenge for many countries. The International Energy Agency (IEA) states that the global temperature increase can be kept within 1.8 °C above pre-industrial levels if countries fully implement their Nationally Determined Contributions (NDCs) submitted at the Conference of the Parties 26 (COP26). To effectively reduce greenhouse gas emissions, it is important for countries to create stable, long-term plans and to upgrade their NDCs annually. By implementing these methods, we can move toward a carbon-neutral future and reduce the impact of climate change.

Climate change exacerbates the damage to poor countries. Figure 1 represents carbon dioxide emissions of the group of 20 (G20) members and non-G20 members. In recent years, G20 members have emitted four-times more carbon than non-G20 members. However, each country in the G20 holds a different opinion about responsibility. China, the world's largest carbon emitter, claims the developed countries' *past* emissions as their responsibility and declined to contribute to the 'loss and damage fund' at COP27, declaring their status as a developing country. On the other hand, developed countries insist that developing countries should also take responsibility, focusing on the *current* emissions. Meanwhile, low-income developing countries struggle to adapt to climate change due to geographical and institutional constraints [3]. These conflicts also pose the economic threat to the low-income developing countries, breaking promises of USD 100 billion in aid [4]. Figure 2 shows the impact on economic growth of a 2 °C rise in global temperature. GDP per capita growth (annual %) is depicted through values and illustrated graphically. This indicates that most low-income countries will experience severe economic difficulties despite contributing low carbon emissions.

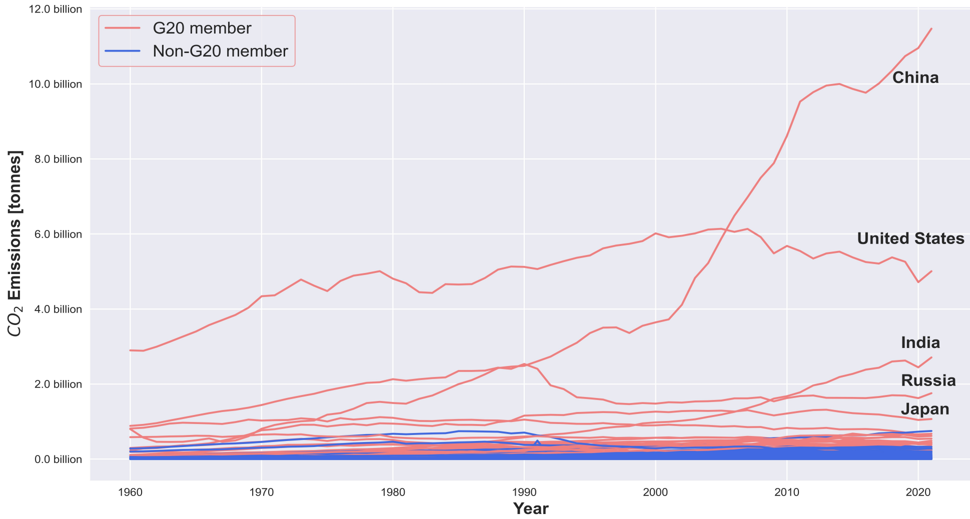

Figure 1. CO_2 emissions of G20 members and Non-G20 members [5].

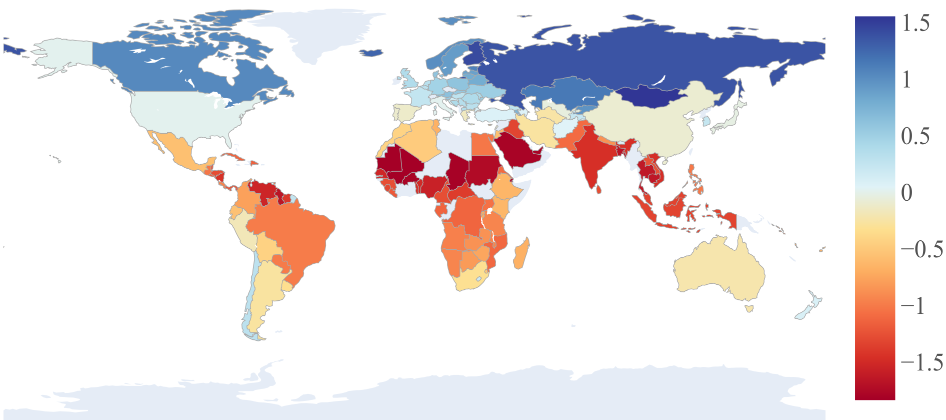

Figure 2. Impact on economic growth due to a 2 °C rise in global temperature [6,7].

