MSc Program
Environmental Technology & International Affairs

Sector coupling and renewable energy integration for the defossilisation of the economy: Status quo and perspectives

A Master's Thesis submitted for the degree of
“Master of Science”

supervised by
Associate Prof. Dipl.-Ing.in Dr.in techn. Albana Ilo

Lara Elisabeth Ottendorfer, BA

01620850

Vienna, 12.06.2024

ACADEMY FOR CONTINUING EDUCATION

diplomatische akademie wien
Vienna School of International Studies
École des Hautes Études Internationales de Vienne

Affidavit

I, **LARA ELISABETH OTTENDORFER, BA**, hereby declare

1. that I am the sole author of the present Master's Thesis, "SECTOR COUPLING AND RENEWABLE ENERGY INTEGRATION FOR THE DEFOSSILISATION OF THE ECONOMY: STATUS QUO AND PERSPECTIVES", 85 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted the topic of this Master's Thesis or parts of it in any form for assessment as an examination paper, either in Austria or abroad.

Vienna, 12.06.2024

Signature

Abstract

This Master's Thesis examines sector coupling as a means to defossilise the secondary economic sector for the energy transition of the economy as a whole. It includes the heating and cooling, gas and electricity sectors and assesses their defossilisation potentials. The research investigates the different existing technologies and P2X pathways for sector coupling. It includes direct and indirect electrification, as well as sources of renewable energies and renewable energy conversion solutions like hydrogen-based technologies. It finds that sector coupling holds particular potential for the defossilisation of the heating and cooling industry.

Historically, it examines the origins of each of the energy vectors and draws conclusions regarding their potential of systems integration. The hydrogen vector, in particular holds potential but lacks infrastructure and technological development, inter alia, regarding storage solutions. Thus, electrification is emphasised in the course of this work.

Geographically, it focuses on coupling strategies within greater Europe, and compares it with the status quo of other internationally relevant energy systems where applicable.

New concepts are emphasised like the holistic *LINK*-based paradigm for smart grids as well as other *smart* solutions. By systemically reviewing literature, analysing policy implications, and addressing technological challenges, this research aims to provide valuable insights that can drive the adoption and implementation of sector coupling strategies, ultimately contributing to the understanding and implementation of integrated energy solutions.

Table of Contents

List of Abbreviations

BEV	Battery Electric Vehicle
CCUS	Carbon Capture Utilisation and Storage
CEP	*Clean Energy For All Europeans*-Package
CHP	Combined heat and power
DC	District Cooling
DG	Directorate-General
DH	District Heating
DSO	Distribution System Operator
EC	European Commission
EEC	European Economic Community
EP	European Parliament
EU	European Union
FF55	*Fit-for-55*
GHG	Greenhouse gas
GIE	Gas Infrastructure Europe
IEA	International Energy Agency
LNG	Liquefied natural gas
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
IRES/RES	(Intermittent) Renewable Energy Sources
MS	Member States (of the European Union)
NECP	EU *National Energy and Climate Plans*
NIMBY	Not in my backyard
P2G	Power-to-Gas
P2H	Power-to-Heat
P2L	Power-to-Liquid/Fuel
SDG	Sustainable Development Goals
TES	Thermal Energy Storage
TSO	Transmission System Operator
VRE	Volatile Renewable Energy

Acknowledgements

I would like to thank my supervisor, Professor Dipl.-Ing. Dr.techn. Albana Ilo for her guidance and continuous support throughout the process of conducting this Master's Thesis.

Moreover, I want to express my gratitude to Professor Hans Puxbaum, our Programme Director who made sure I was on the right track and provided me with literature.

I would further like to thank Mr DI Oliver Dworak from the *Energieinstitut der Wirtschaft* for his offering his time, expertise and valuable insights into the sector coupling landscape in Austria and beyond.

Given the limited timeframe for completing this Master's Thesis, I was fortunate to receive swift assistance and valuable connections to experts in the field.

Finally, I could not have achieved this milestone without the unwavering support from my family and friends throughout this Master's programme.

1. Introduction

The defossilisation of the economy, on a regional and global scale constitutes a key pillar in climate change mitigation. Europe has become a key player in leading the energy transition. As described by the *European Network of Transmission System Operators for Electricity* (2019, 4), ENTSO-E in short, Europe is experiencing a shift away from a fossil-fuelled and supply-centred energy sector '*to a clean, digitalised and electrified consumer centric system with many distributed resources'*.It lays out that future system operations will *'rely upon a system of systems that should work as one'* that ensures the integration of growing shares of Volatile Renewable Energies (VREs) and distributed resources. This allows *' for alignment with needs of all grid connected assets and be further coupled with other sectors'* where innovation and cooperation are '*key enablers'* (European Network of Transmission System Operators for Electricity 2019, 8).

This Master's Thesis examines various aspects of sector coupling as a means for defossilisation, while exploring the opportunities there are at the European level. The persisting challenges and barriers that are technological, market-oriented and socio-economic are assessed. It is aimed at reflecting on the following research question:

> *How can sector coupling enhance energy resilience and security in the face of disruptions, and what strategies should be prioritized to achieve these goals (on the example of Austria)?*

The conclusion rounds up this thesis by integrating the findings on the defossilisation potential of sector coupling. It comprises an outlook in the future and perspectives for Europe looking at potential means of application and implementation.

1.1. Background

The global primary energy consumption is continuing to grow by roughly 1-2% each year despite a small downturn in fossil fuels that are still the dominating share with over 80%.

1. Introduction

This increasing energy demand is posing significant challenges to stakeholders that are among others, governments, energy providers and grid operators around the world (Energy Institute 2023).

The European Union has taken a leading role in the energy transition, with the "Fit-for-55" package aiming to reach carbon neutrality by the year 2050 and cutting overall greenhouse gas emissions by 80-95% compared to the year 1990. To that end, the complete defossilisation of Europe's energy system is essential while maintaining affordability and secured energy supply (European Parliament. Directorate General for Internal Policies of the Union. 2018; European Commission, Directorate-General for Energy 2022).

Through the growing penetration of VREs the distinct need for smart grid stability solutions as a result of increasing fluctuations in the output of renewables and coinciding closures of conventional power plants continues to arise (Khajeh, Shafie-khah, and Laaksonen 2020).

At the same time, due to growing electrification and increased reliance on EVs and electrical appliances, challenges regarding operation and planning of the electricity grid today can already be observed. According to Lai and Locatelli (2023), large-scale energy storage capacities are essential in maintaining the power grid's energy balance. Notwithstanding this distinct need for storage solutions, the scale and amount throughout Europe is still insufficient despite rapid growth.

In this context, the DG for Energy of the EC is calling for the prompt upscaling of available technologies and investment stimulation through incentive-based regulations such as carbon pricing via ETS in order to further foster economic competition with conventional technologies while minimising administrative hurdles. Regarding the necessary skills and skilled workers for the energy transition, the EC recognises the problem that different sectors are competing for '*the same competencies'* which in return requires EU-wide coordination efforts as well as the allocation of sufficient education and training facilities for the desired skills (European Commission. Directorate General for Energy. 2022).

1.2. Motivation

The energy transition is becoming an increasingly pressing issue and sustainable solutions are needed in order to achieve net zero by the year 2050 and the SDGs. Sector coupling potentially represents one of the pivotal approaches in mitigating the climate and associated energy crisis. The consequences of the latter parts of the world are already experiencing to a large extent. This research aspires to contribute valuable insights that can help shape the transition towards a cleaner, more interconnected and sustainable energy future. It aims at providing a holistic overview of sector coupling in Europe and beyond.

1.3. Objectives

The main objective of this Thesis is to provide a holistic understanding of sector coupling dynamics and recommendations for sustainable energy integration in the future. For this, the following research question has been identified as:

> *How can sector coupling contribute to enhancing energy resilience and security in the face of disruptions, and what strategies should be prioritised to achieve these goals?*

Further questions that this Thesis aims to explore are what the role of sector coupling in the defossilisation of the economy actually is and provided positive outcomes, whether it could be applied to other regions and economies in the future.

Since the state of the art regarding sector coupling is at times unclear in terms of terminologies and different understandings, this Thesis aims to provide a uniform definition through thorough assessment of the historic developments and status quo. Providing clarity in terms of the understanding of sector coupling and associated technologies is essential for further research and future deployment of sector coupling technologies. This holistic view on the topic is a key objective of this Thesis which aims to provide a basis for future, in-depth research on all of the associated technologies.

1.4. Scope

The scope of this Thesis encompasses the assessment of history and overview of the status quo of sector coupling and its defossilisation potential. The opportunities and respective challenges and limitations of the sector coupling concept will be elucidated as well as the future perspectives.

Geographically, the focus of this Master's Thesis is limited to Europe. Nonetheless, *Chapter 7 Conclusion* further explores the applicability of the assessed sector coupling strategies to other geographic regions.

1.5. Structure

After outlining the research methodology in *Chapter 2,* the Thesis sets out the findings of the literature review. *Chapter 3* examines the historical overview of the various energy systems and general structure of countries' economies today. In *Chapter 4*, the process of energy systems integration is described. *Chapter 5* includes assessment of the status quo of sector coupling on the holistic level. The research question is closely examined in *Chapter 5.2*, *State of the Art.* It reviews the benefits and opportunity areas of sector coupling, which include an increase in flexibility and decrease of fossil dependence in *Section 5.2.1. Section 5.2.2.* examines the barriers and challenges that are sub-divided into technological, socio-economic and market-oriented. In *Chapter 6* recommendations to policymakers are presented based on the literature review. The *Chapter Conclusion* contains the integration of relevant findings. Included in the conclusion, the future perspectives and outlook are given.

2. Methodology

Figure 1 shows the methodology used in this work. It comprises a state-of-the-art literature review, including a thorough assessment of EU legislation in the context of energy transition and sector coupling.

The comprehensive systematic review aims to roll out the state-of-the-art effects and potential knowledge gaps about sector coupling.

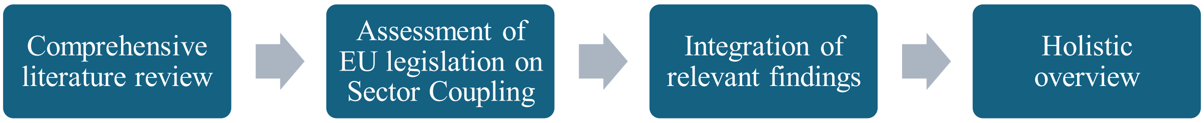

Figure 1: Methodology

Through this approach, the research aims to provide a holistic understanding of sector coupling and offer valuable insights and recommendations for sustainable energy integration. To that end, it aims to holistically answer the chosen research question that is:

> *How can sector coupling enhance energy resilience and security in the face of climate change, and what strategies should be prioritised to achieve these goals.*

Further questions this Thesis aims to explore are what the role of sector coupling in the defossilisation of the economy is and provided positive outcomes, whether it can be applied to other regions and economies in the future. The findings are accordingly summarised in the conclusion.

3. Energy Transition

The energy transition has the aim of enabling a carbon neutral economy based on adherence to the Paris Climate Agreement and the 2018 IPCC report with net zero emissions by the year 2050 and the accompanying European targets by 2030. The European Union (2019) has defined its goal to have '*a clean, affordable and reliable energy system*' by decreasing emissions from greenhouse gases (GHG) by a minimum 40% compared with the 1990s level.

Increasing efficiency of energy consumption and accelerating defossilisation of the energy sources constitute essential strategies in order to achieve this transition to clean energy (Agora Energiewende 2019).

This Chapter provides an overview of the different elements regarding the energy transition including smart grids and the energy trilemma. It sketches the economic structure of the overall economy and briefly outlines the historical background of the different components of the energy system as we know it in the subsequent subsections.

3.1. General structure of countries' economies

In macroeconomics, countries' economies are usually divided in different sectors, according to the share of the workforce carrying out various activities.

While some macroeconomic models consider four or five economic sectors, including e.g. also intellectual activities and the 'knowledge economy', this Thesis only takes into consideration the three main ones as the remaining others can be closely linked with the tertiary sector.

The economy of a nation is categorised per Rosenberg (2020) into three main sectors that are:

- The **primary sector** covers the primary economic activity, i.e. extractions and harvest of raw material and staple foods.

It comprises the industries agriculture, fishing and mining, as well as forestry and quarry extraction. The primary processing and packaging are further included in the primary sector.

- The **secondary sector** involves all further manufacturing, construction and processing activities like, inter alia, the construction industry, chemical and textiles and automotive production.
- The **tertiary sector** covers the commercial service industry, both on a business-to-customer (B2C) and business-to-business (B2B) level. This includes for instance, tourism, insurance and health care, gastronomy and law practices.

This categorisation as a '*continuum of distance from the natural environment*' starts with primary economic activities and increasingly in distance from the natural resources to the extent that the sectors are becoming increasingly decoupled from the processing of raw materials.

In the scope of the energy transition, the secondary sector, and more specifically, the energy utilities contained therein, are most relevant as they involve the production and distribution of the various energy carriers.

Figure 2 provides an overview of the general economic structure of a country and the links of each of the energy systems and sectors with each other.

Furthermore, it depicts the interlinkage between each of the energy systems with their according vector and end users.

Per definition, '*an energy vector allows to transfer*, *in space and time*, *a quantity of energy'* (Orecchini 2006, 1952).

Thus, vectors facilitate the energy use at a temporal and spatial distance from the energy source. The most common vectors currently include fossil fuels like oil and gas and their derivatives, electricity and heat exchanging fluids.

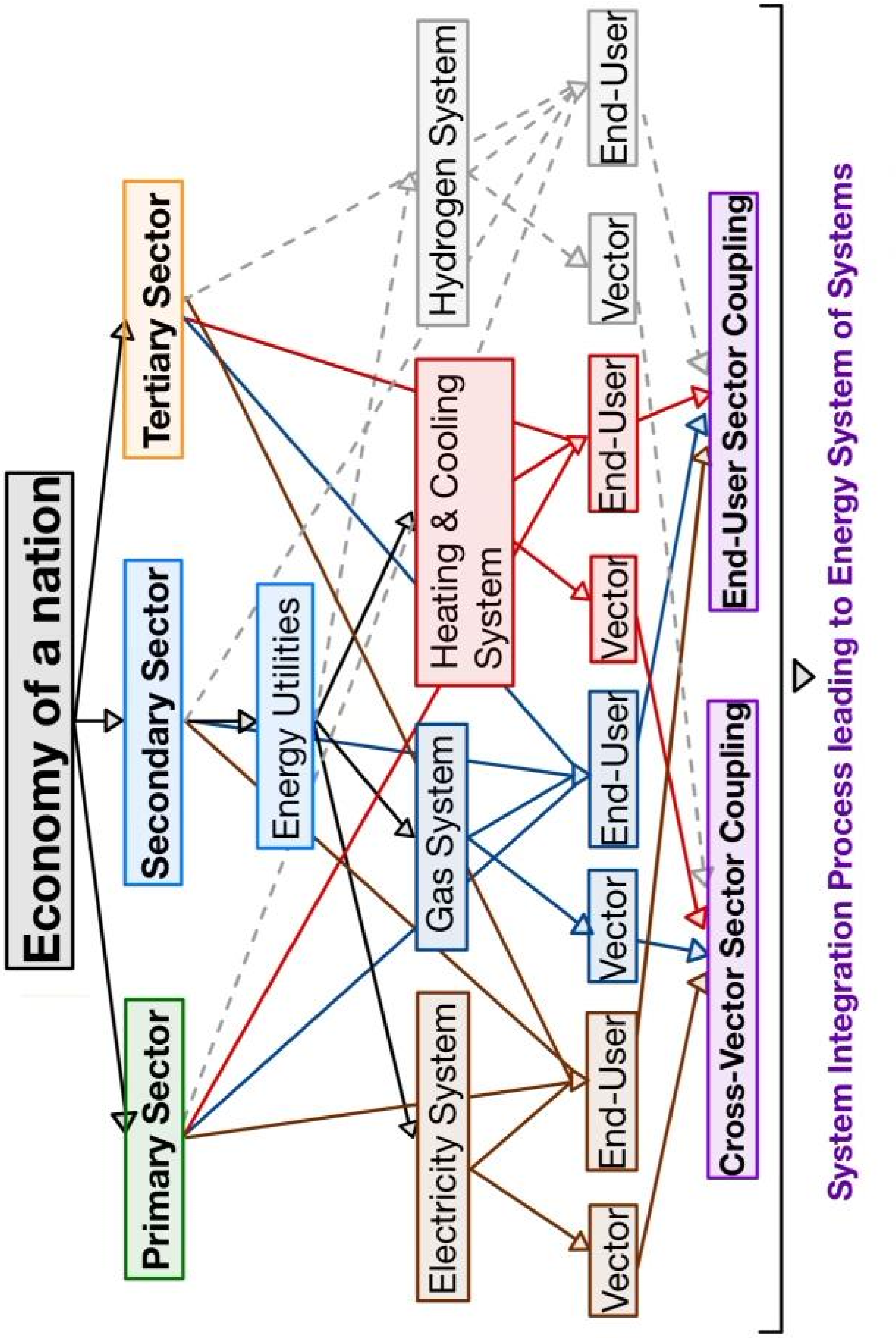

Figure 2: Overview Energy Utilities within economic structure (Source: based on Ilo 2024)

Hydrogen vectors do not yet exist on a broad scale, however, there are supranational initiatives to create the necessary infrastructure like the *European Hydrogen Backbone* (EHB) which is currently being established. It envisions a pan-European hydrogen transmission system that utilises the existing gas infrastructures to construct five hydrogen corridors throughout 28 countries from 2030 to 2050 (European Hydrogen Backbone 2023).

Hydrogen, thanks to its long-term storage and long-range transfer attitude, is described by Orecchini (2006, 1954) as '*the missing vector to be integrated within the global system for accomplishing a complete replacement of fossil fuels*'.

Figure 2 further evinces sector coupling that can be in the form of cross-vector and end-user coupling, both of which are examined in further detail under *Chapter 5*. As can be derived, the different energy vectors, through sector coupling, are moving towards an *Energy System of Systems,* an integration process that is subsequently explained in *Chapter 4*.

When looking at the energy transition, an important but limiting aspect is currently the capacities of the electricity. As many European countries are now increasing the share of renewable energy sources (RES) in their energy portfolios, the fluctuations in the power system are likewise increasing, as are changes in the electricity supply structure.

Another element is the growing number of distributed generation units that are on the one hand becoming more popular due to their small size, advancing technologies and flexibility that can be connected to the distribution grids. On the other hand, however, they can have adverse effects on the network operations when operating '*in an uncoordinated way*' (Ilo and Schultis 2022, 14).

Energy utilities both manage and own the power generation, transmission and distribution components through vertical integration, i.e. direct ownership of the various stages of the production process. Today, the householders, that are electricity customers consume the electricity provided by the closest supplier (Perry 1989).

This poses substantial challenges to the power industry overall and particularly, the management of the electricity market and the use of present transmission and distribution grids.

In this context, the term *Smart Grid* ascribes a

> *'modernization of the electricity delivery system so it monitors, protects and automatically optimizes the operation of its interconnected elements – from the central and distributed generator through the high-voltage transmission network and the distribution system, to industrial users and building automation systems, to energy storage installations and to end-use consumers' (...)*
> (Electric Power Research Institute 2011, 2–1).

The scope of smart grids extends from the generation (distributed and central) on all voltage levels (HV, MV and LV) to the electrical devices in households whereas the power systems of the past ended at the connecting point with the consumers (Ilo 2016).

Since smart grids further involve the consumers, initiated by the California electricity crisis in 2000 and 2001, they made way for a new era of energy production and consumption. This era includes 'prosumers' in the power system that are grid-owning electricity producers with storage capacities. It can thus be inferred that all producers of electricity, notwithstanding their technology and size, must be considered for the successful integration of smart grid solutions.

As they represent a decentralised and deregulated system with high proportion of RES and enabling properties for sector coupling dynamics, smart grids are an essential element for a successful implementation of Energy System Integration (ESI) (Brauner 2022).
The ESI and according processes are discussed in more detail in the *Chapter 4* underneath.

When regarding energy systems, especially in the context of the energy transition, the importance of balance of the dimensions of the *Energy Trilemma* arises. In line with the *World Energy Council* (2024b), '*healthy energy systems are secure, equitable and environmentally sustainable'*.

In their annually released Energy Trilemma Report and Index, it analyses the progress of the energy transition across more than 100 countries, appealing to policymakers and leaders to tackle the competing requirements of the three dimensions of the trilemma.

Figure 3 visualises the energy trilemma, including its core dimensions energy security, energy equity and environmental sustainability of the energy systems.

Energy security involves the capacity of a country to meet its population's energy needs, from own production to imports in a reliable and resilient way. The sustainability dimension assesses the progress towards clean energy according to factors like innovative abilities, governmental stability and attractiveness to investors. The last dimension, energy equity, evaluates the extent of universal access to energy based on factors like electricity access and access to clean cooking fuels.

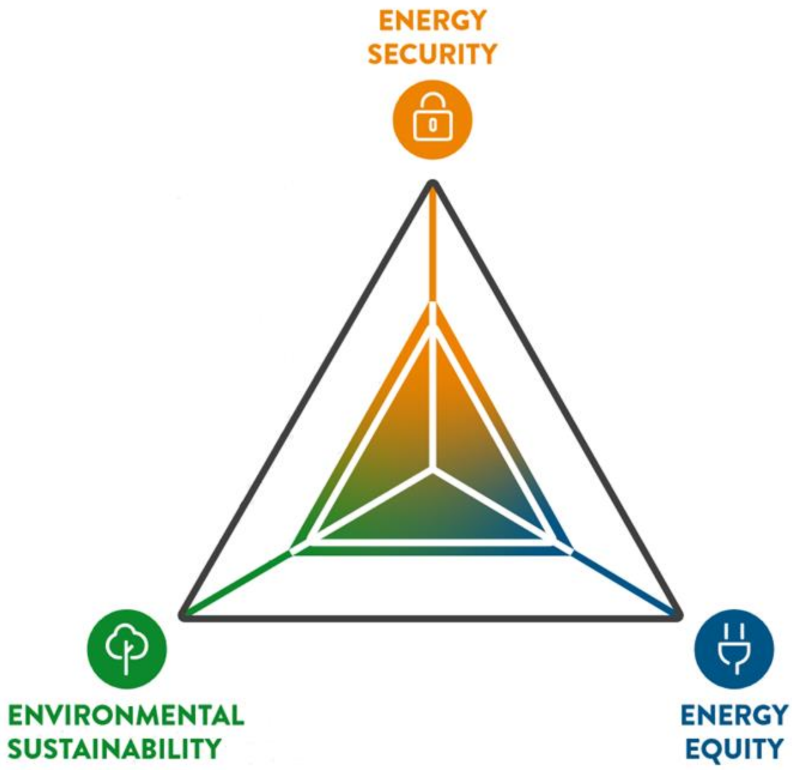

Figure 3: Energy Trilemma (Source: World Energy Council)

As per the report (2024b, 2), a balance of systems enables '*prosperity and competitiveness of individual countries'*.

The Figure depicts the fact that individual dimensions cannot be considered indvidually without the risk of passive trade-offs, in order to keep the system's balance, in the middle.

3.2. Historical overview of energy systems

In order to look at the evolvement and potential of sector coupling, a concept subsequently explained throughout this Thesis, the historical roots of energy systems that paved the way must first be assessed. While the term sector coupling is still rather new in application, dating back to the year 2013, the concept finds its historical roots in as early as the 19^{th} century (Breeze 2018).

This Section aims to provide an overview of the historic developments of the various energy systems, including the gas system, heating and cooling, the power system and more recently, hydrogen.

3.2.1. Gas

The history of utilising natural gas begins with the construction of the renown *Oracle of Delphi* around a natural gas source seeping from the ground in a flame in ancient Greece 1.000 years BC. Roughly 500 years BC, crude bamboo pipes were used as pipelines for the first time in history in China to transport natural gas for the boiling of water. In 1785, Great Britain was the first country in the world to commercialise natural gas for street and house lighting purposes. Baltimore was the first city in 1816 to have fully lit streets with gas lights. 20 years later, the first municipally owned gas distribution company was established in the city of Philadelphia named *Philadelphia Gas Works*, the longest operating American public gas system (American Public Gas Association 2024).

The utilisation of natural gas other than for lighting purposes goes back to the invention of the *Bunsen burner* by German chemist Robert Bunsen in 1855 which made way for new opportunities regarding gas stoves and gar furnaces. Throughout the 20^{th} century, with reliable pipelines being built all over the US and beyond, the power of gas extended from heating, cooking, industrial processes and boilers for power generation.

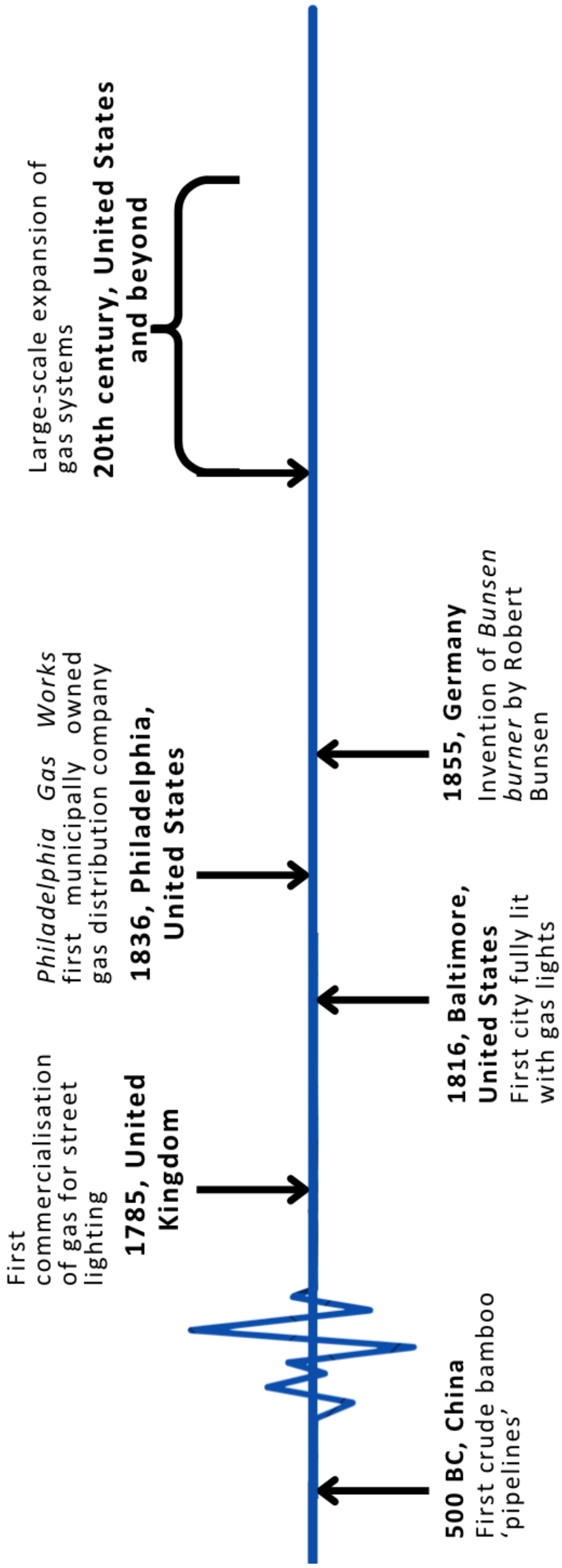

Figure 4: Timeline of relevant historical developments of the gas vector

Nowadays, '*natural gas is a vital component of the world's supply of energy',* the American Public Gas Association (2024) claims with more than one half of energy being consumed by residential and commercial consumers. It further points out the increased demand in LNG, which will require future processing facilities. According to the authors, US imports will increase to 7 or 8% compared with 1% currently by the end of the decade.

Figure 4 visualises the main historical developments regarding the history of the gas system.

In their World Energy Outlook (2011), the IEA first mentioned the '*Age of gas'* which we are experiencing today. A more recent analysis by the IEA (2024), however, acknowledges declining growth rates in natural gas which might result in a foreseeable end of said fossil-based age.

3.2.2. Heating & Cooling

The first district heating approach was recorded in Chaude-Aigues, France, in as early as 1334, when a geothermal source was employed to transport hot water to the village (Werner 2017).

The history of commercial district heating (DH) dates back to the 1870s, ranging over 80.000 systems worldwide (Østergaard et al. 2022).

Literature distinguishes between the first, second and third generation of DH with different features such as heat carriers and within the different periods in history. The **first generation of DH** spanned from the 1880s to the 1930s and involved high-temperature steam that was transported through the pipes. With the invention of Thomas Edison's first power station for lighting located on Pearl Street in New York, heat was used to supply hot water and heating for residential as well as commercial spaces (see *Section 3.2.3*). At the time, the whole system was fuelled by coal. These DH constructions can still be seen in New York today, with hot steam rising from manhole covers, and were soon to expand to other major cities in the world (Breeze 2018).

Following World War I and the Great Depression, district heating experienced an upswing throughout some European cities inter alia in Germany and the US in the 1920s. The **second generation** was established in the 1930s and lasted for roughly 30 years. The heat carrier was pressurised hot water, fuelled by oil and coal. By 1950, Russia as well as Germany and Scandinavia had established DH systems, while in other countries like the UK, '*there was never any great enthusiasm for CHP',* the combined heat and power production, also known as cogeneration. According to the author, '*CHP is seen as a key emission control strategy for the 21st century*' thanks to high efficiencies, despite its growth having remained stagnant in recent years (Breeze 2018, 5; Werner 2017).

Starting in the 1970s, the **third generation** used for the first time pre-insulated pipes that were directly buried into the ground, making possible the operation with lower temperatures below 100 degrees Celsius. This drastically improved their efficiency, which constituted a major objective at the time after the oil crises in 1973 and 1979. DH concepts are widely implemented in the geographic zones of Russia, China and the EU amounting to over 80% of the globally delivered heat through DH systems. With reference to Werner (2017), 8% of the global end-user heat demand are accredited to DH supplies.

As they allow for fuel-and cost-efficient utilisation, DH play an important part in EU legislation on energy as well as on regional levels (Østergaard et al. 2022).

Today, the **fourth generation** of DH is well underway, which aims to integrate high amounts of RES while at the same time providing flexibility to the power system. Modern systems are demand-driven, while ensuring there is sufficient water pressure and temperature to be delivered to the consumers by the suppliers.

Regarding the history of district cooling, its history is likewise separated into four generations. Early district cooling (DC) concepts in the form of collective pipeline refrigeration systems were put in place towards the end of the 19th century in the US, mainly in New York. This period is referred to as the **first generation of DC**, comprising '*central condensers and decentralised evaporators with the refrigerant as the distribution fluid'*, which survived until the 1960s (Lund et al. 2014, 2).

By the time, DC systems were also introduced in France and later Germany. Starting with a shift towards '*comfort cooling'*, the **second generation** of DC began with water as distributing fluid and large-scale compression chillers (Østergaard et al. 2022).

The **third generation** started in the 1990s with a diversification in the cold supply by utilising new cooling sources like natural cold sources and absorption chillers. The concept of heat recovery found some interest from compression chillers as did short-term cold storages. The adoption of the *Montreal Protocol* in 1987 and its entry into force in 1889 further initiated the beginning phase-out away from refrigerators containing ozone-depleting substances, mainly CFCs.

The **fourth generation**, starting with the turn of the century is described by Østergaard et al. (2022, 1) as to be '*combining cooling with other energy sectors sometimes into a renewable energy-based smart energy systems context, including combined heating and cooling'*. Nowadays, estimates regarding the total global cooling demand amounts to almost 20% of the overall electricity demand, in the form of air conditioning and electric fans. While the exact number of DC systems on a global scale has not been identified, roughly 150 European systems are in operation, in comparison to over 5.000 DH systems in Europe. Many metropoles like Vienna, Paris, Stockholm and Middle Eastern and American cities have DC systems in place (Werner 2017; Østergaard et al. 2022).

With rising temperatures and the formation of heat islands in cities as well as increased living standards, this share is expected to rise further. DC is less widespread on a global level compared with DH, however, in line with Østergaard et al. (2022), it '*could provide a more efficient and low-cost option for covering cooling demands'* due to flexibility in conversion and naturality of cooling.

Figure 5 illustrates the historical developments of heating and cooling systems until today.

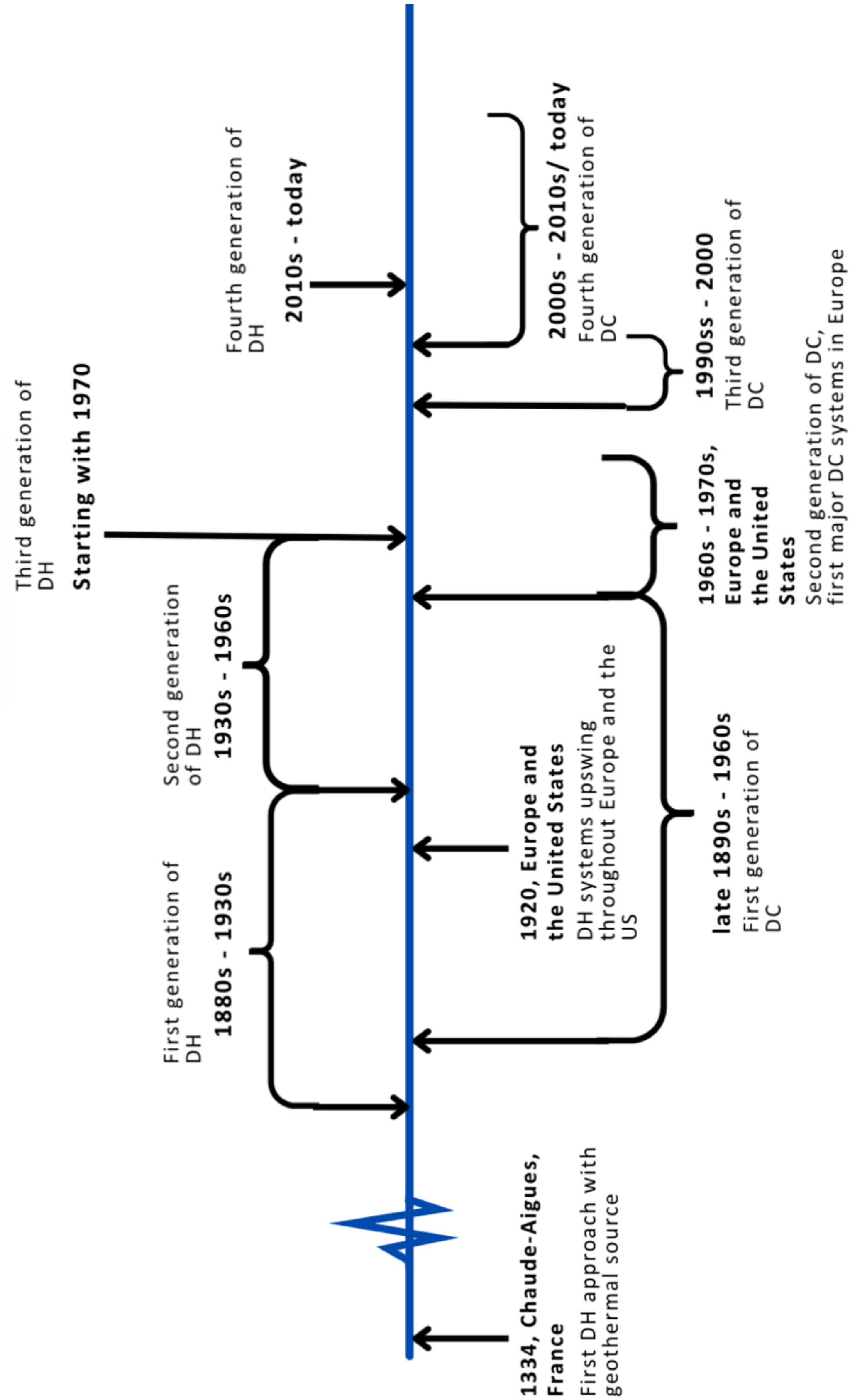

Figure 5: Timeline of relevant historical developments of district heating and cooling vectors

3.2.3. Electricity

The history of electricity finds its roots in the studies of Thales of Miletus, around 600 BC in ancient Greece. By rubbing amber with clothes, for the first time in history, static electricity was discovered. Benjamin Franklin in 1752 succeeded at his famous kite experiment, proving that lightnings are electric phenomena. In 1800, Alessandro Volta invented the electric battery.

Throughout the course of the Industrial Revolution in the 19th century, electromagnetism was discovered by Øersted as well as the principle of electromagnetic induction, by Faraday. Thomas Edison developed the first incandescent lamp for residential lighting purposes in 1879, a true turning point in the history of lighting. The end of the 19th century marks the beginning of the electricity vector as we know it today with the construction of the first low-voltage central power plant located on Pearl Street, New York City under Edison's instructions in September 1882. Its establishment marked a pivotal moment in the history of centralised and large-scale industrial power plants – the '*forerunners'* of today's electricity generation and distribution systems. A former employee of Edison, Nikola Tesla, conceptualised the Tesla coil which facilitated long distance transporting by its transforming from LV to HV capacities. He was to later set in place the first electric system with alternating current (Erenoğlu, Erdinç, and Taşcıkaraoğlu 2019).

The first hydroelectric power plant was installed at Niagara Falls and was to electrify the city of Buffalo by 1896. The Buffalo plant and Edison's Pearl Street plant marked the beginning of the electrical era in which the residential sector experienced significant electrification starting in the United States and soon to be seen in the whole world. This era, until the year 1910 is classified as legacy distributed power era, characterised by small and distributed power plants that supply electricity to nearby consumers (Owens 2014).

During the start of the 20th century a surge in electrical household appliances such as electric stoves, washing machines and lamps took over especially in the US. With the start of this *'all-electric American home'*, the demand for CHP, for which the main application constitutes DH, was slowed down again (Ramsebner et al. 2021, 4).

This furthermore marked the beginning of the 'central power period', where economies of scale led to ever larger power production plants (Owens 2014).

Battery electric vehicles attained popularity in the US after their initial demonstration at the World's Fair in Chicago in 1892. However, with the introduction of the ICE by Henry Ford in 1908, battery electric vehicles (BEVs) lost in market share and interest again.The first practical photovoltaic cell was developed in 1954 by *Bell Laboratories* in the States. In power systems history, large-scale decentralisation happened towards the end of the 20th century, when many vertically integrated utilities were transformed into different legal entities such as generation, transmission and distribution companies, policy makers and so forth. Since then, unprecedented technological developments have had a lasting impact on power systems today such as the development of storage solutions. This also changed the view on the system's components today, making storage an integral part of the architecture (see also *Chapter 4).*

The term Smart Grid, as defined in the Section above, was first mentioned after the major blackout in the US and Canada in 2003. The electricity crisis that preceded the blackout gave rise to distributed power with exhaustive small-scale PVs and the era of prosumers. This 'integrated energy systems era' includes distributed as well as centralised systems that may work together and provide novel services like for instance, CHP (Owens 2014).

Today, marked by technological progress particularly in communication between the different stakeholders in the power system, customers can take active parts in local markets, by bidding and basing their demands on the market prices. With smart meters connected to the households' appliances and demand response programs, load management and simultaneous profit maximation become possible, paving the way for '*the new age of smart digital grids*' where the customers may participate as sellers and/or buyers (Khajeh, Shafie-khah, and Laaksonen 2020, 1).

Illustrated in *Figure 6* is the historical overview of the electricity or power system as we know it today.