Today, we supply and use energy in various fields such as lighting, vehicles, factories, and heating. However, energy is not always readily available. Energy shortages are a major concern that affects people and countries globally. These shortages occur due to difficulties in using energy resources or lack of energy infrastructure. The number of people living without electricity in sub-Saharan Africa increased by 4% in 2021 compared to 2019 [8]. Furthermore, the total installed generation capacity of sub-Saharan countries is smaller than that of Spain, with transmission and distribution losses exceeding 30% in some countries [9,10]. Investing in energy infrastructure to overcome technological limitations is important but difficult for countries with low gross domestic product (GDP). To address these challenges and improve access to energy, innovative research to reduce energy shortage is needed.

Energy resources play a significant role in international negotiations and in the global market. Furthermore, energy resources are valuable because they are limited in quantity and only produced in certain countries. Most countries depend on imports for resources such as oil. Therefore, strengthening *energy security* has become even more important for many countries. Energy security is defined by the IEA as the uninterrupted use of energy at a reasonable price [11]. When energy security is threatened, societies and economies can become unstable. As an example, the war in Ukraine has shocked energy markets around the world and now threatens energy security, which leads to energy price volatility and instability in the economy. Hence, many countries have taken action to revise their energy policy in response to the threat. One way to increase energy security is to diversify the national energy mix, and another way is to reduce energy imports and invest in sustainable energy sources. This can help with energy security and carbon neutrality.

2. Electric Power Industry and Carbon Neutrality

Multinational global companies such as Apple, Google, and Nike have joined RE100 to break away from traditional production methods that emit large amounts of greenhouse gases. This is also enforced on their suppliers to make the industry more clean. However, carbon dioxide emissions are increasing in the industrial sector every year, in particular, the electric industry accounts for a large portion of emissions [12]. Electric power systems have been using coal-fired power generation for a long time and are still the norm in most countries. However, since coal emits the most greenhouse gases among fossil fuels, it is not certain that thermal power plants will continue to meet most of the electricity demands in the future. Decommissioning dates have been assigned to 750 thermal power plants, and capacity reductions in each country have continued over the past four years. As a result, power system operators are forced to seek alternatives. Additionally, the commitment of G20 countries to end public funding for new thermal power plants in 2021 underscores the importance of considering changes to power systems. Therefore, power system operators must start preparing for these changes [13].

Renewable energy has been extensively studied as a mean to replace thermal power generators since it has several advantages. First, it does not emit greenhouse gases during power generation. Second, the sustainability of renewable energy is also attracting attention. Unlike thermal power generators, it does not require the supply of fossil fuels but uses things that can be obtained from nature, such as wind, solar heat, sunlight and geothermal heat, so there is no risk of depletion. Third, renewable energy improves energy security. For example, countries such as Germany and Italy are at risk for energy security issues due to their dependence on Russian gas, but the growth of renewable energy is expected to reach 180 TWh by 2023, which is about the same as the amount of power generated from Russian gas. Therefore, increasing the use of renewable energy is expected to improve energy security by reducing the need for foreign energy sources [14].

3. Problems with Renewable Energy

Renewable energy has been introduced in large quantities for the migration to a carbon-neutral power system. However, complete migration presents a challenge because it gives rise to other issues. In particular, renewable energy is highly dependent on weather conditions, resulting in various problems in the power system. There is a duck curve as an anomaly caused by the rapid increase in renewable energy. The duck curve refers to a load curve that appears when the net load sharply decreases during the daytime due to the rapid increase in solar power generation [15]. The volatility of renewable energy makes it challenging to predict the net load, which can affect system operation and planning, and may even require shutting down the base load power plant [16]. Moreover, integrating renewable energy into the existing power grid and ensuring that it can be dispatched effectively can pose technical challenges. There may be other obstacles related to public acceptance of the required infrastructure, such as transmission towers and power lines. It is important to carefully address these issues in the development and integration of renewable energy into the power system.