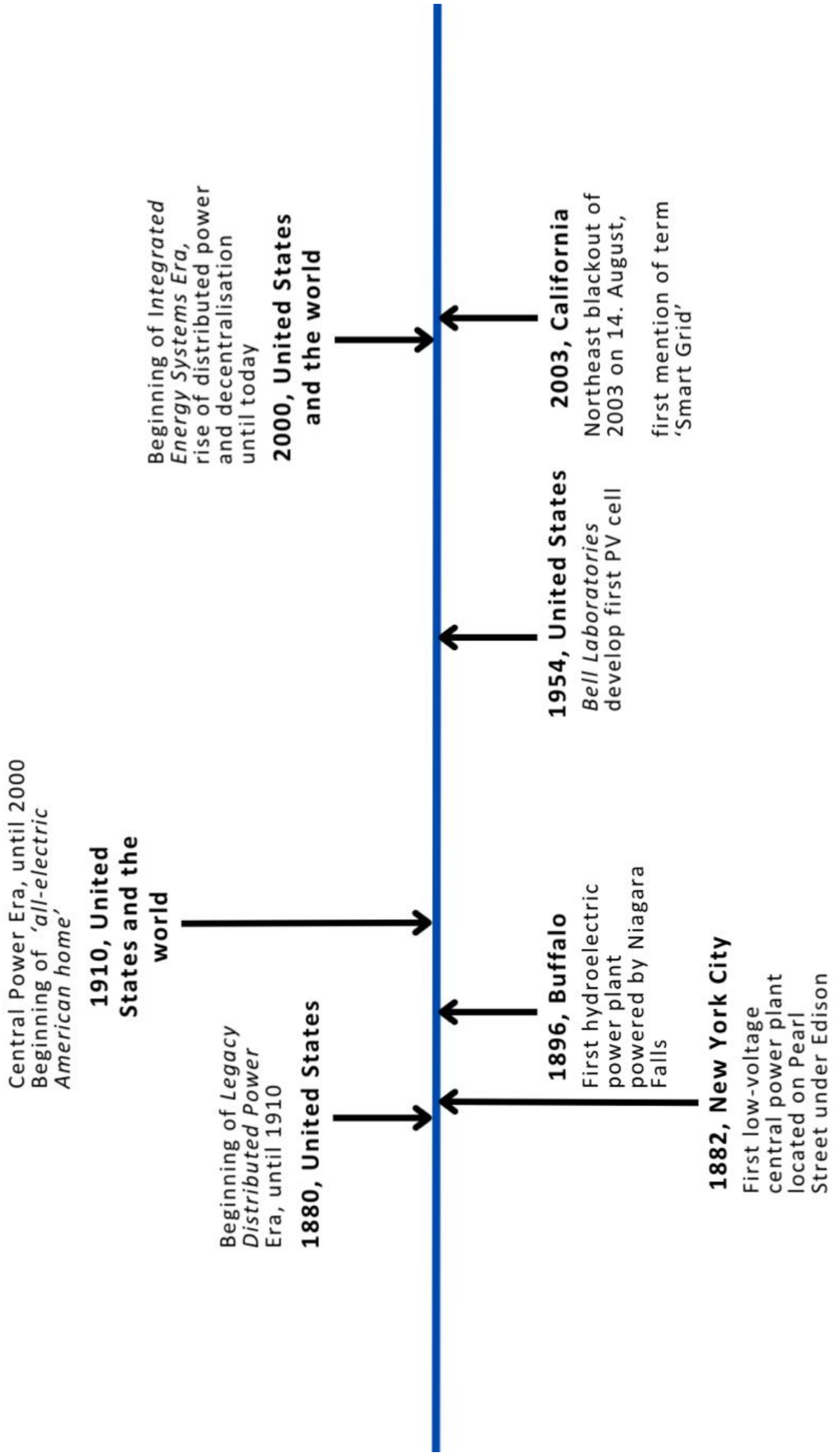

Figure 6: Timeline of relevant historical developments of the electricity vector

3.2.4. Hydrogen

With regard to the history of hydrogen, it has to be noted that the energy vectors do not yet exist despite its discovery dating back to the year 1766 by British scientist Henry Cavendish. By reacting zinc with hydrochloric acid, hydrogen was separated and Cavendish' later demonstrations led to the finding that water is made out of hydrogen and oxygen. In 1800, the British scientists Sir Anthony Carlisle and William Nicholson discovered the electrochemical process of electrolysis, separating water into hydrogen and oxygen.

Swiss pharmacist Christian Schönbein observed the fuel cell effect in 1839, producing water and an electric current from hydrogen and oxygen. Six years later, sir William Grove finalised Schönbein's findings, developing the world's first 'gas battery' for which he was later named *'Father of the Fuel Cell'*.

On May 6 1937, the *Hindenburg* airship disaster happened over New Jersey in the course of a transatlantic flight from Germany to the US, after ten successful prior flights. The incident was followed by a wave of negative publicity, and marked for the time being, an abrupt end of the passenger-carrying zeppelin era.

The next breakthrough was achieved in 1959 when Sir Francis Bacon invented the first hydrogen-based fuel cell battery. Later experiments included the first hydrogen-powered car, however, efficiencies up to this are not economically feasible. In 1973, induced by the oil embargo, the search for alternative fuels was officially commercialised marking the beginning of development of conventional hydrogen fuel cells. Four years later, 1977 marks the year of establishment of the IEA, with the aim of advancing, inter alia, energy from hydrogen and other technologies. The following decades were marked by numerous experiments and prototypes such as hydrogen-powered fuel cells for buses, cars and freight vehicles.

1999 was the year where Europe saw the first fuel stations for hydrogen in German cities, Hamburg and Munich. In 2001, the first proton exchange membrane fuel system was established by *Ballard Power Systems* for the integration into industrial and end-appliance applications (Office of Energy Efficiency & Renewable Energy, Metropolitan Washington Council of Governments, and Hydrogen Association 2004).

Today, hydrogen is used to a large extent in the industry but only 0.1% account for the fabrication of fuels containing hydrogen, power generation and storage, '*the key for the clean energy transition*' referring to the IEA (2023).

China represents the global leader in hydrogen production and consumption, accounting for almost 30% of global hydrogen use (International Energy Agency 2023).

According to a survey conducted by IRENA, in 2020 the hydrogen consumption in China amounted to roughly 24 million Mt as opposed to some 120 million Mt on the global scale. The world's second largest consumer is the United States with above 10 million Mt. The national space agency, *NASA* in particular is using liquid hydrogen for rocket propulsion systems and developing alternative fuel solutions (IRENA 2022).

The IEA (2023) lays out that the global hydrogen usage increases continuously. Nonetheless, this increase is ascribed to traditional applications that are, among others, the chemical industry and refining. In 2022, the global production of hydrogen amounted to roughly 95 Mt which represents an increase of 3% compared with the previous year. Nonetheless, Europe's growth has been stagnant in recent time, especially in the chemical sector, in consequence to the Russian invasion of Ukraine and the resulting energy crisis. The US and Middle East on the other hand, observed strong growth around 7%, compensating by far for Europe's drop in hydrogen consumption from 2022 to 2023. The IEA subsequently recognises that the increased demand in hydrogen is not a result of policies but rather one of worldwide energy trends. It follows that thus far, the growth regarding hydrogen demand has had '*no benefit for climate change mitigation purposes*' (International Energy Agency 2023, 21).

The future vision in accordance with the IEA's Net Zero Emissions Scenario by 2050 includes predicts annual growth in hydrogen use by 6% until 2030.

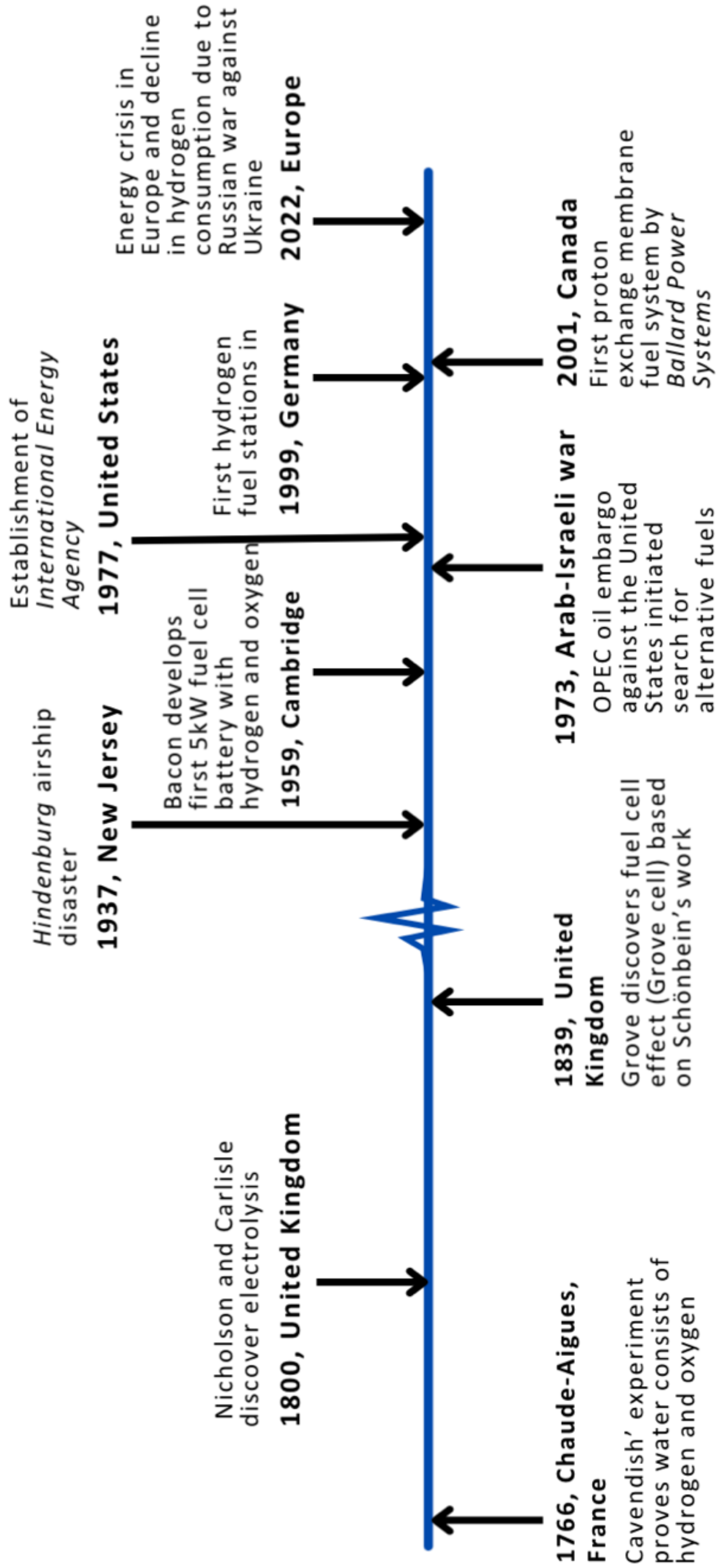

Figure 7: Timeline of relevant historical hydrogen developments

Figure 7 provides a timeline of relevant historic developments regarding the hydrogen system that date back to the 18th century, despite hydrogen being the 'youngest' of all energy utilities.

3.3. Enabling concepts

In this context, a distinction is drawn between the term decarbonisation and the defossilisation. **Decarbonisation**, per definition, is the process of '*reducing carbon intensity in energy sources, that is, the carbon emissions per unit of energy generated'* (Donthi 2020, 127).

While it describes the efforts to remove carbon through an economy's activities, **defossilisation** can be described as the process of replacing fossil-based feedstock with renewable sources. Defossilisation is indispensable for industries that are carbon-based like the chemical industry as well as fuels in the transport sector as they comprise bound carbon which will, at some point in the future be released, i.e. emitted. Examples for such include the incineration of waste plastics as well as ammonia in fertilisers.

However, Kullmann, Linßen, and Stolten (2023) point out that most scenarios only consider decarbonisation rather than the substitution of fossil-based fuels or feedstock that is defossilisation. According to the authors, insufficient alternatives are proposed other than renewable hydrogen. This in consequence poses a challenge regarding the achievability of the aforementioned climate goals of the EU and beyond.

Electrification, the process of electrifying conventional sectors or processes is an essential lever for cutting carbon emissions and thus, the sustainable energy transition. Since electric appliances oftentimes exhibit greater efficiency than fossil alternatives as well as recently, more competitive production costs for renewable electricity sources, electrification constitutes one of the key concepts for the defossilisation and respective decarbonisation of the energy sector (European Parliament. Directorate General for Internal Policies of the Union. 2018; European Commission, Directorate-General for Energy 2022; Bloomberg Finance L.P. and BloombergNEF 2020).

There are two types of electrification that are direct and indirect electrification as illustrated in *Figure 9*.

- **Direct electrification** refers to electrifying processes via electric technologies such as heat pumps and BEVs.
- **Indirect electrification**, on the other hand, involves processes that exhibit the conversion of electrical energy to chemical energy. This involves intermediary synthetic or electro fuels that are based on, most prominently but not limited to, hydrogen (Schreyer et al. 2024).

In the understanding of Ramsebner et al. (2021), indirect electrification also includes power-to-heat (P2H) technologies like heat pumps as well as electric boilers, which is also applicable for district cooling (DC).

The latter becomes particularly important in sectors that are *hard to abate* or *hard to electrify* respectively such as industry, shipping and heavy duty road freight.
(Agora Energiewende 2019).

In this context, carbon-neutral energy carriers as well as other renewable forms of energy may provide complementary solutions and support the decarbonisation of these sectors. Particularly for high-temperature demanding industrial processes, renewable or emission-neutral gas can provide a feasible form of indirect electrification (European Parliament. Directorate General for Internal Policies of the Union. 2018).

Figure 9 illustrates the energy flow including direct electrification for the different sector coupling pathways. Chemical storage options for hydrogen and methane can enable the long term storage and possibility of feeding the gas into the existing gas grid. The process of re-electrification is possible at times of low availability, however, exhibits low efficiency (round trip efficiencies of below 40 %) and thus considerable losses (Ramsebner et al. 2021; Büchi et al. 2014).

.

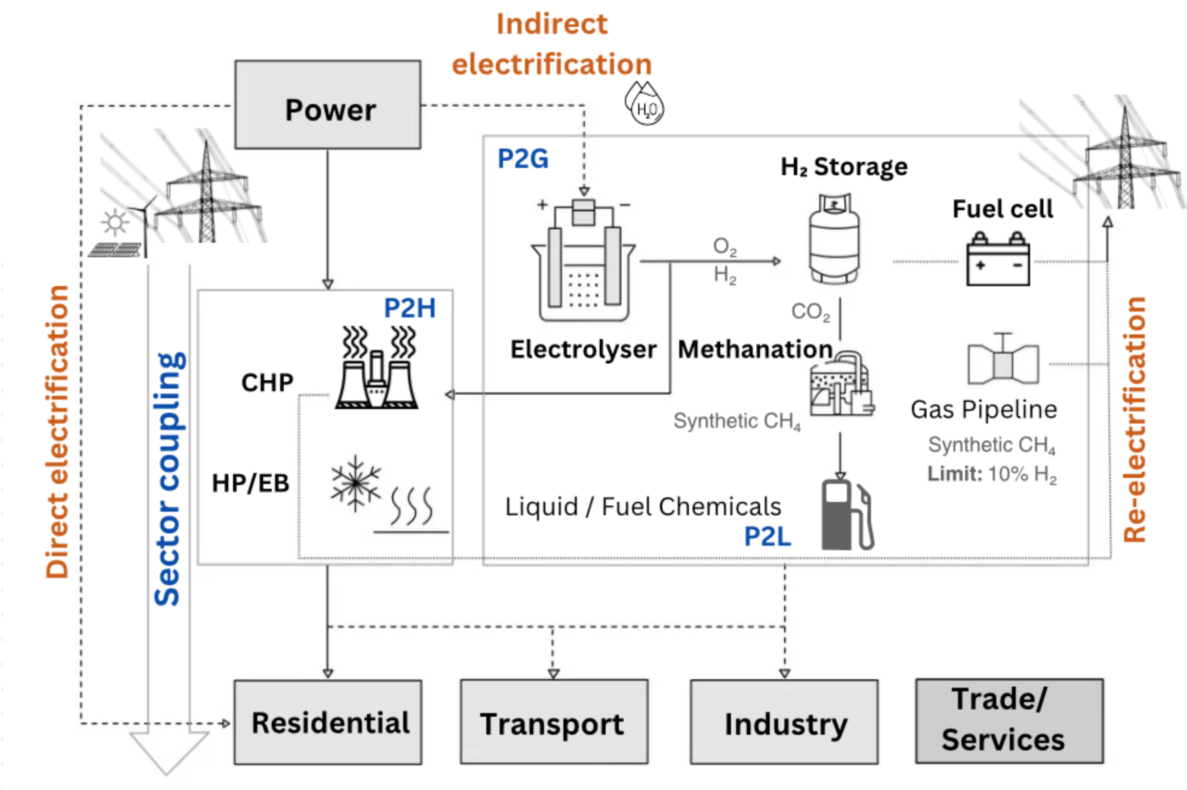

Figure 8: Comprehensive high-level overview of sector coupling pathways from a technological view (Source: based on Ramsebner et al. 2021, 18)

Reconversion scenarios with highest possible efficiencies in the first place can nonetheless achieve round trip efficiencies greater than 50%. With reference to Büchi et al. (2014), the direct conversion of hydrogen into electricity (G2P) is substantially more efficient as opposed to its further conversion into synthetic gas and respective combustion.

The hydrogen generated from this process may further be used for power-to-gas (P2G) technologies in sector coupling in the future, as examined in *Chapter 5*.

4. Energy Systems Integration

According to Ilo and Schultis (2022, 133), the defossilisation of the economy throughout all sectors is '*one of the most significant challenges of this century*' and thus, integrating the energy systems of the different economic sectors is considered the '*most suitable way to decarbonise them and reduce CO2 emissions*'.

This is further reflected in Ramsebner et al. (2021, 17) who mention an *'increased focus on the overall integration of power, heat, industry and mobility'*.

The Energy Systems Integration process '*coordinates the operation and planning of energy systems across multiple pathways and geographical scales to deliver reliable, cost-effective energy services with minimal impact on the environment'* (O'Malley et al. 2016, 6).

The maximisation of energy use, as well as minimisation of emissions and waste are underlying paradigms. With reference to a briefing paper from the *Imperial College London*,

> '*ESI could be a potentially cost-effective way to decarbonise the multiple facets of our energy sector, use limited resources in a sustainable way and produce a more resilient system by incorporating greater flexibility and diversifying energy sources'* (Hanna et al. 2018, 3).

ESI, per definition, encompasses the economy in its entirety, that is made up of the three main economic sectors: the primary, secondary and tertiary sector as elaborated in *Chapter 2* above.

Figure 10 depicts the integrated energy systems through sector coupling based on the holistic LINK-architecture by Ilo (2019, 20) which considers '*the entire power system from high, medium and low voltage levels, including plants and the market'* to facilitate '*the description of all power system operation processes'*.

The *LINK*-solution considers the optimisation within the power system as a whole '*by coordinating and adapting the locally optimised Links'* (Ilo and Schultis 2022, 60).

Sector coupling, according to the EC (2022), can be realised through the same principle regarding the optimisation of the power system and other systems. This is assessed in more detail in the subsequent *Chapter 5*.

The architecture allows for the formation of energy communities and sector coupling as it encompasses all the different components of the system, i.e. the market, grid, storage, customer plants and electricity producers and takes into consideration their respective relations.

If managed properly, sector coupling can further ameliorate the way ancillary services, i.e. services that ensure reliability and support the transmission of electricity from generation sites to customer loads (electrical appliances), are delivered and traded in the market.

Illustrated in the Figure are the different partially bi-directional conversion processes that are, inter alia, P2G and P2H/P2T which are examined in more detail in *Chapter 4*. It distinguishes between the producers and end users that are consumers and prosumers.

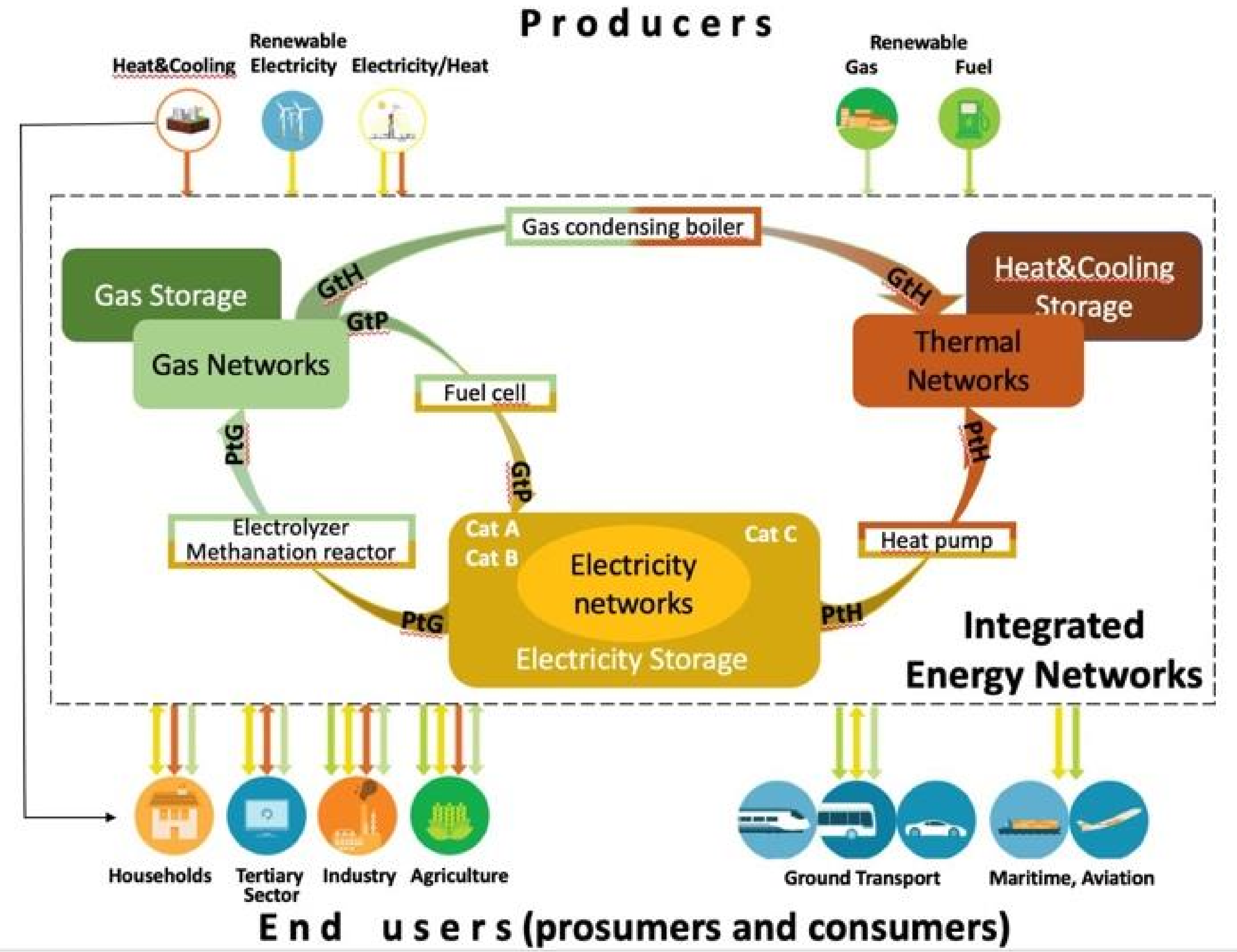

Figure 9: The integrated energy systems through sector coupling, as given by the holistic LINK-Solution (Source: European Commission. Directorate General for Energy. 2022, 33)

The *LINK*-solution comprises three main elements in its architecture that are the producers, including all sizes of energy production plants, the grids including transmission and distribution levels (TSOs and DSOs) and the storages, counting all storage sites notwithstanding technological development and size.

It further sets out three conversion stages that are categorised as initial, intermediate and final. The different stages are comprised as follows:

- In the **initial conversion stage**, the primary energy sources that include inter alia solar and wind are converted into the energy carriers i.e. electricity, heating or cooling. For this generation technologies like generators or CHP are utilised.
- For the **intermediate conversion stage**, the energy is converted between the different sources of energy in order to balance out the surplus electricity in the electricity grid. Coupling components, as examined in *Section 5.3.1*, represent the conversion technology that enables the coupling across vectors. This conversion process can be unidirectional or bidirectional when for instance, an electrolyser is combined with a fuel cell.
- The final conversion **stage** usually comprises the conversion with end-user appliances. In this stage, the energy is converted among the different energy sources such as heat for DH grids and electricity (European Commission. Directorate General for Energy. 2022).

Furthermore, ESI can be categorised in three ‘opportunity areas’ being: *Streamline, Synergise, and Empower*, determining how different ESI strategies can contribute to tackling climate change related problems (O’Malley et al. 2016).

In this context,

- ***Streamlining*** refers to improvements made within the existing energy system by leveraging institutional power and respective investments in the infrastructure.
- ***Synergising*** implies the process of connecting energy systems through ESI solutions.

- ***Empowering*** involves customer-related ESI actions like changes in energy consumption and shifting energy modes through investments in RES and participation in energy communities, as well active citizen involvement in the regulatory frameworks e.g. through citizen initiatives.

The *LINK*-architecture further derives that storage may no longer be seen as part of the power plant as it cannot be used to construe P2X processes (see *Section 5.1.3.* for more detail) but that is to be viewed as one of the new main components (Ilo and Schultis 2022). This aspect is explained in more detail in *Chapter 5, Section 1.3.* below.

5. Sector Coupling

This Chapter examines the necessary underlying concepts for sector coupling by providing the historical overview as well as status quo. Understanding the historical development is essential for a holistic understanding of where we stand today in the face of the renewable energy transition. Firstly, the historical overview of sector coupling is elaborated on including the relevant definitions, EU legislation and technical developments. Subsequently, the state of the art on sector coupling encompasses a thorough analysis of the opportunities and barriers.

5.1. Brief historical overview

While the concept of sector coupling is still rather new in application, dating back to the year 2017 in Germany, the concept finds its historical roots already in the early 19th century (Breeze 2018).

Underlying concepts like electrification and district heating historically go back a lot further which is elaborated in *Section 3.2*. This Section aims to illustrate the developments of sector coupling dynamics since their first mention up until today.

The term 'sector coupling' originates in Germany where it was first mentioned in 2013 regarding the electrification of end-use sectors such as heating and cooling in the course of the German energy transition, often referred to with the German term '*Energiewende'*. It subsequently gained popularity through the use in German ministries in 2017 (European Parliament. Directorate General for Internal Policies of the Union. 2018; Ramsebner et al. 2021).

Although there are many early applications of sector coupling in electricity generation like CHP plants dating back to the end of the 19th century (Breeze 2018), most approaches in the past involved fossil fuels, mainly oil, gas and coal rather than RES. This further reflects the ambiguity of definition that still exists today, as laid out by Ramsebner et al. (2021). This aspect is further discussed in *Chapter 7.*

Nonetheless, the knowledge of respective implementation of past applied concepts and deployed technologies like CHP may be taken as reference for the defossilisation in the 21st century.

5.1.1. Definitions

The *Oxford English Dictionary* (2023) defines the act of *coupling* as to '*connect, conjoin, or link one* [thing] *with another or together'*. This indicates an activeness of action also in the term sector coupling, indicating that the economic sectors are actively being conjoined (see also *Chapter 7, Conclusion*).

Regarding the scope of sectors, Ramsebner et al. (2021) recognise broad variations in definition of sectors throughout literature depending on the perspective of research. In line with the authors, for the scope of this work, the energy-economic (or techno-economic) approach is chosen, in comparison to a more technical approach based on the energy carriers that would include also heat or gas.

The chosen approach is more '*technology-neutral'* and '*allows for a broader range of solutions independently of the energy carrier applied'* as it sets out the classified through the end-consumption as the following:

- the **industrial sector**,
- the **trade and commerce sector**,
- the **transport sector**, and
- the **residential sector**, i.e. households and their appliances.

The residential sector does in this case include the heating demand of the households, as does the trade and commerce sector for heating in buildings.

The lack of a uniform definitions to this day for sector coupling as a concept constitutes a major problem regarding the implementation and analysis thereof, as observed by Ramsebner et al. (2021).

In the beginning, the term sector coupling was predominantly used to describe electrification of end-use sectors such as households, commerce and transportation, aimed at increasing the renewable energy share of the overall electricity supply. In recent years, the concept has been widened to the supply-side through emerging technologies like Power-to-Gas (P2G).

The European Parliament (2018, 8) defines sector coupling as

> *'a strategy to provide greater flexibility to the energy system so that decarbonisation can be achieved in a more cost-effective way'*.

Some literature like a major report published by *Bloomberg Finance* L.P. (2020), refer to sector coupling and electrification interchangeably. It has to be noted, however, that this understanding is not comprehensive as electrification is a mere part of sector coupling with other accompanying coupling processes such as methanation, electrolysis and storage.

Moreover, there are several mentions of 'sectorial integration' throughout literature, which as defined by the *Gas Infrastructure Europe* association, GIE (2019, 1), is '*the integration of different sectors across the energy system' (...)* where *'the aim is to make optimal use of the potential of each energy carrier across all sectors (...)'*.

In the understanding of GIE, the terms sector coupling and sector/sectorial integration are mutually used where affordability and energy supply security are key elements of the transition. For purposes of clarity, this Thesis exclusively uses the terminology sector coupling.

Sector coupling is usually categorised in *Cross-Vector Sector Coupling* and *End-Use* or *End-User Sector Coupling* which are explained in detail in the subsequent sections.

Figure 11 depicts an overview of the different options, as part of the *LINK*-solution.
It visualises the different storage links that are P2X pathways for the coupling across vectors, that are examined carefully under the subsequent *Section 5.1.3., Technical developments*.

End-use sector coupling involves the coupling of the different economic sectors like transport within the customer plant, i.e. with the end users that are consumers and prosumers. This is for the most part implemented through existing Power-to-Heating and Cooling technologies.

5.1.1.1. Cross-Vector Sector Coupling

Cross-vector sector coupling refers to the coupling across the different energy vectors, i.e. the integration of different energy carriers and vectors which can be supply- or demand-sided. This includes particularly the electricity, heat and gas as well as potentially in the future a hydrogen carrier. Cross-vector sector coupling can for instance be leveraged from electricity surplus conversion or using waste heat from industrial processes or power generation for district heating purposes, as well as through Power-to-Gas approaches.
Sector coupling across the different energy vectors helps to

> '*decarbonise the energy supply while ensuring system security and adequacy and enhancing the potential to utilise the available renewable energy and existing energy infrastructure in the most cost-effective way*'

(European Parliament. Directorate General for Internal Policies of the Union. 2018, 51).

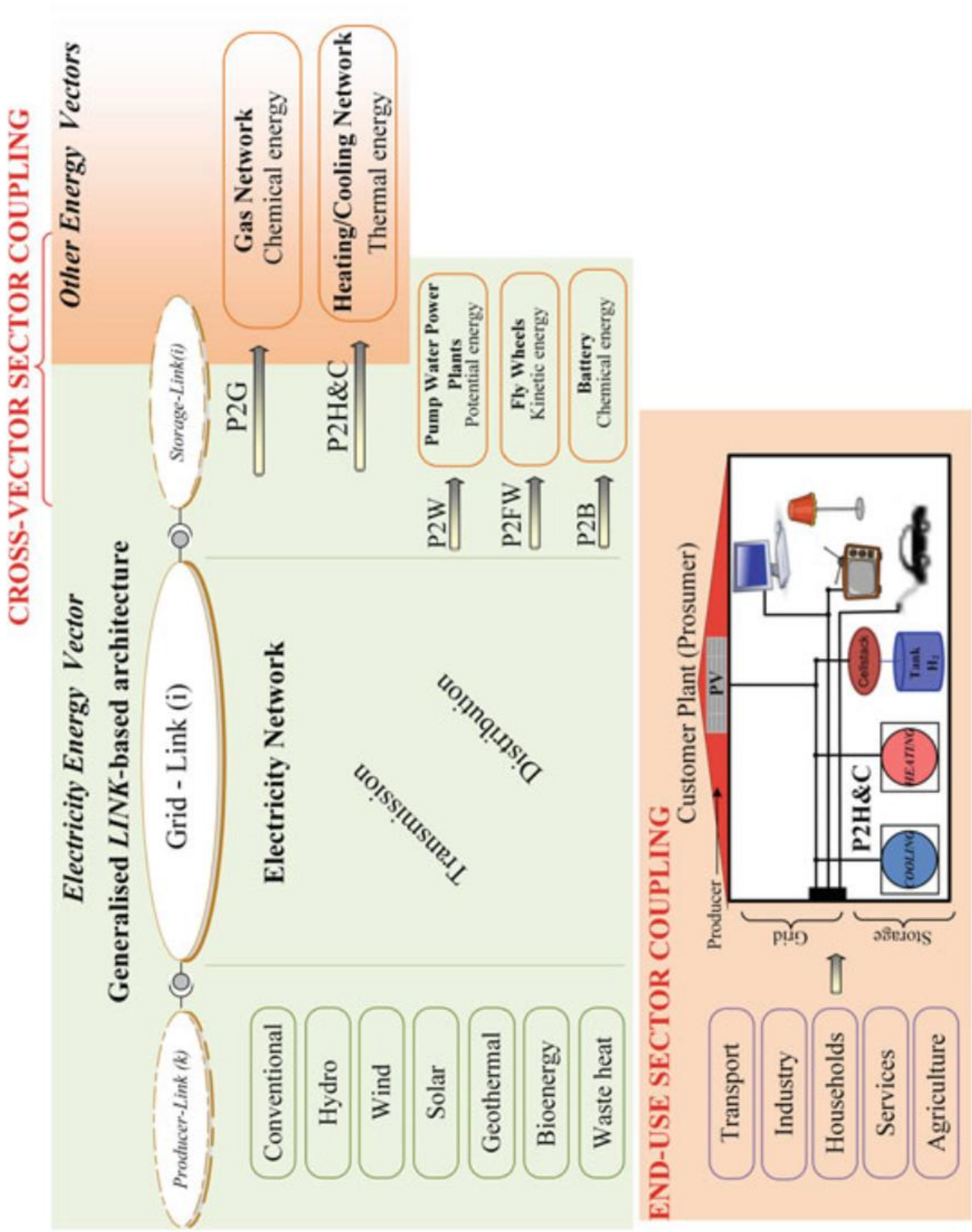

Figure 10: Cross-vector and end-use sector coupling embedded in the LINK-solution (Source: Ilo and Schultis 2022, 136)

5.1.1.2. End-User Sector Coupling

The latter, End-Use Sector Coupling, likewise includes the end users i.e. households and electrical appliances in its conception.

The European Parliament (2018, 7) refers to end-use sector coupling as the

> '*electrification of energy demand while reinforcing the interaction between electricity supply and end-use*'.

IRES penetration in the grid can according to this study conducted by the *Policy Department for Economic, Scientific and Quality of Life Policies* of the EP (2018) be increased through end-use sector coupling, by strengthened demand-supply interaction and growing electrification, facilitating system reliability and efficiency.
In accordance with Ilo and Schultis (2022, 152), end-user sector coupling '*contributes to the effective decarbonisation of all economic sectors*'.

The enabling technologies of sector coupling, often referred to as P2X technologies, are examined closely under *Section 5.1.3*.

5.1.2. EU Legislation

The starting point of EU legislation regarding energy and climate-related policies in recent years is the *European Green Deal* which was approved by the European Parliament on January 15, 2020. It is set to '*making the EU's economy sustainable*' by covering all economic sectors.
(European Commission 2019, 3).

Pictured in *Figure 12* is an overview of the different elements concluded by the Member States (MS) in the *Green Deal* in 2019.

A large part of the *Green Deal* is covered by the *Fit for 55* legislative package proposed by the EC, adopted on October 9, 2023.

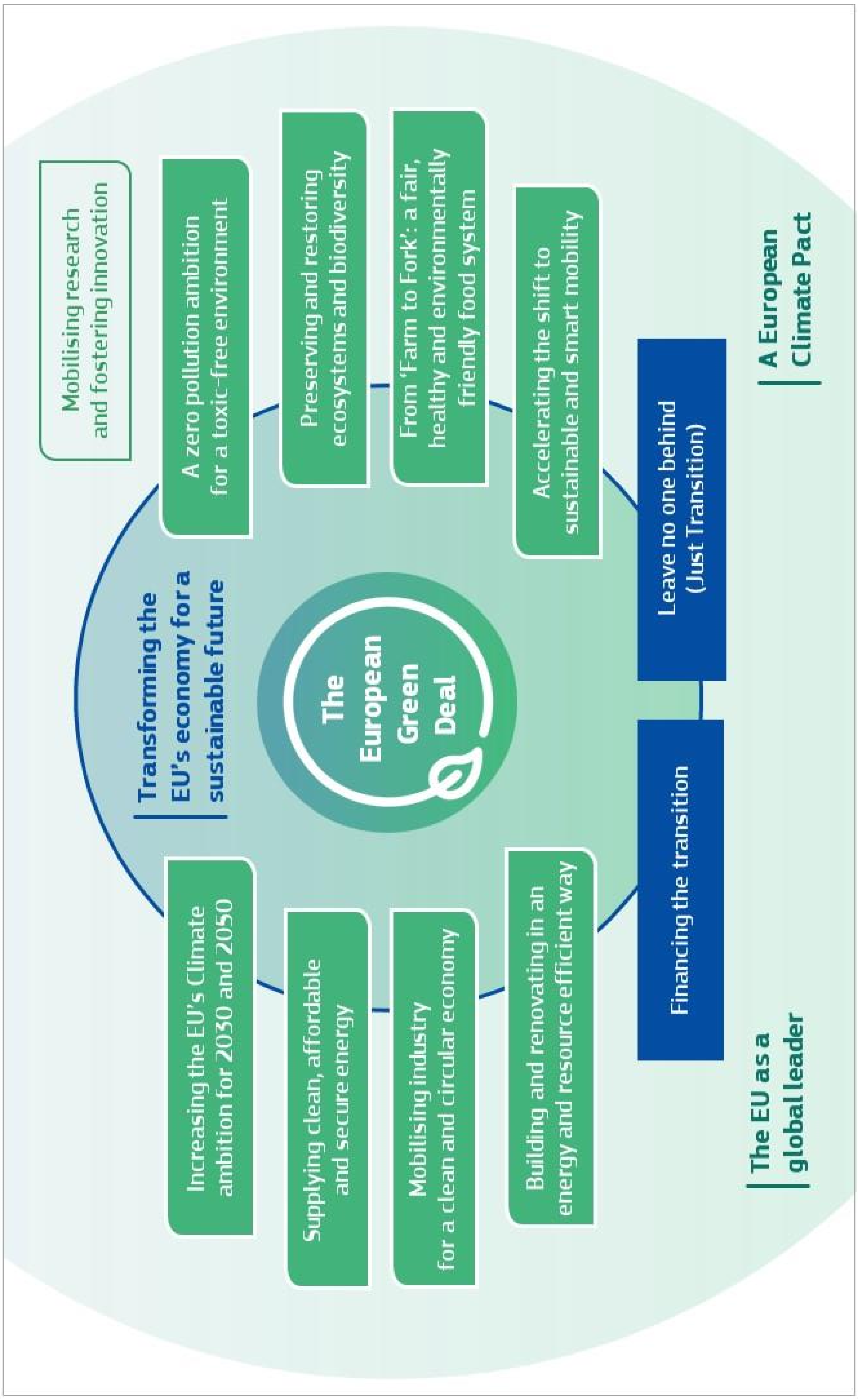

Figure 11: The European Green Deal (Source: European Commission 2019, 3)

The *European Climate Law, as part of the Fit for 55,* was adopted in July 2021 and obliges the EU to reduce net emissions by a minimum of 55% until the year 2030.
According to the EC (2022, 1), '*it sets the EU on a path to reach its climate targets in a fair, cost-effective and competitive way*'.

In terms of implementation of the ESI, the EU mentions several barriers, particularly in the field of cross-sector links to create a '*level playing field'* for the different energy carriers in competition. It is further necessary to facilitate a '*cost-effective decarbonisation'* of the EU economies by building a more decentralised and digitalised system which provides more flexibility to consumers. Since they different starting points and considering also different policies in place, the integration will likely take divergent in the different MS. These are partially reflected in their national climate and energy plans up to the year 2030 (European Commission, Directorate-General for Energy 2024).