4. Sector Coupling

Various attempts have been made to address the aforementioned renewable energy problems. However, most of them focus only on improving efficiency, prediction accuracy, and control performance within the power system. Very recently, a new approach was proposed to expand the domain of the problem and solve it together with other energy sectors. Energy sources commonly considered for interaction with the power system include heat, hydrogen and gas [17]. This integration of listed energy sources leads to a new concept known as sector coupling. Sector coupling is defined in various ways for each paper. For example, IRENA defines 'sector coupling' as the process of integrating various energy sources to match demand and supply through the process of co-production, co-consumption and transformation [18]. Similarly, ref. [19] defined sector coupling as solving an integrated optimization problem for power, mobility and heat sectors. The sector coupling is also called Power-to-X and the authors of [20] included gas, liquid, and chemicals in the definition. Meanwhile, this paper defines sector coupling as interactions between sectors with their own independent energy sources. Therefore, in this paper, electricity, hydrogen, heat, and gas are defined as sectors and examined. Figure 3 represents a framework of the sector coupling, and various transformations are shown centering on renewable energy. The yellow, blue, red, and green lines represent the flow of electricity, hydrogen, heat, and gas, respectively. The circled numbers will be used in explanations in later sections. This paper focuses on examining the interaction between two sectors given that multiple conversions can lead to significant energy loss and incur high complexity.

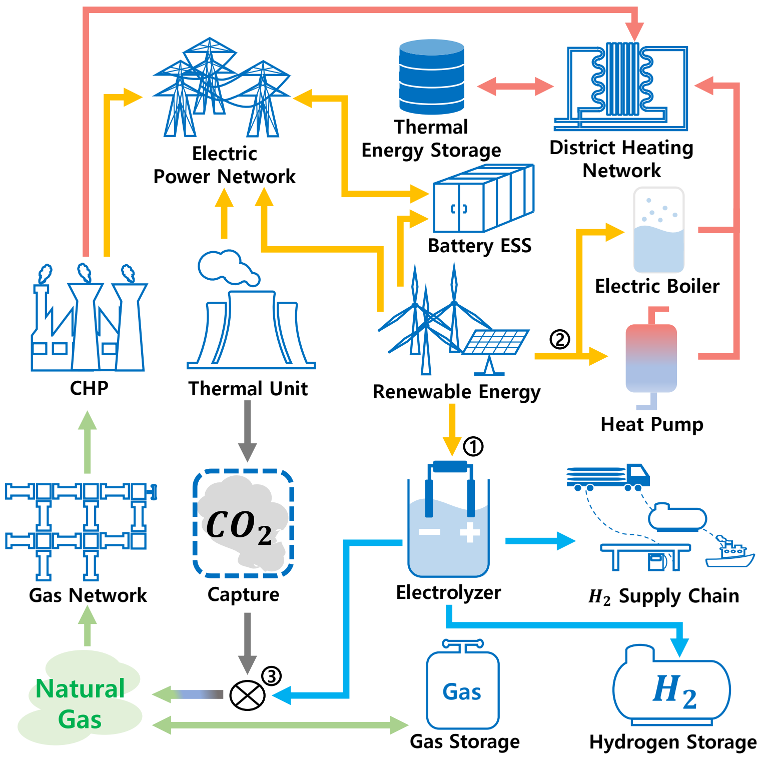

Figure 3. Flow Diagram of Sector Coupling.

5. Components of the Sector Coupling

5.1. Power-to-Hydrogen

Hydrogen is a universal energy source that can be produced by all countries and is attracting attention as an energy carrier that is easy to compress and store. The ability to store larger amounts of electricity for longer periods of time can form a supply-chain of production, storage, transportation and consumption [21]. Through this, it can be linked to various industries and can be used as a fuel for vehicles, trains, and ships, so the potential value of the hydrogen sector is high. Many countries that have recognized its value have presented visions and roadmaps for the 'hydrogen economy', and the hydrogen sector is forming an independent ecosystem.

However, one of the most important things is to use clean hydrogen. In other words, one has to think about how to make it before how to use it. Hydrogen can be classified into three types according to the production method, namely grey, blue, and green hydrogen [22]. Most of the hydrogen currently produced is grey hydrogen obtained by reacting natural gas with high-temperature steam and can be obtained as a by-product of the reforming process or refinery. However, the biggest drawback of grey hydrogen is that a very large amount of carbon dioxide is generated in the process of making hydrogen. The technology for capturing and utilizing or storing emitted carbon dioxide is called carbon capture, utilization and storage (CCUS), and hydrogen obtained through this process is called blue hydrogen. However, most of the produced hydrogen is still grey because CCUS technology has not yet reached maturity [23]. On the other hand, green hydrogen produced without pollution uses surplus power from renewable energy to produce hydrogen and oxygen through water electrolysis. It is similar to sector coupling in that it converts surplus power from renewable energy into other energy sources and processes it. In particular, this process is called Power-to-Hydrogen. The circled number 1 in Figure 3 represents Power-to-Hydrogen. Figure 4 illustrates the process described above, with the grey and the blue going through a similar process, while the green follows a distinct process.

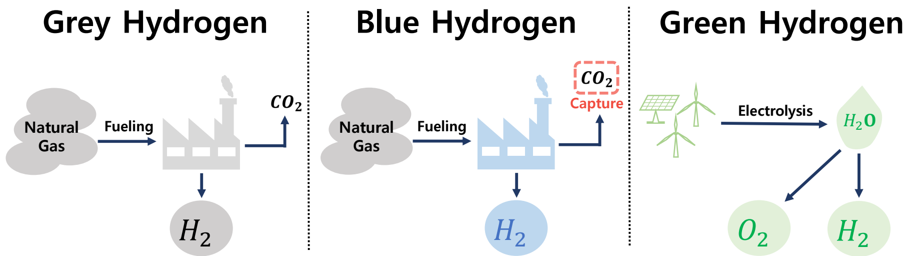

Figure 4. Classification by Hydrogen Production Method.

5.2. Power-to-Heat

About half of global final energy consumption is in the form of thermal energy, and the other half comes from electricity and transport sectors. The heat sector also has its own networks and production facilities and supplies energy to a wide range of households, buildings and industries. The heat and electricity sectors bear many interfaces, and among them, combined heat and power (CHP) utilizes the heat discarded in the process of generating electricity. In this way, CHP achieves 65–75% efficiency and is involved in both the power system and district heating [24]. Unlike CHP, Power-to-Heat is a process of converting surplus power into thermal energy in terms of sector coupling (of course, the reverse process is also possible). The converted heat can be stored or consumed in the heat sector, which can also help reduce carbon emissions in district heating systems. Combining these two sectors is therefore urgent given the extremely high consumption of electrical and thermal energy.

Electric boilers and heat pumps can be used to convert electricity into clean heat. An electric boiler operates on the same principle as a gas boiler, but uses electricity instead of gas. A heat pump absorbs heat from a cold space and releases it into a warm space. Thermal energy has the property of moving from a warm space to a cold space, and a heat pump performs the opposite process by receiving external electrical energy [25]. In particular, heat pumps have been recognized as important for decarbonizing the heat sector and have received policy support in several countries over the past few years. However, the electrical energy supplied to obtain clean thermal energy must be produced based on renewable energy. The circled number 2 in Figure 3 represents Power-to-Heat. Figure 5 shows a close correlation between the heat and the electricity sectors. Heat networks can meet their own demand with surplus power, and electrical networks can alleviate the renewable energy curtailment.

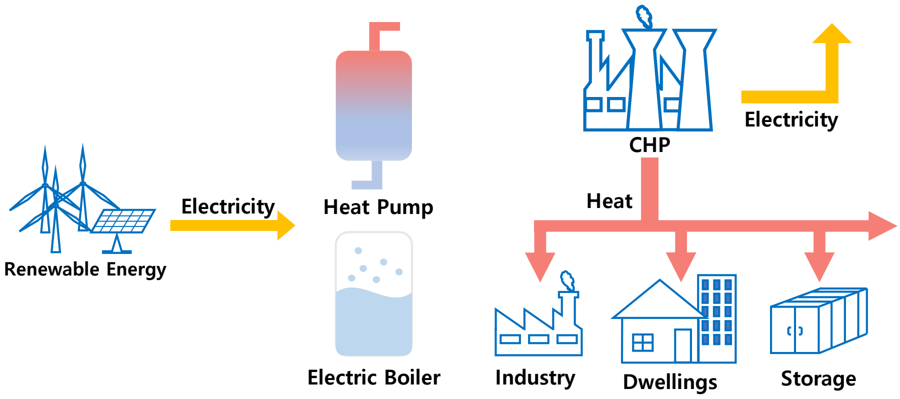

Figure 5. Concept of Power-to-Heat.