Figure 13 underneath depicts the future energy system of the European Union as per the *Green Deal*, visualising the system's integration and decentralisation in a circular form. In line with the legal text thereof, it facilitates reduced costs by integrating circular economy consideration throughout the whole system.

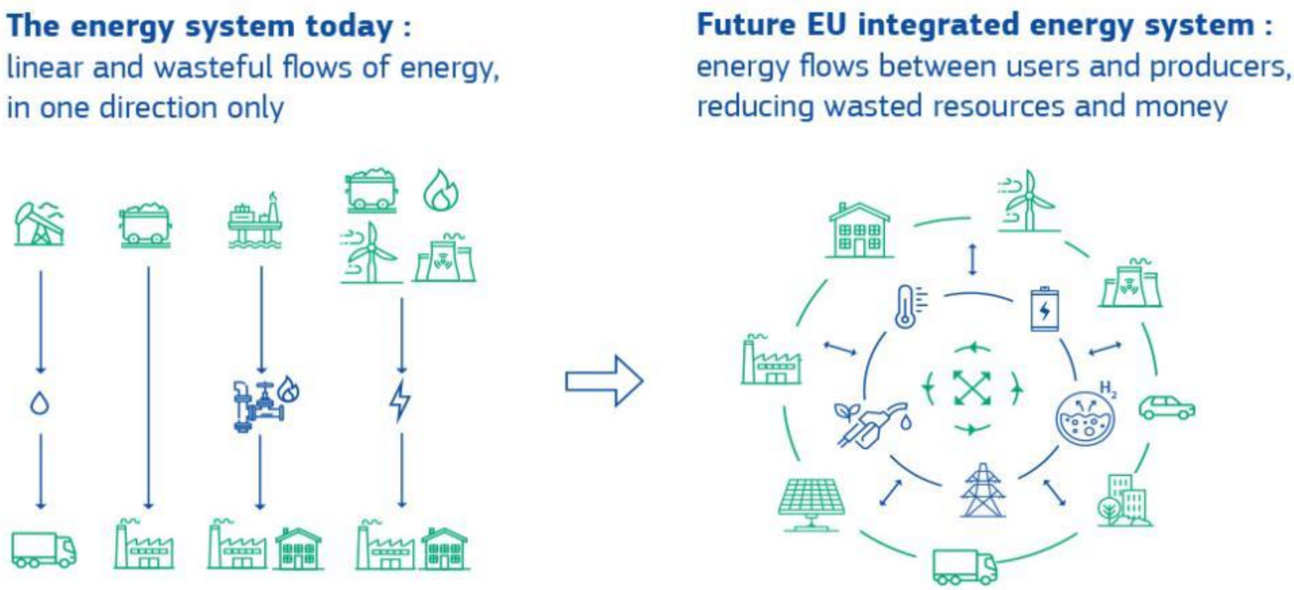

Figure 12: Energy System Integration (Source: European Commission, Directorate-General for Energy 2024)

The *Strategy for Energy System Integration* of the EU, together with the *EU Hydrogen Strategy* presented in Brussels in July 2020, are cornerstones for a future defossilised energy system in Europe. In synergy, they '*will pave the way towards a more efficient and interconnected energy sector*' (European Commission, Directorate-General for Energy 2020).

Comprised of 38 action points, and an additional clean energy investment agenda, the strategies aim to advance competitiveness, resilience and create European jobs.

The scope of this Thesis solely covers *Strategy for Energy System Integration* in more detail.

As part of the *EU Strategy for Energy System Integration*, three main pillars were identified.

- The **first pillar** aims at promoting '*a more "circular" energy system, with energy efficiency at its core'*.

  It includes specific actions to source energy locally and effectively, specifically mentioning waste heat from inter alia, industrial processes and wastewater treatment plants. Circularity regarding agricultural waste is named to be incentivised as well as the improvement of synergies between European energy infrastructure in the course of the revision of the *Trans-European Network in Energy Regulation.*

- The **second pillar** introduces more '*direct electrification of end-use sectors'*, implying end-use sector coupling. Heat pumps, EVs and electric furnaces are mentioned together with RES expansion.

- The **third and last pillar** of the strategy, emphasizes '*clean fuels, including renewable hydrogen and sustainable biofuels and biogas'*. This aspect is particularly relevant for hard-to-electrify sectors. Carbon capture, storage and use solutions are further mentioned in this regard.

The strategy on the integration is facilitated on the legal basis of the implementation of the eight legal act of the *Clean energy for all Europeans* package which was adopted in 2018 and 2019 (European Commission, Directorate-General for Energy 2024).

ENTSO-E's Vision towards 2030 (2019, 5) highlights the CEP as an '*important stepping stone towards a decarbonised energy system'* and recognises the change in public discourse away from *climate change* to *climate crisis.*

In their *Clean Energy for All-package*, the EU (2019) has identified 5 Energy Union Dimensions in 2019 which does not *per se* include sector coupling. It provides a framework for the MS and the EU to facilitate the synergies between the trajectories of national regulations as well as on the EU.

Figure 14 depicts the *Energy Union Dimensions* as contained in the CEP that includes a full integration of the energy market, energy security and energy efficiency. Regarding the dimension of the 'decarbonisation of the economy', the clarification of the usage of terminology can be found in *Section 3.3* of this Thesis.

The CEP sets out ambitious climate targets that comprise for instance 32,5% in energy efficiency of overall energy use with a particular emphasis on the energy output in the building sector, 32% in RES and a 40% reduction in GHG emissions by the year 2030. The package obliges the MS to draft National Energy and Climate Plans (NECP) for the years 2021 to 2030 that should further contain a strategy in line with the Paris Agreement until 2050.

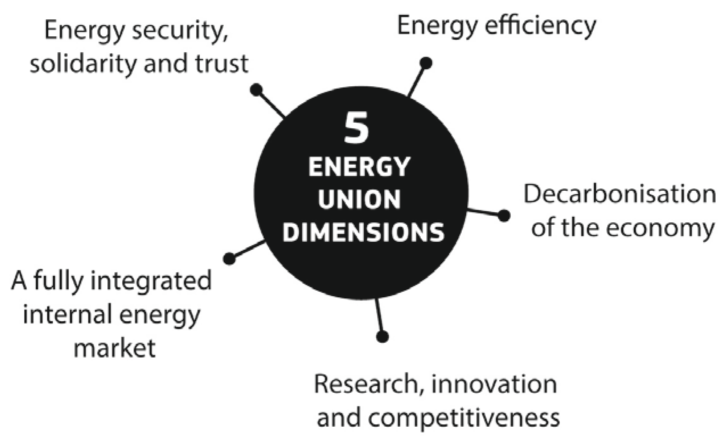

Figure 13: 5 Energy Union Dimensions (Source: European Commission. Directorate General for Energy. 2019, 11)

While it is aimed at empowering consumers and prosumers and their rights, it also introduces the creation of an EU DSO entity that strengthens the pan-EU coordination between TSOs and DSOs (European Commission. Directorate General for Energy. 2019; European Network of Transmission System Operators for Electricity 2019).

One major element included in the CEP is the reform of the European Emissions Trading System that included, inter alia, building and road transport fuels (European Commission. Directorate General for Communication. 2023).

In line with Schreyer et al. (2024, 234) the ETS '*is a key driver of power sector decarbonization'*, and a prerequisite for both direct and indirect electrification for emissions abatement. The EU ETS represents a cornerstone in combating climate change mitigation, that encompasses a comprehensive cap and trade system with the aim of decreasing emissions from GHG. The cap sets out emission allowances that decrease with the climate targets, the sale of allowances generates revenues for the selling country which feed into national budgets. It is currently in its fourth trading phase that spans from 2021 to 2030 (European Parliament 2024).

One project worth mentioning by the EU is the ITER ('International Thermonuclear Experimental Reactor') energy project located in the South of France where 35 nations are currently collaborating on the world's largest magnetic fusion apparatus. Its aim is to harness the potential of fusion and prove *'the feasibility of fusion as a large-scale and carbon-free source of energy'* (European Commission. Directorate General for Energy. 2019, 15).

According to the operators, it has already made a positive impact in Europe regarding job creation and international corporate energy partnerships.

In response to the Russian invasion of Ukraine in February 2022, the Commission presented a plan to reduce energy dependence, from Russian fossil fuels. The *REPowerEU* plan intends to accelerate the diversification of energy imports, substitute fossil fuels by scaling up inter alia, biomethane and frontload energy savings and electrification.

It sets out new targets regarding reduced energy consumption by an additional 13% and increased renewable energies share of 45 instead of 40% by 2030. In line with the Commission, the NECPs play a key role in the framework of fossil fuel reduction through investment planning and investor confidence. The plan mentions smart investments to facilitate timely innovation on the EU level.

Moreover, *RePowerEU* contains a proposal for the establishment of a EU Energy Platform for the voluntary common purchase of gas, LNG and hydrogen as well as an EU Solar Industry Alliance (European Commission, Directorate-General for Energy 2022).

Figure 15 visualises its ambitions, as included in the official communication of the EC. Despite some specific studies conducted, inter alia by the DG energy, no specific policy on sector coupling of the EU exists up to this day. This constitutes a major gap as it hinders the way for according regional policies to be set in place.

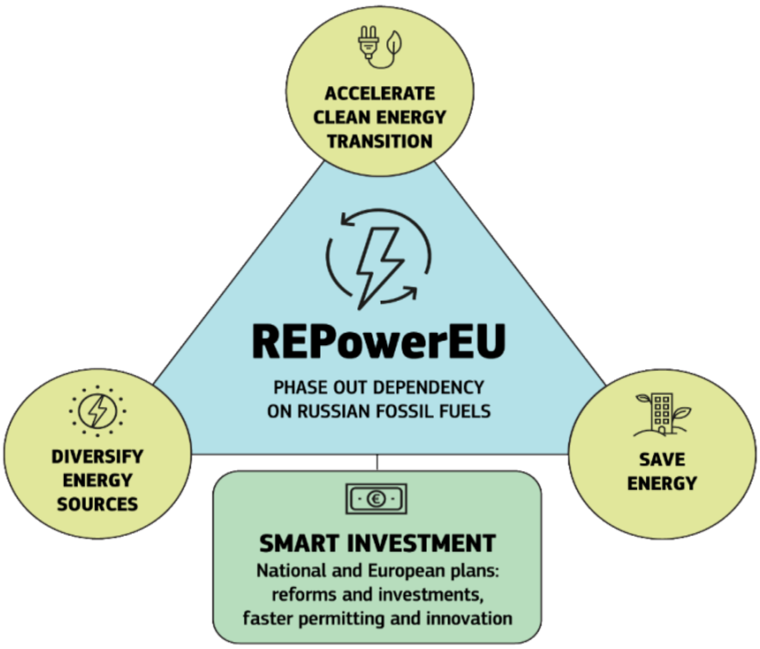

Figure 14: RePowerEU plan (Source: European Commission, Directorate-General for Energy 2022, 1)

5.1.3. Technical developments

Sector coupling is based on the different P2X technologies, some of which exhibit higher defossilisation and decarbonisation potential than others. In literature, they are usually divided either according to the form of energy that is converted, i.e. according to the energy sector or according to purpose of use. The former includes the classification of power-to-gas (P2G), power-to-liquid (P2L) and power-to-heat (P2H) whereas the latter implies power-to-power (P2P), power-to-mobility (P2M) and power-to-fuel (P2F) (Brauner 2022).

In accordance with the classification by Ramsebner et al. (2021), this Thesis follows the former style of classification in accordance with the energy sector.

Figure 16 depicts an overview of the different power-to-x pathways that are classified in the subsequent sections.

Storage management plays an important role when assessing the different energy conversion technologies for sector coupling.

Due to extended research and developments in storage solutions, surpluses in times of high renewable energy availability may be stored and utilised in other sectors. These P2X pathways make it necessary to view storage as an own, key component within the architecture of the power and energy system rather than part of the electricity plants.

The categorisation of the different storage-links is reflected in Ilo and Schultis (2022, 137) as follows:

- Under the Category A (Cat. A) storage-links, the stored energy is fed back into the grid at the charging point. Examples include stationary batteries and hydroelectric storage.
- Category B (Cat B.) is exemplified by P2G as well as batteries of electric cars (EVs), where the stored energy is not injected back at the charging point.
- Category C (Cat C.) refers to stored energy that reduces the power consumption at the charging point. Examples include DH and DC systems i.e. '*consuming devices with energy storage potential*'.

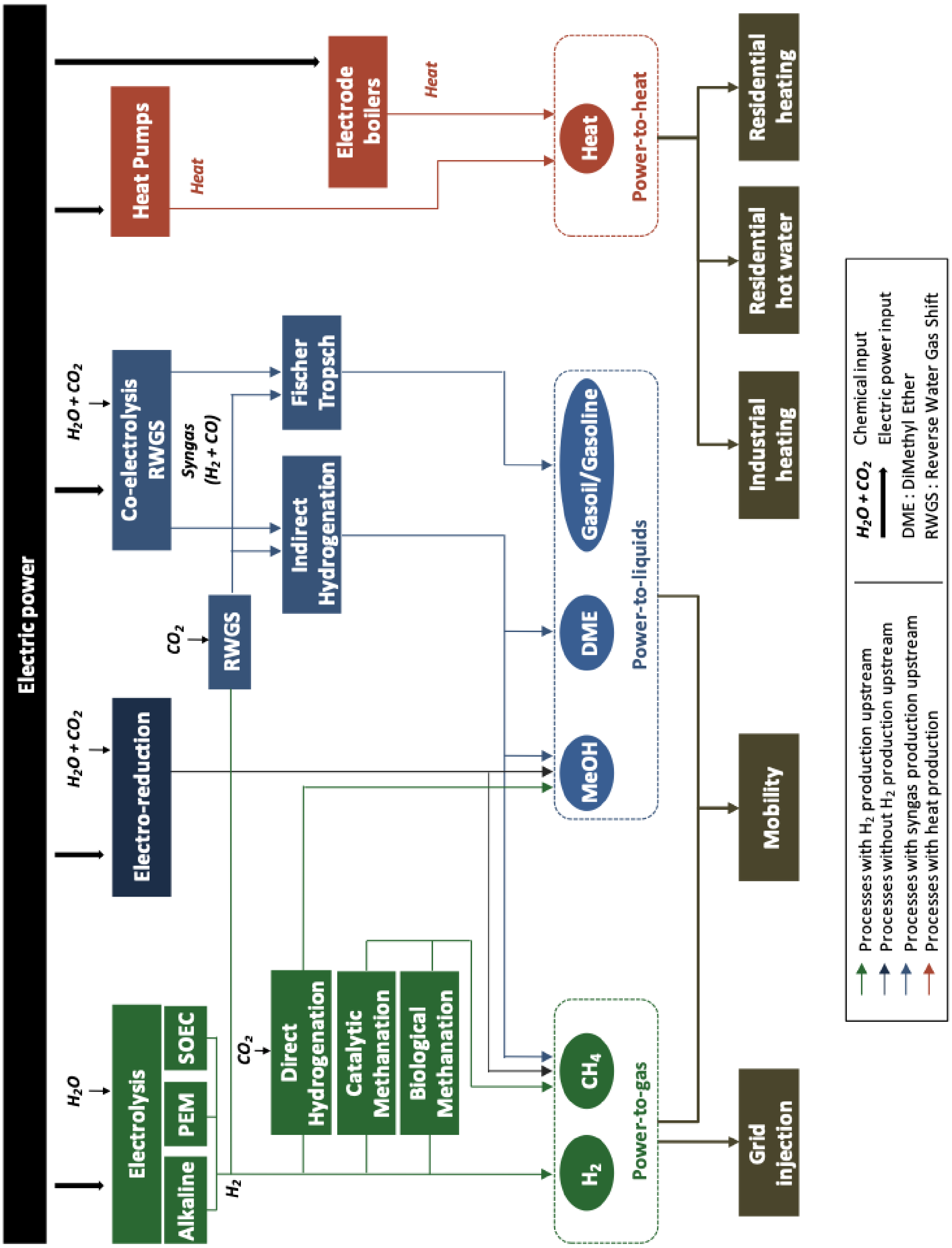

Figure 15: Power-to-gas, power-to-liquids and power-to-heat routes and their energy markets (Source: Enea consulting 2016, 9; as seen in Lewandowska-Bernat and Desideri 2018)

The households, i.e. electricity customers have furthermore changed their role when it comes to production and storage, as they may nowadays own grids, production and storage devices like PV panels and batteries. In line with the authors (2022, 51), prosumers may '*be perceived as virtual vertically integrated utilities'* (see definition above) as they are able to store surpluses via HC devices or Power-to-Thermal.

A further distinction is drawn between the coupling components and coupling processes. Sadeghian et al. (2022, 8) define coupling components as '*conversion systems'* that '*relate to different energy carriers to efficiently use the energy sources.'*

The processes include for instance electrolysis and methanation. The figure below provides an overview of each of the former and latter. Coupling components include, inter alia, generators, PV cells, fuel cells and pumps whereas the coupling processes refer to the conversion of energy from one sector to another.

It can therefore be drawn that with the components, the coupling processes are realised.

Illustrated in *Figure 17* are the different components or links of the architecture that are producer, grid and storage and the corresponding energy carriers as well as coupling components that, from the grid and storage link, finally lead to consumption.

Heat pumps enable the coupling through P2H, while gas condensing boilers (G2H) and CHPs couple gas and heating sectors with the power grid.

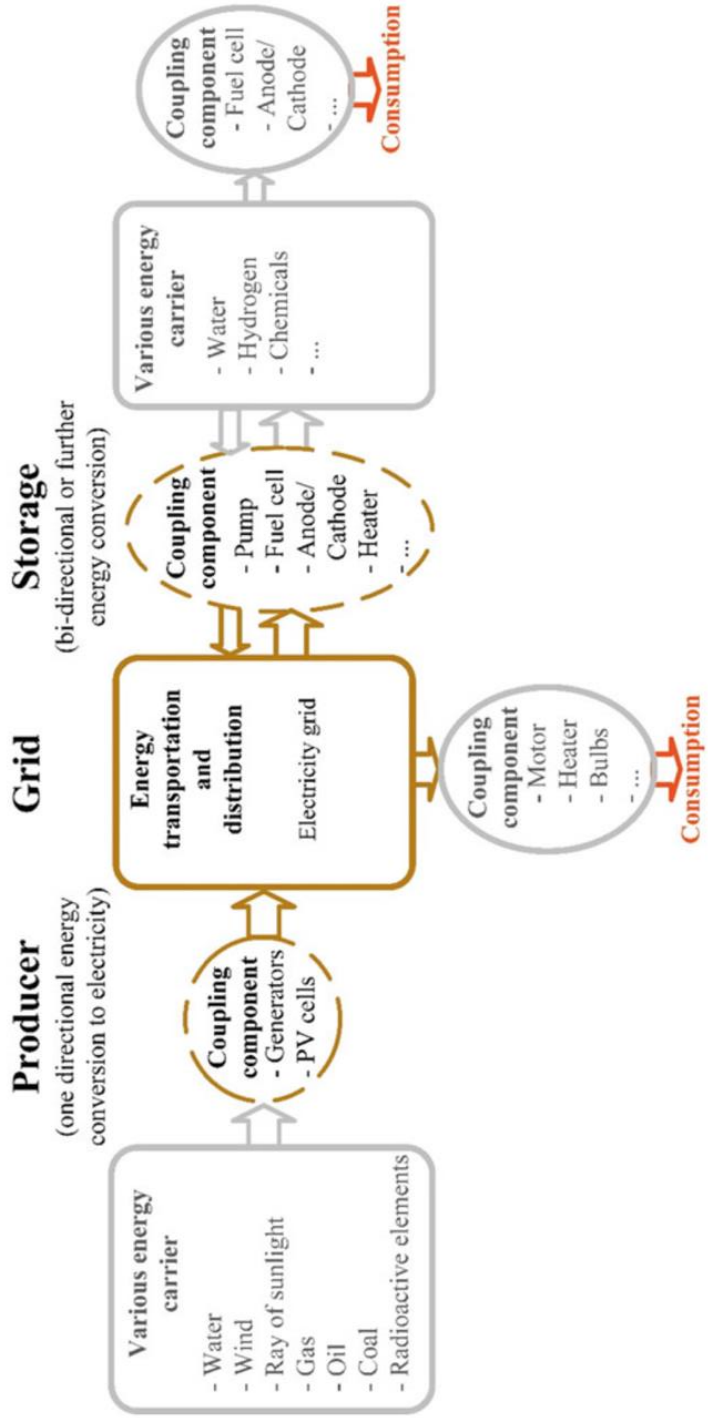

Figure 16: Overview of the energy carriers and means of transport used in the energy conversion process (Source: Ilo and Schultis 2022, 53)

5.1.3.1. Power-to-Heat

Power-to-Heat can be generated either directly through heating rods or electrode boilers, or more commonly, indirectly with the utilisation of heat pumps.
Depending on the interpretation, P2H can also entail Power-to-Cold (P2C), as is the case for this Thesis.