The surplus power can be supplied to the heat network and processed at the heat demand point, or it can be utilized as a heat storage device. Thermal energy storage (TES) can be classified into three types: sensible, latent and thermochemical [26]. Sensible storage employs a method to raise the temperature of the medium in the container, and is commonly used since it is the simplest and cheapest. Latent storage stores or releases heat through changes in the state of matter. The material used during the changes is called phase change material (PCM) and absorbs heat when melting between liquid, solid and gas and releases heat when condensing. Thermochemical storage uses the principle of storing heat during endothermic reactions and releasing heat during exothermic reactions [27]. The main characteristics of heat storage devices are summarized in Table 1, where it can be seen that each bears different characteristics. The main advantage of heat storage devices is their longer storage capacity compared to battery energy storage system (BESS), which is expected to contribute to making renewable energy a base load power plant. Furthermore, harmonics, voltage flicker, transient stability, and dynamic stability can be improved in the short term, and volatility and congestion can be alleviated in the long term [28].

Table 1. Typical characteristics of TES [29].

TES Type	Capacity (kWh/t)	Power (MW)	Efficiency (%)	Storage Period (h,d,w,m)	Cost (€/kWh)
Sensible	10–50	0.001–50	50–94	d/m	0.1–30
Latent	50–150	0.001–10	75–90	h/w	0.4–70
Thermochemical	120–250	0.01–0	75–100	d/m	10–130

5.3. Power-to-Gas

Gas, which refers to natural gas in this paper, is utilized in various industries, including CHP, air conditioning/heating, vehicles, and industry, due to its widespread network and high energy density. Methane, which makes up most of the natural gas (70–90%), can be obtained from natural sources or produced through Power-to-Gas [30]. A representative Power-to-Gas is CO_2 methanation, and (1) represents the corresponding reaction formula [31].

$$4\,H_2 + CO_2 \longrightarrow CH_4 + 2\,H_2O \qquad \Delta H = -165 \mathrm{kJ/mol} \tag{1}$$

In (1), H_2 and CO_2 need to be obtained through clean processes. Methanation can be classified as biological process or chemical process depending on the catalyst. In biological methanation, microorganisms serve as catalysts, while in chemical methanation, a metal catalyst is mainly used. Ni is commonly used in chemical methanation due to its cost-effectiveness.

Table 2 compares chemical and biological reactions for temperature, pressure and catalyst.

Table 2. Comparison of chemical and biological reactions [32–34].

Reaction Type	Temperature (°C)	Pressure (bar)	Reusability of Catalyst
Chemical	200–550	1–100	X
Biological	20–70	1–10	O

The circled number 3 in Figure 3 represents Power-to-Gas. Figure 6 shows Power-to-Gas in more detail. Methanation is essentially a process for producing natural gas, but it also serves the needs of other sectors. In the gas sector, clean natural gas is produced, and in the electricity sector, the use of CCUS in thermal power plants can help reduce carbon emissions, while also increasing the proportion of renewable energy through the production of green hydrogen.

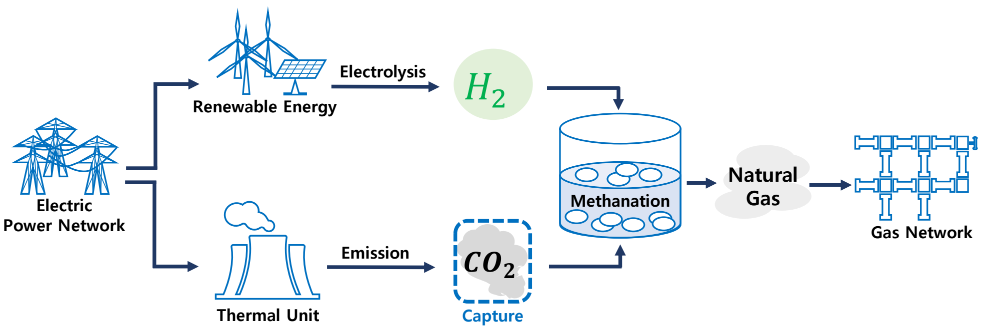

Figure 6. Concept of Power-to-Gas.

6. Pilot Projects of Sector Coupling and Power Systems

A carbon-neutral power system using sector coupling faces several challenges. We have expanded the domain of the problem and identified how the electricity sector interfaces with the gas, hydrogen and thermal sectors. This section shows how each sector makes its power system carbon-neutral and mitigates the challenges of renewable energy. In particular, we examine the feasibility through several pilot projects in each sector.