With regard to Brauner (2022), P2H is a *'cost-effective and flexible way to use renewable surplus energy in the heating sector of buildings and industry'*.

P2H on a central level implies district heating, whereas decentralised entails the direct energy consumption on site. The latter is also possible for small-scale applications. Centralised P2H applications utilise either sizable heat pumps and geothermal (ground-sourced heat), excess thermal energy or brine. Another option involves the use of electric boilers, usually electrode boilers for centralised P2H. Decentralised P2H options generally include the same options, however on smaller scale. Heat pumps for decentralised approaches source air or ground-heat whereas the electric heating elements in boilers, other than fully electric boilers are often fuelled by natural gas. These are sometimes mentioned as 'hybrid heating' approaches, i.e. a heating system based on water, with a gas-fuelled boiler and supplementary electric element (Bloess, Schill, and Zerrahn 2018).

Generally, heat pumps exhibit higher efficiencies than electrode boilers. There are compression and absorption heat pumps that convert low-temperature heat sources to higher temperature levels. They usually function both ways, i.e. for the purpose of cooling. In accordance with the Danish Energy Agency (2024), compression heat pumps in particular, demonstrate high efficiency with heat output that is three to five times higher than the electricity input. Electric boilers exhibit lower investment costs than heat pumps and generate heat similarly to conventional gas or oil boiler systems. Electrode boilers for more extensive applications can be connected seamlessly to the grid, however, at lower efficiency than the utilisation of heat pumps (Bloess, Schill, and Zerrahn 2018).

Figure 18 demonstrates the different P2H options for the residential sector and buildings overall. It shows the difference in centralised and decentralised choices, ranging from heat pumps and electric boilers that are classified as resistive to direct heating and heating involving Thermal Energy Storage (TES).

The former, centralised concepts, encompass the conversion of electricity into heat at a location different to the location of actual heat demand where DH networks are deployed for distribution of heat. The latter, decentralised P2H concepts utilise the generated heat on site or nearby the point of heat demand. Bloess, Schill, and Zerrahn (2018) lay out, however, that these lines are *in realita* intertwined.

Moreover, the authors distinguish between P2H options that exhibit TES capacities and those that do not. The latter is referred to as direct heating. In general, centralised heating approaches involve some extent of TES, depending mainly on the size of storage capacity, whereas decentralised options do not necessarily feature any.

To avoid confusion regarding the terminology in this context, it has to be mentioned that some literature, e.g. Hu et al. (2020) utilise P2H for Power-to-Hydrogen, which in the frame of this Thesis is included in the subsequent points that are P2G and P2L approaches.

5.1.3.2. Power-to-Gas

Power-to-Gas usually involves hydrogen that is produced through electrolysis from renewable electricity sources, which can in return be stored as a gas. The gas can in times of low availability either be re-converted (re-electrification) to electricity with a lower efficiency or be directly fed into the conventional gas grid with a share of up to 10%. Other sub-forms of P2G technologies are constitute inter alia, Power-to-Syngas which involves synthetic methane.

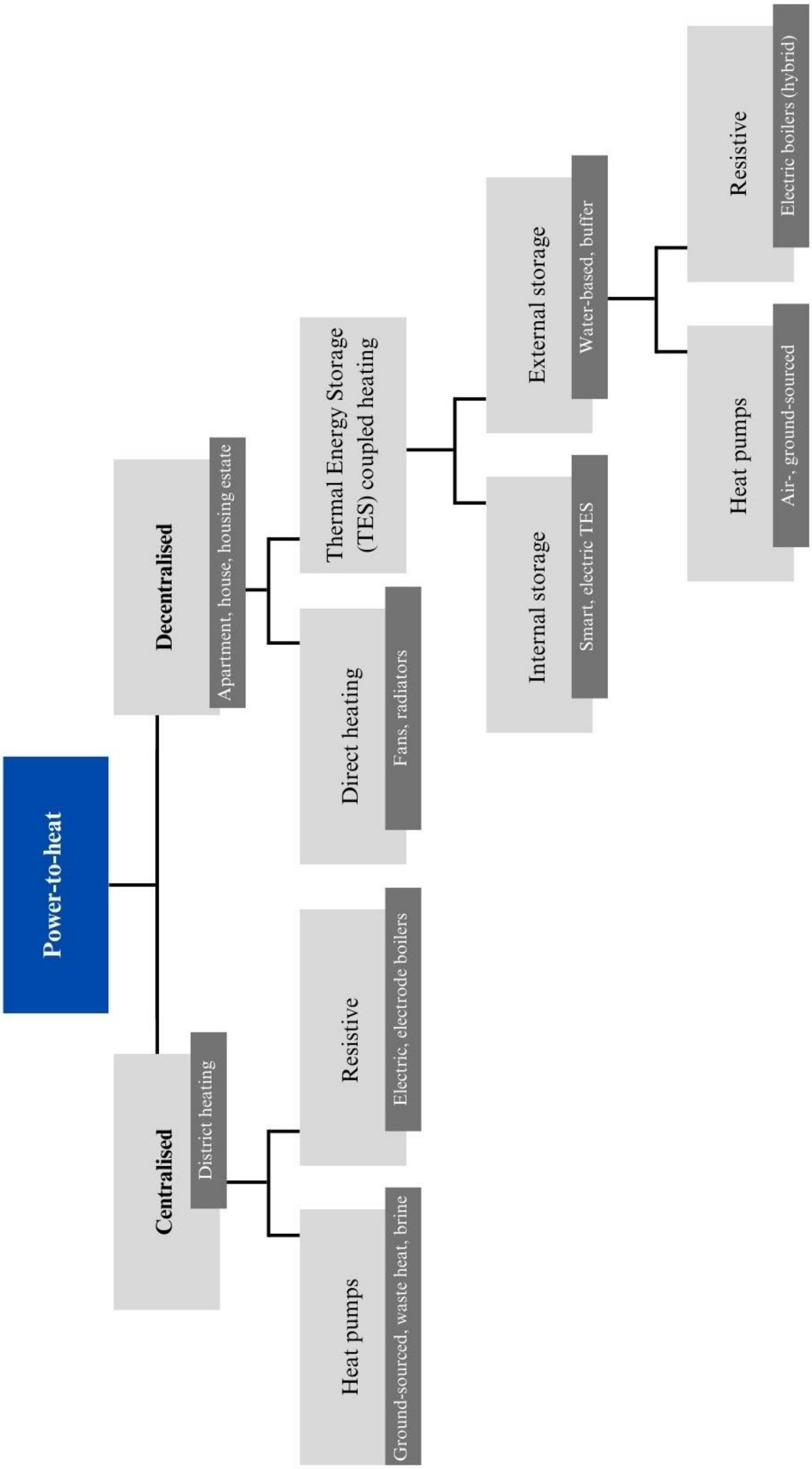

Figure 17: Overview of residential P2H options (Source: Based on Bloess, Schill, and Zerrahn 2018, 1612)

With regard to recent figures by the *International Energy Agency*, roughly 62% of hydrogen are produced globally from natural gas without Carbon Capture Utilisation and Storage applications (CCUS), seconded by coal with 21%. The remaining 16% can be ascribed to 'by-product hydrogen' production, for instance at refineries and the petrochemical industry in the form of hydrocracking and desulphurisation (International Energy Agency 2023).

These figures demonstrate the unabated use of fossil fuels in the global hydrogen production which constitutes a problem as they seem to respond to global energy trends rather than renewable energy policies.

The uptake of hydrogen for new applications like in heavy industry and alternative fuels, as well as electricity storage and generation on the other hand, only ascribes for roughly 0.1% despite projected increases through growing RES penetration.

As per the IEA (2023, 21), this share is a '*key for the clean energy transition'* and demonstrates that '*growth [in hydrogen demand] has had no benefit for climate change mitigation purposes'*.

Nonetheless, the Net Zero Emissions by 2050 Scenario by the IEA project annual hydrogen use growth by 6% until 2030, of which 40% would be accounting for such new applications.

Referring to Ramsebner et al. (2021), electrolysers achieve efficiencies between 60 to 81% depending on the load and type of technology.

Methanation as a process may be applied in order to further convert hydrogen together with a carbon dioxide source into methane i.e. liquid synfuels. This is especially useful as methane may directly substitute natural gas and can be fed into the existing gas grid, whereas hydrogen, in dependence of on-site technical conditions, may only be fed into to up to a certain amount.

5.1.3.3. Power-to-Liquid

Power-to-Liquid entails the liquefication of hydrocarbons (HCs) that can be gases for easier transportation as well as the generation of electrolytic hydrogen. P2G and P2L technologies enable the coupling of the power sector with the gas, mobility and heating sectors. Furthermore, they make long-term storage of renewable gas and liquids possible, in earlier conventional gas and oil storages as well as electrochemical storage sites (Brauner 2022).

Regarding the sequence of processes, it can thus be inferred, that as a first step the electricity is converted into gas and then for easier transportation, transformed into liquid form, highlighting the interdependence of the different coupling processes.

Some literature refers to specific P2L procedures as Power-to-Fuel (P2F), however, Ridjan, Mathiesen, and Connolly (2016) caution about potential misinterpretation as the term P2F is utilised for both synthetic and electrofuels despite having entirely different generation processes. Synfuels are generally subject to the Fischer-Tropsch synthesis[1], whereas e-fuels are characterised by 'a high share of electricity in the production process', as in the production of hydrogen or methanol by electrolysis.

Renewability in the former term should in line with the authors only be utilised when '*electricity and carbon are obtained from renewable energy sources*' (Ridjan, Mathiesen, and Connolly 2016, 3718).

For the latter, fuels from renewable feedstock should be distinguished according to Ridjan, Mathiesen, and Connolly (2016, 3717) from '*fossil synthetic fuels'*. For processes which generate fuel from emissions, they are considered 'renewable' since it exhibits a closed emissions loop.

[1] The Fischer-Tropsch synthesis is a catalytic process for converting syngas (CO and H2) into a petroleum-like product termed as FT crude readily upgradable into a wide range of transportation grade liquid hydrocarbons (ETIP Bioenergy 2021).

5.2. State of the Art

As per IRENA, we are currently experiencing the '*renewable energy era'*. (IRENA, IEA, and REN21 2018).

Nonetheless, as already established under *5.1.2.,* there is a distinct lack of legislation or enabling policies. While sector coupling is not yet applied on a broad scale in Europe, there are some ongoing projects like the FEDECOM partnership with pilots in Switzerland, Spain and the Benelux region across European energy communities (Fedecom Project 2022).

Since this Thesis follows a holistic approach and for reasons of scope, the ongoing European projects are not assessed in further detail. This Section tries to summarise the different opportunities and advantages sector coupling brings, as well as corresponding barriers or bottlenecks.

5.2.1. Opportunities

This Section aims to explore the opportunities there are regarding sector coupling approaches, distinguished in technical, market-oriented, socio-economic and environmental.

Figure 19 provides an overview of the classification and contained elements thereof.

5.2.1.1. Technical

Increasing the VRE sources in any energy mix can serve as an effective stepping stone for defossilisation. By definition, the understanding of sector coupling involves for one the substitution of fossil-based fuels with RES *(see Section 3.1.)*.

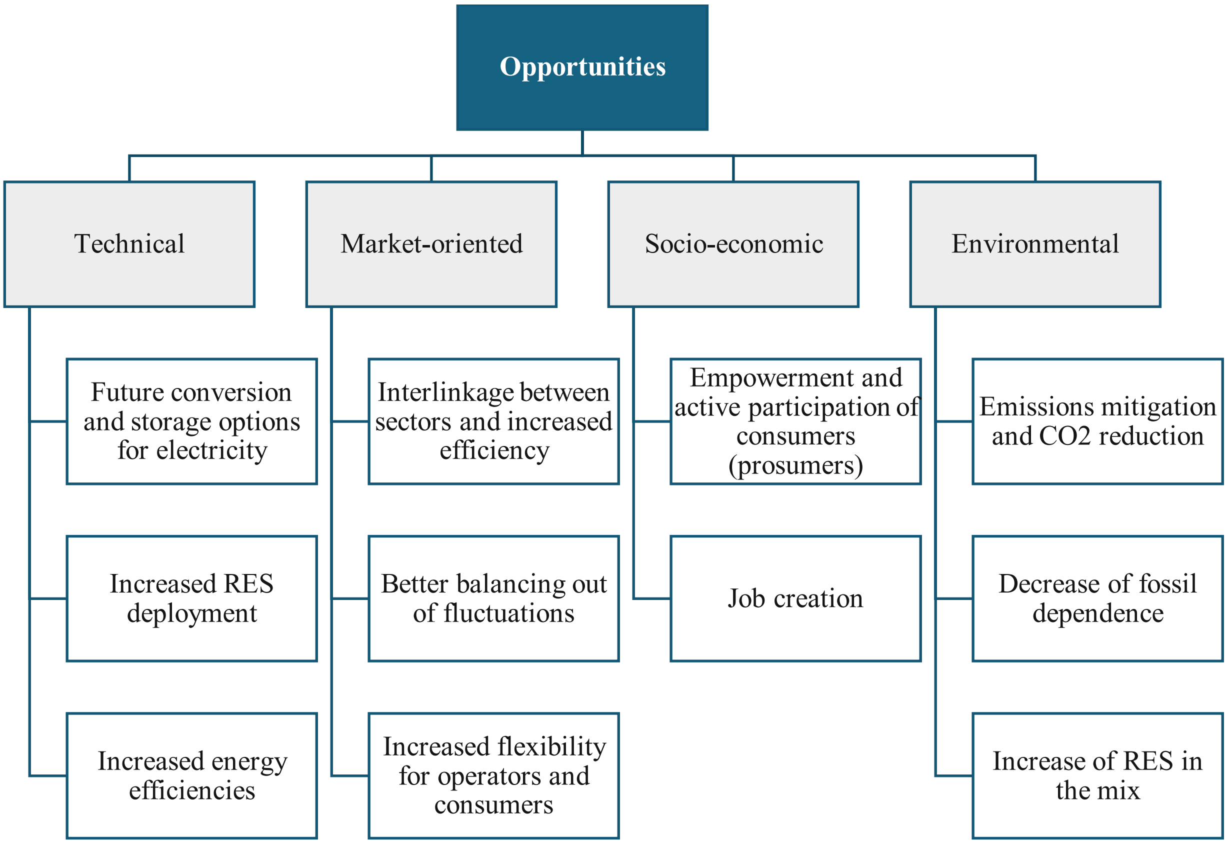

Figure 18: Overview of the opportunities for sector coupling

In order to meet the climate goals in the middle- and long term, the defossilisation of the space heating sector is as crucial as it is of the power sector. As per the European Parliament (2018, 15), coupling between the electricy, gas and heating sector '*can serve as an additional source of energy system flexibility and security of energy supply'*.

The study by the EP finds that sector coupling holds particular potential for the defossilisation of the heat demand in buildings, that can be residential as well as industrial and commercial. Furthermore, electric appliances oftentimes exhibit greater efficiencies than fossil-fuelled options.

This is further reflected in Bloess et al. (2018, 1623) who declare the '*flexible coupling of power and heat sectors appears to be a promising strategy*' to simultaneously meet the required additional flexibility of integration of RES by leveraging the different P2H technologies.

It is therefore of increased importance for future energy systems which may progress defossilisation and support increased integration of VREs when they are abundantly available.

The authors mention the need for a substantial expansion of the P2H industry to reach the high level of deployment in the future in line with the climate targets. Despite P2H technologies like heat pumps still holding a comparably small share in the heating sector, thanks to more stringent regulatory requirements on energy standards and more directed supporting efforts, their share is growing continuously. One specific field of opportunity for sector coupling is the potential of CHP systems, by utilising waste heat for applications such as district heating, industrial processes like paper manufacturing or for hot water. As common heat engines that convert combustion heat into electricity exhibit efficiency of a maximum of 60%, the remaining 40% are waste in the form of heat, constituting great potential for wide-spread application (Bloess, Schill, and Zerrahn 2018).

Regarding the gas sector, as well as fuels in the transport sector, hydrogen and hydrogen-derived fuels have the potential to pose an alternative in future new applications. According to IRENA and the IEA (2018), P2G technologies can be advantageous, considering the extensive gas infrastructure in Europe. Renewable gases like green hydrogen could potentially substitute fossil carriers in end-use electrical appliances. The *World Hydrogen Review* by IRENA (2022, 18) identifies low-emission hydrogen as *'a vital driver of the clean energy transition'*.

Furthermore, storing electricity in the form of gas (P2G) can be a powerful means to balance out seasonal fluctuations in RES availability and demand, and can provide flexibility to the consumers. Further applications include the utilisation of renewable gases in fuel cells as well as gas-fired power plants, as '*low-carbon back-up capacity'* in times of low RES availability (European Parliament. Directorate General for Internal Policies of the Union. 2018, 8).

5.2.1.2. Market-oriented

Market pricing of electricity and other commodities constitute an essential regard for successful sector coupling strategies. Adjusted market structures through demand driven programs can raise the flexibility of choice favouring the substitution of renewable energy carriers while at the same time guaranteeing price stability and decreased risks due to more linkage (Ramsebner et al. 2021; Khajeh, Shafie-khah, and Laaksonen 2020).

According to the EU, multiple studies show that the deployment of sector coupling can be a powerful lever to decrease the costs of the energy transition overall (European Parliament. Directorate General for Internal Policies of the Union. 2018).

The advantage is that it can be applied on a centralised level with large-scale integration as well as on a decentralised level i.e. closer to the location of power consumption. These two are not mutually exclusive, leaving many opportunities in terms of governmental and directed implementation (Ramsebner et al. 2021).

Since smart grids exhibit great potential in terms of enhanced coordination, flexibility through demand response, the enhancement of energy storage systems and the integration of decentralised resources. While they are not technically a prerequisite for sector coupling, they hold great complementary opportunities for the electricity market together with sector coupling. With intelligent planning and monitoring of the grid and its operations, fluctuations from RES can be better anticipated and acted upon accordingly by the DSOs (Brauner 2022; IRENA, IEA, and REN21 2018).

One area of opportunity is reflected in the fact that recently, the cost of RES for electricity has become increasingly competitive with conventional i.e. fossil energy sources. Hence, improvements in energy efficiency through increased deployment of electric end-uses from RES can be achieved through sector coupling. Regarding end-uses that are hard to electrify, the European Parliament (2018, 7) suggests '*other renewable or carbon-neutral energy vectors*' to '*provide a complementary solution*'.

5.2.1.3. Socio-economic

From a socio-economic perspective, sector coupling exhibits the ability to significantly decrease the cost of the renewable energy transition mainly due to the fact that RES are in nature, abundant and free (European Commission. Directorate General for Energy. 2022).

Furthermore, the energy transition as we experience it now can contribute drastically to the creation of new jobs as new specific skillsets will be in high demand. The ITER project located in the South of France, is an energy research project funded by the EU, with the aim to build the largest tokamak, i.e. a magnetic fusion reactor for low/zero-carbon energy production. According to the *Clean Energy for All-* Report, it '*already has a clear positive impact in making Europe more competitive*' and harnesses partnerships between different sized companies from 35 different nations (European Commission. Directorate General for Energy. 2019).

The CEP (2019, 5) mentions some 400.000 additional jobs to be created related to the energy efficiency sector and 900.000 overall in clean energy. The package furthermore includes a plan to actively strengthen consumers and their rights, for example through greater transparency in energy billing, more flexibility in the choice of energy supplier and less bureaucracy.

5.2.1.4. Environmental

The environmental benefits or opportunities of sector coupling, when implemented effectively, are numerous. Referring to the European Parliament (2018), it can lead to CO2 reductions across the various sectors, particularly through the integration of renewable energy generation. This way, the fossil dependence and dependence of energy imports can be drastically reduced. This aspect is particularly important given the recent crisis Europe has seen caused by the Russian invasion of Ukraine in February 2022 (European Commission, Directorate-General for Energy 2022).

As laid out in the *RePowerEU Package (2022),* decreasing overall energy consumption as well as decoupling from fossil fuels is an important aspect in overcoming the energy crisis Europe is partially still facing. Some sector coupling technologies like the abovementioned heat pumps exhibit high efficiencies which in return, lead to lower end consumption. Since the surpluses and downphases can be handled better, seasonal fluctuations of energy may be balanced better, thus ensuring security of supply.

Sector coupling further ensures efficient use of the energy infrastructure, which in consequence maximises the efficiency of each energy vector on its own. By defossilising the energy system, sector coupling may substantially contribute to the renewable energy transition. The VREs harness renewable energy that can be solar, (geo-)thermal, wind and hydro as well as from biomass. Through this increased deployment of renewable energy sources, less energy in return needs to be imported which contributes highly to mitigation of emissions. The sectors of heating and transport are particularly well suited for sector coupling, utilising among others, heat pumps and BEVs. A combination of liquid hydrogen and other synthetic fuels may be suitable solutions for heavy-duty transport, especially for road freight transport, aviation and maritime shipping in line with the EP (2018). This, despite large uncertainty due to technical developments, provides a particularly substantial area of opportunity as the transport sector constitutes one of the largest CO2 emitters.

Non-electrifiable or difficult-to-electrify sectors like the chemical industry can according to future scenarios be defossilised to an extent where they do not rely on fossil sources anymore (Kullmann, Linßen, and Stolten 2023).

This would however, in return require the according policies to be in place, which is elaborated on in the following Section, *Barriers*.

5.2.2. Barriers

When looking at the status quo and current developments, it can be derived that there are various barriers and challenges regarding sector coupling.

The research and technology gaps need to be resolved in order to deploy sector coupling solutions successfully. Furthermore, Ramsebner et al. (2021) mention competition among the different technologies which constitutes a barrier regarding their complementary and supplementary nature.

Figure 20 provides an overview of said barriers, classified from a technical, market-oriented, socio-economic and environmental perspective.

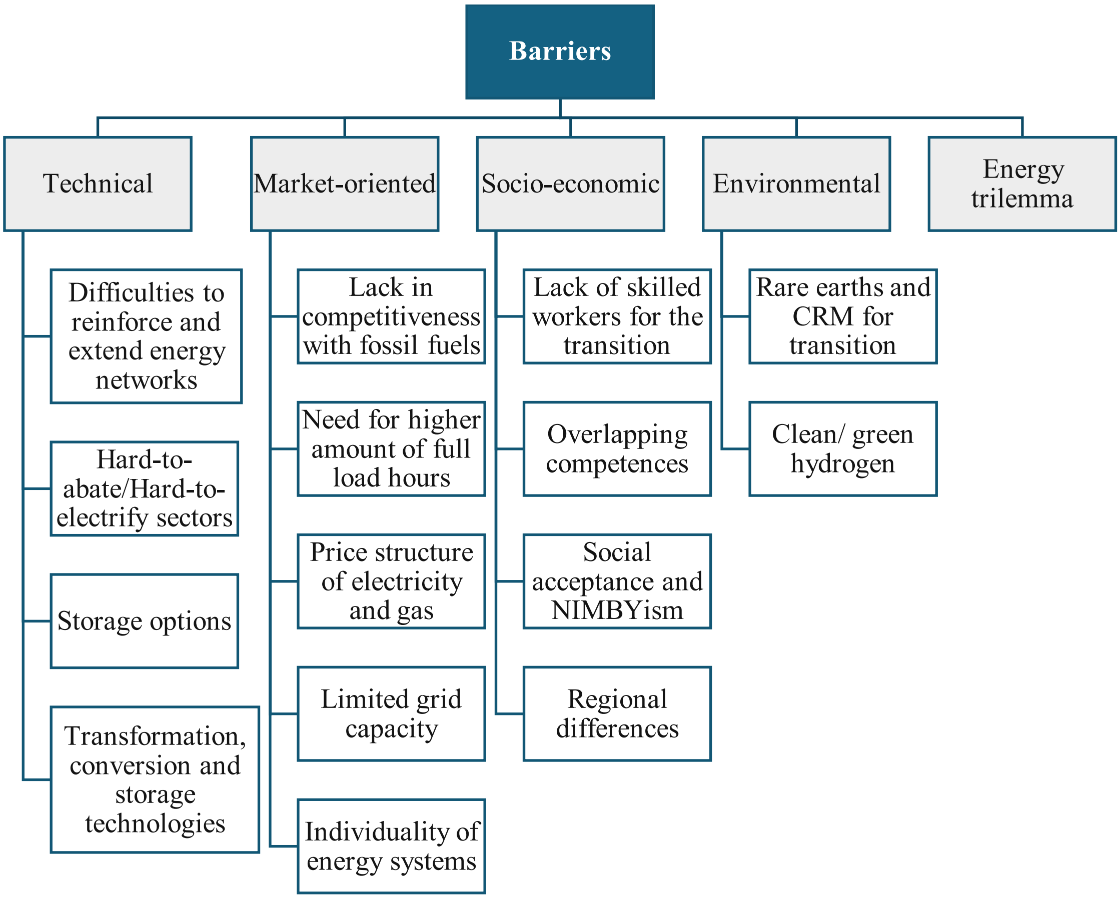

Figure 19: Overview of the barriers for sector coupling

5.2.2.1. Technical

Despite the many opportunities and advantages of sector coupling, the technological perspective may not be overlooked. There are various technological challenges and lacks that need to be tackled in order to facilitate successful sector coupling strategies throughout Europe.

One of the biggest bottlenecks of current sector coupling technologies currently may be their lack in cost and performance competitiveness compared with fossil alternatives. This is further interlinked with the investment attractiveness and lack thereof, for instance, regarding the heat network compared to gas and electricity grids (Sadeghian et al. 2022).

According to the authors, reinforcing and extending the energy networks is required for effective coupling. The increased electrification in one system like HC has direct effects the line flows in the power system.

Furthermore, the availability of planning and operation tools with capacities to be used in integrated systems are crucial. While they have increased in recent years, there is still insufficient synergy potential. In this context, the challenge of spatial and temporal resolutions in energy infrastructure modelling and complexity of interlinkage of the different systems arises. In line with the authors (2022, 14), a *'fundamental understanding'* of the dynamics is crucial to resolve this challenge.

The transmission grid expansion remains one of the biggest challenges throughout the economies, as the conventional power grids do not yet have the necessary capacities at their command. This hinders in return the economic feasibility as small amounts of full load hours are not as profitable. The hard-to-abate sectors where direct electrification is usually not possible pose a particular hurdle within the technological possibilities.

One particularly important bottleneck is infrastructure and the lack thereof. When regarding hydrogen, it has to be noted that thus far, the vectors i.e. energy carriers do not yet exist. When considering future scenarios of potential green hydrogen and biomethane injections into the existing gas grid and infrastructure, it has to be clear that this is highly limited, for instance for the gas grid currently at 5-10% (European Commission 2024).

Nonetheless, the *EU Science Hub* (2024) in accordance with the *EU Hydrogen Strategy* sees potential to increase this share up to 15-20% by 2030. With the use of a buffer storage and electrolysis, the article mentions blending potential of 40% of hydrogen into the gas grid while making necessary infrastructure changes.

Thus, technological progress in such solutions as well as storage options for hydrogen and other renewable gases would be desirable in this context. One option that may be taken into consideration here is the concept of re-electrification which exhibits, however, very low efficiency yields to this day (Ramsebner et al. 2021).

The fact that direct electrification is however, not possible for all sectors and processes constitutes a barrier, especially in the transport sector with the aim of defossilising the heavy freight transports. Here, the development of P2L and indirect electrification becomes particularly important, despite still in its infancy. In order to facilitate efficient management of renewable energy systems, a minimum amount of P2G will further be necessary. The technical conditions of which that are, among others, the hydrogen vector and legislative framework do not yet exist.

In this respect, Ramsebner et al. (2021) mention *'trade-offs to consider'* between direct electrification and P2G, as well as the expansion of the transmission grid, the system-wide effects of which are difficult to predict.

Regarding storage solutions, the P2X pathways of sector coupling cannot be disregarded. Storage should in line with Ilo and Schultis (2022) be treated as a main component within the energy system's architecture.

For the transport sector, battery capacities and their ranges constitute a barrier. The EP (2018) mentions for the medium-term hybrid solutions involving also hydrogen, which in return would yield rather low energy efficiency. Overall, a prerequisite for sector coupling is the availability of adequate coupling components in the overall system which is nowadays on the European level not yet the case.

5.2.2.2. Market-oriented

Lacking stability in market regulation is identified by the EP (2018) as a restriction since they increase investment uncertainty. Flawed market designs especially hinder the deployment of sector coupling and have a negative impact on their competitiveness compared with fossil fuels.

Moreover, when looking at sector coupling one confining aspect is the electricity grid and its capacities. High RES penetration in the electricity grid necessitates the need for higher amount of full load hours. Leaving this unmanaged can with reference to IRENA (2018, 93) '*become a long- term challenge for the power system'*.

Another aspect which may not be disregarded is the price structure of electricity and gas: consumers could incur consumption peaks in periods of abundance of RES when inelastic charges make a large percentage of the power share and respective bill (IRENA, IEA, and REN21 2018).

Furthermore, transformation and conversion technologies face several ambiguities among which are also the pricing mechanisms of electricity and the expansion of the transmission grid and respective competition. As transformation for the most part becomes useful in times of excess generation, the economic feasibility might suffer due to limited hours of full load.

In respect to Ramsebner et al. (2021), keeping the price of electricity low can encourage direct electrification over P2H and P2G when possible. Price and market coupling of commodities within the energy systems that include, for instance electricity, heat and hydrogen constitutes a key element for the economic success of sector coupling activities. Since unadjusted market structures do not provide the necessary flexibility for substitution of energy carriers to the consumers, it may also result in lower price stability and increased price risks as there are lower interdependencies between each of the commodities.

Looking at the hydrogen market, as laid out in *Section 3.2.4*, Europe is lagging behind the global large players that are China, the US and the Middle East. This recent drop in consumption can be attributed to the Russian war, however, effective energy policies and policies for hydrogen in particular further hinder Europe's position. The hydrogen production is based almost to its entirety on unabated fossil fuels, contributing further to global emissions. It would be crucial for Europe to establish itself as a new competitor regarding the development and production of green or carbon-low hydrogen for innovative applications other than in the chemical sector and refineries.

One of the most pivotal elements regarding the deployment of sector coupling is the availability of funding and investment. The EU appeals to the necessity of private funding in addition to the amounts provided by the EU itself, as well as public funding from national and local levels. The growing competition in manufacturing in renewables poses significant challenges to the economic power of the EU (European Commission. Directorate General for Energy. 2019).

As derived in this Thesis, Europe is lagging behind, especially in the field of hydrogen. In addition, China and the US are the market leaders regarding PV cells and BEVs (International Energy Agency 2023).

The CEP (2019, 6) mentions research and innovation as a key approach to maintain competitiveness and become a '*technology leader*'. Investments in infrastructure should be made to overcome the barrier of lacking grid capacities and in particular, hydrogen infrastructure.

Finally, the need of truly accounting for externalities is underlined by the EP (2018). Currently, there is still no comprehensive carbon pricing system in place which reflects the true costs of fossil fuels and would in return favour sector coupling from RES.

5.2.2.3. Socio-economic

One important aspect that does not yet find as much attention in current literature is the distinct need for skilled workers and trained personnel to be able to stem the transition.

The DG Energy (2022) describes the emergence of a '*lack of design, planning and installation skills*' in response to which EU-wide co-operation and coordination efforts are recommended. Having the necessary education and training strategies in place and attracting youth as well as staff from existing workforces in the form of retrainings to careers in renewable energy should be emphasised in the future.

An additional challenge is that oftentimes, the competition for skills and competences among the different sectors and industries due to the low penetration and representation of such in the labour force.

Hence, key measures and labour strategic policies should be put in place to advance this issue (European Commission. Directorate General for Energy. 2022).

Since the different technological conditions vary vastly over European countries, the different priorities need to be set accordingly. In Norway for instance, highly developed P2G and P2L solutions are already applied in a broad scale as well as developments of P2H making it easier to advance than is the case for other countries.

Most other regions of the world are faced with uncertainty regarding the economic feasibility of the implementation of such solutions as they are highly dependent on global energy demand and supply as well as the countries' different climate roadmaps. However, with regard to Ramsebner et al. (2021), in other countries it might not be as economically feasible.

Moreover, depending on the resource availability in each MS, their options for sector coupling in terms of technology and supply, the socio-economic consequences vary (European Parliament. Directorate General for Internal Policies of the Union. 2018).

Areas that are limited in their access to RES are likely to be at a disadvantage and have in consequence, less economic return on the deployment of sector coupling. This applies in particular for land-locked areas as opposed to areas with access to waters for hydroelectricity. The regulatory barriers for the establishment of additional power plants from RES play an important role in this context.

When looking at social acceptance or potential resistance against the energy transition, the not-in-my-backyard (NIMBY) syndrome comes into play. One of the first definitions of NIMBYism was established by Dear (1992, 288) as the '*the protectionist attitudes of and oppositional tactics adopted by community groups facing an unwelcome development in their neighbourhood'*.

In line with Biresselioglu et al. (2024), building up public trust, inclusivity and public participation are crucial means to overcome opposition. Moreover, the authors lay out the unique character and complexity of resistance and cases of NIMBYism on a social, political, and cultural level and thus, analyses should take into consideration the specific particularities of each case.

5.2.2.4. Environmental

As aforementioned under the techno-economic barriers, the variance in availability of RES also strongly affects the environmental aspects.
The unabated use of fossil fuels in hydrogen production constitutes a major problem, also looking at potential misperceptions among the population (International Energy Agency 2023).

The demand for raw materials, particularly cobalt and lithium for electrification as well as the deployment of necessary infrastructure have their toll on the environment. Additionally, metals like platinum for the construction of hydrogen fuel cells would need to be addressed in respective sector coupling projects (European Parliament. Directorate General for Internal Policies of the Union. 2018).

While seasonal fluctuations of renewable energies may be to a part overcome (see *Section 5.2.1.4*), it cannot be denied that VREs exhibit lower predictability. In face of the climate crisis it is likely that certain events may exacerbate these fluctuations. Furthermore, due to the increasing warming, the cooling demand is likewise rising in Europe. This could, however, to a part be extenuated by the defossilisation of the HC sector through sector coupling.

5.2.2.5. Energy trilemma

The energy trilemma constitutes in itself a techno-economic-environmental barrier or bottleneck which additionally needs to be taken into consideration for sector coupling for the transition (see *Chapter 3).* The complexities of said trilemma are annually and regionally analysed by the World Energy Trilemma Report (2024a) which is designed to help governments to better understand their specific situations. In return, the annual assessment may guide policymakers on how to move closer towards the balance between energy security, equity and environmental sustainability (see *Figure 3).*

6. Recommendations for Sector Coupling Strategies

This Chapter summarises, in accordance with the literature assessed, some relevant recommendations for policy-making strategies on sector coupling in the European area. In addition, an attempt is made to answer the second part of the research question regarding the strategies for sector coupling that should be pursued as a priority.
It has to be noted that this Chapter is not exhaustive given the scope of this Thesis, but rather aims at providing the right stimuli of elements that would need to be considered in the future, as sector coupling represents an indispensable approach in the course of the European energy transition.

A major point mentioned by the EC is the lack of skilled workers (see *Chapter 5.3, Barriers).*

A distinct target skill level for the 'renewable energy career path' within the EU competence system is mentioned in the study alongside annual EU Skills summits to monitor its success. Stock-taking of trainings and other activities should be conducted on the European level, as well as in each MS including the display of best practices. Educational measures and the advancement of (re-)training facilities are important elements to ensure sufficiently skilled personnel for the transition to renewable heating and cooling as well as overall.

Based on the findings, the necessity of bottom-up studies and scenario modelling, especially for the roles of electricity and hydrogen in EU policy guidance arises. In this context, the three '*cornerstones of a successful policy strategy on direct and indirect electrification'* are laid out by Schreyer et al. (2024, 234).

- The first cornerstone mentioned involves the importance of **carbon pricing**.

  The European Emissions Trading System (ETS) is referred to as '*a prerequisite for both direct and indirect electrification*' for emissions abatement.
  In addition, the authors emphasise end-user sector carbon pricing to increase the necessary pressure for the transition and unveil the competitiveness.

Technology-neutrality awareness among consumers is mentioned in this regard. Individuals' decisions and behavioural patterns, especially in the residential and transport sectors can be perceived as '*myopic and subject to non-monetary factors*'. In return, the recommendation is to have complementary policies in place to counteract against this lack of awareness.

- The second cornerstone recalls the **roles of hydrogen and electrification** in a way they do not contract or compete with each other.

The lack of widespread phase-out regulations for gas-powered heating systems which bears the risk of lock-in effects into said conventional heating systems needs to be recognised by policymakers. The importance of efforts towards the repurposing of gas infrastructure for low-carbon gases, mainly hydrogen should be made evident.

In addition, the ban on new ICE vehicles by the European Commission that does in fact exclude cars powered by synthetic fuels yet might create confusion for owners as well as manufacturers. '*Fossil lock-in'* effects that in return require a costly *'lock-out'* should be avoided as they can result in failure to fulfil the European climate goals. Nonetheless, some recent regulations containing drop-in quotas have already been proposed and adopted by the Commission like *ReFuel EU Aviation Regulation* and the *FuelEU Maritime Regulation,* as well as an update on the *Renewable Energy Directive* with elements on green hydrogen (European Commission. Directorate General for Communication. 2023).

- An **adaptive policy approach** is advisable, that in the short and middle term favours direct electrification while options with green hydrogen are being explored.

Generally speaking, an energy system with a high degree of electrification is superior in respect of electricity generation and the need for hydrogen imports. Nevertheless, should hydrogen options in the future be found to be economically feasible and competitive, policies would need to be adapted accordingly.

6. Recommendations for Sector Coupling Strategies

> The timely development of infrastructure with long lead times like hydrogen pipelines could be favourable to further take into consideration the optimistic scenarios towards hydrogen.

Overall, policy making is the process of balancing between redundancies for risk-hedging and efficiency of cost, which is according to the authors '*key for the acceptance of the energy transition as a whole*' (Schreyer et al. 2024, 235).

Sufficient carbon pricing may further lower the number of technology-focused regulations needed and result in a responsibility shift towards the stakeholders in the market. The authors identify that direct electrification is the prevalent strategy with a share of 42% to 60% of electricity in the final energy mix. Indirect electrification holds a share of 9% to 26%, particularly in sectors that are hard to electrify. In line with this, the distinct sectoral roles of these strategies should be respected, prioritising end-use transformation with direct electrification and hydrogen and synfuels for new applications where they are necessary. The integration of CCUS approaches in the ETS is fundamental especially when considering that carbon cycles in the future will tend to become more complex. Lock-ins into fossil-based fuel production should be avoided by regulations as long term defossilised production chains will be necessary in the future.

Moreover, the necessity for a new boundary in German energy system models regarding the bound carbon in final products like plastics and ammonia in fertilisers to be able to fully account for emissions bound in products, notwithstanding the time and place of consumption, becomes evident. These 'potential emissions' are to this day not considered in national emissions accounting approaches (Kullmann, Linßen, and Stolten 2023).