6.1. Power-to-Hydrogen Pilot Projects

Due to the high potential value of hydrogen, countries and companies are competing to accumulate experience by conducting pilot projects. Research and projects in the hydrogen sector are more popular than in other sectors and are easy to find. The Utsira Island project in Norway has demonstrated the feasibility of using a multi-energy system comprising wind and hydrogen power plants to independently power 10 homes. Utsira is an area where fossil fuel supply is uncertain due to frequent bad weather. However, strong winds are good conditions for wind power generation, so a power supply project using renewable energy and a hydrogen system was undertaken. Key components include wind turbines, electrolyzers, hydrogen compressors, hydrogen storage devices, hydrogen engine generators and fuel cells. In windy conditions, the wind generator directly supplies power, but the electrolyzer is designed to operate when surplus power occurs. Conversely, in adverse conditions where the wind power generation is difficult, a hydrogen engine generator or stored hydrogen can be used to continuously supply power by injecting it into a fuel cell [35]. The Utsira project has been stable and successful for three years, with high levels of power quality and customer satisfaction. However, it has experienced technical difficulties such as hydrogen engine problems and fuel cell operation errors. Nevertheless, for the first time, renewable energy and hydrogen systems have shown the feasibility of long-term stable operation in an independent grid [36].

6.2. Power-to-Heat Pilot Projects

Drake Landing Solar Community (DLSC) conducted a district heating system validation project using solar energy and seasonal heat storage. DLSC focused on the seasonal mismatch between solar thermal resources and heating load, and tried to demonstrate the potential for energy savings by supplying heating in the coming winter with thermal energy stored in summer [37]. The DLSC was conducted in Okotoks, south of Calgary, and 52 homes use solar collectors, short-term thermal storage (STTS) and borehole seasonal thermal energy storage (BTES). STTS plays an important role for long-term heat storage because they can absorb and distribute heat more rapidly than BTES. When heating is required, the STTS heats the fluid, and when the energy of the STTS is insufficient, the BTES transfers energy to the STTS. Conversely, if there is enough thermal energy in STTS, heat is stored in BTES. Thanks to this control system, most of the solar thermal energy is stored in the BTES during the summer when heating demand is low and released during the winter [38]. DLSC was conducted for 10 years from 2007, and the BTES Efficiency was 6% in the first year, but 54% was imported in the last year. In addition, the solar fraction, i.e., the supplied solar energy out of the total required energy, started at 55% and reached a maximum of 97%. The size of the project was found to be small and not competitive with natural gas prices in North America [37]. However, decarbonization in electricity and heat sector through Power-to-Heat and seasonal support leveraging short-term and long-term storage devices are found to be of great significance.

6.3. Power-to-Gas Pilot Projects

STORE&GO is a project for a large-scale storage-based Power-to-Gas migration by 2050 in the EU. From a mid- to long-term perspective, future gas demand in 2050 is expected to reach between 4373 and 4443 TWh, and it is estimated that 550 GW of Power-to-Gas installed capacity will be required [39,40]. In particular, Europe has an advanced gas supply system, which is advantageous to gas utilization. Test plants have been built in Germany, Switzerland and Italy out of a total of six countries, and all three regions have a very large amount of renewable energy generation. Germany's Falkenhagen is the first facility to be operated, and the existing hydrogen production facility was expanded to a 1 MW methanation facility in May 2018. CO_2 from bioethanol was used and supplied to the gas network via chemical methanation. Although a Power-to-Gas efficiency of 53% was achieved, this was due to the low efficiency of the AEL. Solothurn, Italy, supplied gas to the urban gas distribution grid via biological methanation. The Solothurn facility was operated up to full load and achieved an efficiency of 76%. Lastly, Troia in Italy carried out chemical methanation and achieved a low efficiency of 29%, but has the advantage of being able to operate independently of the gas network because of liquefaction. In the project, the use of the generated gas reduced its carbon footprint by more than 80% compared to natural gas.

7. Hurdles to Overcome for Sector Coupling

There are several challenges that should be addressed in order to fully implement sector coupling. These challenges include technological limitations, economic considerations, and market and regulatory barriers. Technologies related to sector coupling are often not fully developed, and large-scale integration can be successful only if it is cost-effective. For example, the production of hydrogen through electrolysis is currently limited by the size of available electrolyzers. The hydrogen sector also lacks a supply network, and faces challenges in terms of efficiency, technical standards, and supply chain optimization. Economically, the price of renewable energy should be competitive with traditional power sources in order to support the migration to carbon-neutral power systems. While the cost of renewables has decreased in recent years, it still varies significantly by country, and many countries subsidize renewable energy. Without price competitiveness, the reliance on fossil fuels would continue, and the goal of carbon-neutral power systems and sector coupling may not be possible.

Operation and market are other big barriers to the integration between electricity sector and other sectors. Electricity, gas and heat networks have been operating independently for a long time; each sector has its own system operator, and the exchanges between sectors have not been considered. Cooperation between multiple system operators is important for smooth operation; however, the existence of a single integrated operator discourages other sector operators to invest. Therefore, a theoretical approach is needed to increase the utility of all sector operators. What makes cooperative control between system operators more difficult is the different supply characteristics and load profiles. For example, hydrogen can be transported over long distances through compression and transport, but heat suffers. Planning efforts that consider all the components of each sector remains a complex optimization problem, but the case of CHP, which has been operated across two sectors for a long time, can provide clues for the sector coupling operation.

Finally, discussions and reports on sector coupling are active recently, but many concepts are still undefined. Policies for large-scale energy integration are still lacking, making it very difficult for infrastructure companies to plan their investments. For example, there is no legal basis for cross-sector integration in most countries, and there are legal and regulatory barriers for an infrastructure company to deal with more than one energy sector [41]. Market design and pricing of energy sources are also not sufficiently discussed. There are currently few reports on energy trading markets where sector coupling is taken into account, and individual regulatory frameworks are turned into barriers to sector coupling [42].

8. Outlook and Conclusions

As global interest in climate change continues to increase, power system operators are exploring the integration of renewable energy into their systems. To address the various challenges posed by the widespread implementation of renewable energy, sector coupling is being considered as a technical solution. The sectors involved include electricity, heat, gas, and hydrogen, with the electricity sector serving as the core and the remaining sectors acting as buffers for surplus power and mitigating curtailment through energy conversion and long-term storage. Improving energy efficiency and increasing the share of renewables in the electricity sector is key to achieving a carbon-neutral power system. Ongoing research into energy storage, water electrolysis, and methanation will support this goal, as demonstrated by the Utsira Project which has shown the potential for independent grid operation through sector coupling.

This paper did not include transportation in its analysis of sector coupling, although it will be a significant part of the future energy system. The commercialization of electric vehicles (EVs) has already taken place, offering not only reduced greenhouse gas emissions but also grid solutions for the power system. For example, Tesla vehicles have been found to emit 6.8 million fewer metric tons of CO_2 compared to traditional combustion engines [43]. Furthermore, Tesla provides energy storage solutions, solar panels, and electricity market bidding strategies, making EVs a key component in strengthening the electricity sector's role as the center of sector coupling [44].

On the other hand, barriers to implementing sector coupling also persist. The major issue is the technological immaturity of the facilities involved. Much of the research remains at the component level, and the integration of large-scale systems has yet to be fully explored. This makes it difficult to establish related definitions and regulations. Further study is also needed in terms of cooperation methods and boundaries, information exchange, and security issues with multiple operators.

A potential solution is to start with multi-energy microgrids before transitioning to larger systems [45]. Microgrids offer a good starting point for sector coupling as they have already been the subject of numerous studies and demonstration projects, allowing for valuable experience to be gained. Though there may be initial investment challenges and potential disruptions to existing systems, the long-term benefits of sector coupling are expected to be significant and will likely drive its adoption in the coming years. This is why we believe sector coupling has the potential to make the power system carbon-neutral in the long run.

Author Contributions: M.S.: writing—original draft preparation; M.S. and M.K.: investigation, writing—review and editing; H.K.: supervision and review. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and the Ministry of Trade, Industry and Energy (MOTIE) of Korea (20192010107290).

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

UNFCCC	United Nations Framework Convention on Climate Change
IEA	International Energy Agency
NDC	Nationally Determined Contribution
GDP	Gross Domestic Product
COP26	Conference of the Parties 26
G20	The Group of 20
BESS	Battery Energy Storage System
IRENA	International Renewable Energy Agency
CCUS	Carbon Capture Utilization and Storage
CHP	Combined Heat and Power
PCM	Phase Change Material
DLSC	Drake Landing Solar Community
STTS	Short-Term Thermal Storage
BTES	Borehole Seasonal Thermal Energy Storage
LCOE	Levelized Cost of Electricity
TES	Thermal Energy Storage
EV	Electric Vehicle

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