It is therefore essential to take these emissions into consideration for defossilisation strategies and in model design analyses. The authors conclude with the distinct appeal to policy makers for defossilisation of the chemical sector under holistic review of the energy system. It is found that such defossilisation would lead to additional costs of the transition of an additional 32% (212 billion EUR) in Germany, as a result of more hydrogen imported for the most part. It is probable that these findings also apply to other European countries as they follow similar energy accounting approaches.

6. Recommendations for Sector Coupling Strategies

Needless to say, the future demand and supply are crucial factors for policy making regarding the chemical sector and the energy transition on the whole.

The European Parliament (2018, 45) accentuates the need for an integrative approach that focuses on the future of the *'European energy system'*. This would further require stable EU energy policies that involve sufficient pricing of carbon, that in return enable sector coupling at a large scale. Sufficient planning and funding are necessary in this regard (European Parliament. Directorate General for Internal Policies of the Union. 2018).

Figure 21, as seen the Study conducted by the EP's Directorate-General for Internal Policies identifies three main policy objectives of current EU energy policies that are: *Sustainability, Security of supply* and *Competitiveness*. It furthermore depicts how sector coupling strategies can help enable these policy objectives.

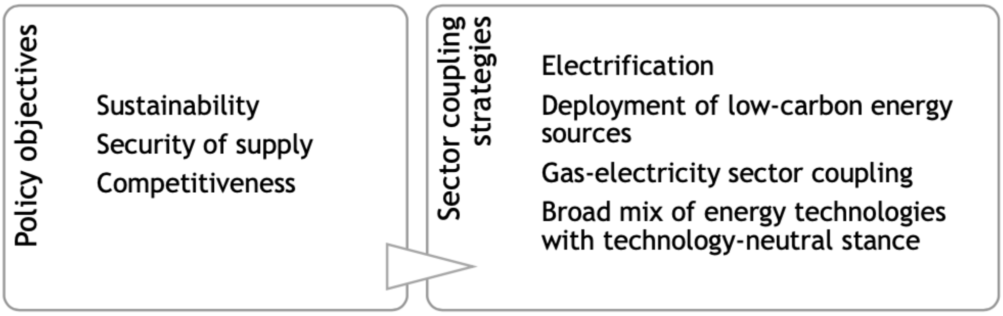

Figure 20: Sector coupling strategies contributing to the EU Energy and Climate policy objectives (Source: European Parliament. Directorate General for Internal Policies of the Union. 2018, 15)

The DG Energy of the EC (2022) has identified the four following research and development needs in order to progress sector coupling of the heating, cooling and electricity sectors in a renewable energy-driven Europe. These R&D needs are classified as follows:

1. Development of '***adequate coupling components'*** for the realisation of the intermediate conversion stage (see *Chapter 5, Section 1.3*)

6. Recommendations for Sector Coupling Strategies

The coupling components are needed as to balance out potential surpluses of electricity from RES and should take place at all voltage levels of the grid.
The EC describes rooftop PVs as particularly promising in this regard as they do occupy additional land.

2. Development of '***customer plant management units'*** for the realisation of P2H and P2C, optimisation of energy sources and provision of grid flexibility

The customer plant management units act as so called 'black boxes' that exchange minimal data with the grid in order to ensure data privacy.

3. Development or extension of '***real-time grid applications in all voltage levels'***

The real-time application and monitoring enables price- and emergency-driven responses to demand, that facilitate sector coupling dynamics.

4. Development of '***appropriate market structures for all relevant vectors'***

Cutting-edge business models like smart networks and investment attractiveness is unlocked by having the necessary market structures for the various energy vectors in place.

7. Conclusion

Circling back to the research question it can be followed that in line with the findings of this Thesis, sector coupling does in fact contribute to both, energy resilience and energy security in the face of the European defossilisation. The latter can particularly be enabled through cross-vector sector coupling, as an important means of ensuring the flexibility of the energy system and security of supply.

Moreover, sector coupling serves as an approach to on the one hand substitute fossil fuels with renewable energy sources, mainly renewable electricity throughout the sectors that are industry, residential, as well as transport.

On the other hand, the coupling implies efficiency maximisation and increased flexibility by unlocking new potential of storage and conversion of technologies, especially where direct electrification is not possible.

While it can be stated that sector coupling is generally on the rise across Europe as well as in other geographic areas such as the US, further research is needed on various aspects. Different geographic conditions need to be considered when considering the applicability of sector coupling.

For areas where not enough VREs are available, solutions through P2L facilities as well as gas-fuelled for low carbon alternatives may be sought. However, due to vast variations within Europe, no concrete assertions about different geographic zones can be concluded within the scope of this Thesis. This consitutes a field where further research is necessary in the future.

The importance of energy partnerships in Europe should however not be underestimated. This becomes particularly important when looking at the geoeconomic implications of future green hydrogen productions where players such as Morocco and Chile, among others, are particularly important.

The ambiguities regarding definition of sector coupling remain to be clarified as well as the inaccurate utilisation of terms. On the basis of this, this Master's Thesis has examined the different sectors as well as an attempt of a concise definition. The interchangeability between sector coupling and sectorial integration varies.

To avoid any confusion, contrary to the opinion of the *Gas Infrastructure Europe* association (see *Chapter 5*), it is advisable to utilise the term sector coupling. The same goes for the over-usage of the term electrification as it is not sufficiently comprehensive for the concept of sector coupling. Interchanging sector coupling with electrification in consequence overlooks the difference between direct and indirect processes of electrifying and disregards entirely sectors or areas where it is not possible. Nevertheless, increasing the share of electricity in the European energy mix is one of the most promising strategies to defossilisation and increasing RES penetration in the electricity grids is desirable.

Another aspect that has been observed is the misutilisation of the word ‘decarbonisation’ as in many cases, the correct terminology is ‘defossilisation’. This Thesis emphasises that the energy system as we know it is far from being fully ‘decarbonised’ or defossilised respectively. Nonetheless, defossilisation measures where applicable are urgently sought for in light of the renewable energy transition. It finds that sector coupling serves as an approach to decouple from fossil sources.

An important element to consider is the difference in historical evolution of the different energy utility systems. As can be observed, there were close to no overlaps or synergies between the different utility systems in the past. This is reflected in the fact that sector coupling represents an entirely new and disruptive approach with great defossilisation potential. Examples of CHP can be taken as ancillary measures and reference for successful sector coupling deployment today.

In line with the views of the EU, sector coupling is necessary for the ESI on the European level, which in consequence facilitates the energy transition. Furthermore, this Thesis finds that sector coupling can and will be necessary to manage the future extensive use of RES within the energy system. The competition between the different developing technologies, however, constitutes a barrier as well as a research gap on enabling technologies for sector coupling.

The different components of the emerging new architecture of the power system need to be clarified. The P2X pathways can only be described with the different conversion and storage options, hence, they should be considered in the system accordingly. Prosumers may further be perceived as virtual vertically integrated utilities.

In light of the progress towards the international climate and defossilisation goals, it can be concluded that sector coupling approaches are indispensable for the European energy future. Through the increased use of RES in the energy system, sector coupling can be realised and vice versa. Hence, including sector coupling strategies in energy policies on the regional and EU level represents a crucial means for future deployment.

7. Conclusion

While the barriers are numerous, the opportunities of sector coupling bear a lot of potential, especially in sectors that are feasible to electrify. This includes in particular the heating and cooling as well as the transport sector to a certain extent. In Europe, the potential of district heating and cooling approaches can be a powerful lever for the defossilisation of these sectors. For sectors where direct electrification is hard or impossible to implement, renewable or carbon-neutral gases will play an essential role.

The future of hydrogen especially continues to remain insecure, with Europe standing at a crossroad in terms of proving itself as 'technology leader' in the face of growing or overtaking competition. Thus, following strategies on direct electrification can be concluded to be more promising instead. The development of long-term infrastructure and consumers' devices for future scenarios should additionally be taken into account.

Bibliography

Agora Energiewende. 2019. “European Energy Transition 2030: The Big Picture. Ten Priorities for the next European Commission to Meet the EU’s 2030 Targets and Accelerate towards 2050.” https://www.agora-energiewende.de/en/publications/european-energy-transition2030-the-big-picture/.

American Public Gas Association. 2024. “A Brief History of Natural Gas - American Public Gas Association.” 2024. https://www.apga.org/aboutus/facts/history-of-natural-gas#.

Biresselioglu, Mehmet Efe, Berfu Solak, and Zehra Funda Savas. 2024. “Unveiling Resistance and Opposition against Low-Carbon Energy Transitions: A Comprehensive Review.” *Energy Research & Social Science* 107 (January):103354. https://doi.org/10.1016/j.erss.2023.103354.

Bloess, Andreas, Wolf-Peter Schill, and Alexander Zerrahn. 2018. “Power-to-Heat for Renewable Energy Integration: A Review of Technologies, Modeling Approaches, and Flexibility Potentials.” *Applied Energy* 212 (February):1611–26. https://doi.org/10.1016/j.apenergy.2017.12.073.

Bloomberg Finance L.P. and BloombergNEF. 2020. “Sector Coupling in Europe: Powering Decarbonization.” https://data.bloomberglp.com/professional/sites/24/BNEF-Sector-Coupling-Report-Feb-2020.pdf.

Brauner, Günther. 2022. *System Efficiency by Renewable Electricity: Strategies for Efficient Energy Supply until 2050*. Wiesbaden: Springer Fachmedien Wiesbaden. https://doi.org/10.1007/978-3-658-35138-0.

Breeze, Paul. 2018. “An Introduction to Combined Heat and Power.” In *Combined Heat and Power*, 1–11. Elsevier. https://doi.org/10.1016/B978-0-12-812908-1.00001-8.

Büchi, Felix N., Marcel Hofer, Christian Peter, Urs D. Cabalzar, Jérôme Bernard, Uwe Hannesen, Thomas J. Schmidt, Alexandre Closset, and Philipp Dietrich. 2014. “Towards Re-Electrification of Hydrogen Obtained from the Power-to-Gas Process by Highly Efficient H_2/O_2 Polymer Electrolyte Fuel Cells.” *RSC Adv.* 4 (99): 56139–46. https://doi.org/10.1039/C4RA11868E.

Danish Energy Agency, and Energinet. 2024. “Technology Data - Energy Plants for Electricity and District Heating Generation.” http://www.ens.dk/teknologikatalog. https://ens.dk/sites/ens.dk/files/Analyser/version_14_-_technology_data_catalogue_for_el_and_dh.pdf.

Dear, Michael. 1992. “Understanding and Overcoming the NIMBY Syndrome.” *Journal of the American Planning Association* 58 (3): 288–300. https://doi.org/10.1080/01944369208975808.

Donthi, Narasimha Reddy. 2020. “Decarbonization: A Method to Ensure Equity and Justice in Addressing Climate Change.” In *Responsible Consumption and Production*, edited by Walter Leal Filho, Anabela Marisa Azul, Luciana Brandli, Pinar Gökçin Özuyar, and Tony Wall, 127–37. Encyclopedia of the UN Sustainable Development Goals. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-95726-5_71.

Electric Power Research Institute, (EPRI). 2011. “Estimating the Costs and Benefits of the Smart Grid A Preliminary Estimate of the Investment Requirements and the Resultant Benefits of a Fully Functioning Smart Grid.” 1022519. 3420 Hillview Avenue Palo Alto, CA 94304-1338 USA. https://smartgrid.gov/files/documents/Estimating_Costs_Benefits_Smart_Grid_Preliminary_Estimate_In_201103.pdf.

Enea consulting. 2016. “The Potential of Power-to-Gas. Technology Review and Economic Potential Assessment.” Paris. https://www.enea-consulting.com/static/3663dbb115f833de23e4c94c8fa399ec/enea-the-potential-of-power-to-gas.pdf.

Energy Institute. 2023. “Statistical Review of World Energy 2023 | 72nd Edition.” Energy Institute Statistical Review of World Energy 2023. Energy Institute. www.energyinst.org.

Erenoğlu, Ayşe Kübra, Ozan Erdinç, and Akın Taşcıkaraoğlu. 2019. “History of Electricity.” In *Pathways to a Smarter Power System*, 1–27. Elsevier. https://doi.org/10.1016/B978-0-08-102592-5.00001-6.

ETIP Bioenergy. 2021. In *Bioenergy Fact Sheet: Fischer-Tropsch Synthesis*. ETIP Bioenergy. https://www.etipbioenergy.eu/images/ETIP_B_Factsheet_FT_R1.pdf.

European Commission. 2019. *Communication From The Commission To The European Parliament, The European Council, The Council, The European Economic And Social Committee And The Committee Of The Regions. The European Green Deal. COM/2019/640 Final*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52019DC0640.

European Commission. Directorate General for Communication. 2023. *The European Green Deal: Delivering the EU’s 2030 Climate Targets.* LU: Publications Office. https://data.europa.eu/doi/10.2775/591824.

European Commission. Directorate General for Energy. 2019. *Clean Energy for All Europeans.* LU: Publications Office. https://data.europa.eu/doi/10.2833/21366.

———. 2022. *Coupling of Heating/Cooling and Electricity Sectors in a Renewable Energy-Driven Europe.* LU: Publications Office. https://data.europa.eu/doi/10.2833/284458.

European Commission, Directorate-General for Energy. 2020. *Communication From The Commission To The European Parliament, The Council, The European Economic And Social Committee And The Committee Of The Regions. Powering a Climate-Neutral Economy: An EU Strategy for Energy System Integration. COM/2020/299 Final*. https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=COM%3A2020%3A299%3AFIN.

———. 2022. *Communication From The Commission To The European Parliament, The European Council, The Council, The European Economic And Social Committee And The Committee Of The Regions. REPowerEU Plan. COM/2022/230 Final*.

———. 2024. "EU Strategy on Energy System Integration." Energy, Climate Change, Environment. 2024. https://energy.ec.europa.eu/topics/energy-systems-integration/eu-strategy-energy-system-integration_en.

European Commission, EU Science Hub. 2024. "Blending Hydrogen into the EU Gas System," May 2, 2024. https://joint-research-centre.ec.europa.eu/jrc-news-and-updates/blending-hydrogen-eu-gas-system-2022-01-19_en.

European Hydrogen Backbone. 2023. "European Hydrogen Backbone Implementation Roadmap — Cross Border Projects And Costs Update." Guidehouse Stadsplateau 15, 3521 AZ Utrecht The Netherlands: 2024 European Hydrogen Backbone. https://ehb.eu/files/downloads/EHB-2023-20-Nov-FINAL-design.pdf.

European Network of Transmission System Operators for Electricity. 2019. "ENTSO-E Vision on Market Design and System Operation towards 2030."

European Parliament. 2024. *Directive 2003/87/EC Of The European Parliament And Of The Council of 13 October 2003 Establishing a Scheme for Greenhouse Gas Emission Allowance Trading within the Community and Amending Council Directive 96/61/EC. Directive 2003/87/EC*. http://data.europa.eu/eli/dir/2003/87/oj.

European Parliament. Directorate General for Internal Policies of the Union. 2018. *Sector Coupling: How Can It Be Enhanced in the EU to Foster Grid Stability and Decarbonise?* LU: Publications Office. https://data.europa.eu/doi/10.2861/63462.

Fedecom Project. 2022. "FEDECOM." Official website. 2022. https://fedecom-project.eu.

GIE, Gas Infrastructure Europe. 2019. "Position Papers and Public Responses." *Gas Infrastructure Europe* (blog). 2019. https://www.gie.eu/publications/position-papers/.

Hanna, Dr. Richard, Dr Evangelos Gazis, Dr Jacqueline Edge, Dr Aidan Rhodes, and Dr Rob Gross. 2018. "Briefing_Paper2_EnergySystemsIntegration.Pdf | Powered by Box." 2018. https://imperialcollegelondon.app.box.com/s/0sil57fndc5tn9gfy6ypzp8v61qnv3mg.

Hu, Guoping, Chao Chen, Hiep Thuan Lu, Yue Wu, Congmin Liu, Lefu Tao, Yuhan Men, Guangli He, and Kevin Gang Li. 2020. "A Review of Technical Advances, Barriers, and Solutions in the Power to Hydrogen (P2H) Roadmap." *Engineering* 6 (12): 1364–80. https://doi.org/10.1016/j.eng.2020.04.016.

Ilo, Albana. 2016. "'Link'—The Smart Grid Paradigm for a Secure Decentralized Operation Architecture." *Electric Power Systems Research* 131 (February):116–25. https://doi.org/10.1016/j.epsr.2015.10.001.

———. 2019. "Design of the Smart Grid Architecture According to Fractal Principles and the Basics of Corresponding Market Structure." *Energies* 12 (21): 4153. https://doi.org/10.3390/en12214153.

Ilo, Albana, and Daniel-Leon Schultis. 2022. *A Holistic Solution for Smart Grids Based on LINK– Paradigm: Architecture, Energy Systems Integration, Volt/Var Chain Process*. Power Systems. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-81530-1.

International Energy Agency, ed. 2011. *World Energy Outlook 2011*. World Energy Outlook 2011. Paris. https://iea.blob.core.windows.net/assets/cc401107-a401-40cb-b6ce-c9832bb88d85/WorldEnergyOutlook2011.pdf.

———. 2023. "Global Hydrogen Review 2023." *IEA Publications*.

———. 2024. "Electricity 2024 - Analysis and Forecast to 2026." https://iea.blob.core.windows.net/assets/18f3ed24-4b26-4c83-a3d2-8a1be51c8cc8/Electricity2024-Analysisandforecastto2026.pdf.

IRENA, International Renewable Energy Agency. 2022. "Hydrogen Consumption Worldwide by Country 2020." Chart. Statista. https://www.statista.com/statistics/1292403/global-hydrogen-consumption-by-country/.

IRENA, International Renewable Energy Agency, OECD/ IEA, and Renewable Energy Policy Network for the 21st Century REN21. 2018. "Renewable Energy Policies in a Time of Transition."

Khajeh, Hosna, Miadreza Shafie-khah, and Hannu Laaksonen. 2020. "Chapter 7 - Blockchain-Based Demand Response Using Prosumer Scheduling." In *Blockchain-Based Smart Grids*, edited by Miadreza Shafie-khah, 131–44. Academic Press. https://doi.org/10.1016/B978-0-12-817862-1.00007-5.

Kullmann, Felix, Jochen Linßen, and Detlef Stolten. 2023. "The Role of Hydrogen for the Defossilization of the German Chemical Industry." *International Journal of Hydrogen Energy* 48 (99): 38936–52. https://doi.org/10.1016/j.ijhydene.2023.04.191.

Lewandowska-Bernat, Anna, and Umberto Desideri. 2018. "Opportunities of Power-to-Gas Technology in Different Energy Systems Architectures." *Applied Energy* 228 (October):57–67. https://doi.org/10.1016/j.apenergy.2018.06.001.

Lund, Henrik, Sven Werner, Robin Wiltshire, Svend Svendsen, Jan Eric Thorsen, Frede Hvelplund, and Brian Vad Mathiesen. 2014. “4th Generation District Heating (4GDH).” *Energy* 68 (April):1–11. https://doi.org/10.1016/j.energy.2014.02.089.

Office of Energy Efficiency & Renewable Energy, Metropolitan Washington Council of Governments, and Hydrogen Association. 2004. “Fact Sheet Series: History of Hydrogen Timeline.” Office of Energy Efficiency & Renewable Energy. https://www.mwcog.org/file.aspx?&A=zkpv0NhzZDWLPqP7LLLYTPZMIgxuq1QGhT8%2BMkINPbo%3D.

O’Malley, Mark, Benjamin Kroposki, Bryan Hannegan, Henrik Madsen, Mattias Andersson, William D’haeseleer, Mark F. McGranaghan, et al. 2016. “Energy Systems Integration. Defining and Describing the Value Proposition.” NREL/TP--5D00-66616, 1257674. https://doi.org/10.2172/1257674.

Orecchini, F. 2006. “The Era of Energy Vectors.” *International Journal of Hydrogen Energy* 31 (14): 1951–54. https://doi.org/10.1016/j.ijhydene.2006.01.015.

Østergaard, Poul Alberg, Sven Werner, Anders Dyrelund, Henrik Lund, Ahmad Arabkoohsar, Peter Sorknæs, Oddgeir Gudmundsson, Jan Eric Thorsen, and Brian Vad Mathiesen. 2022. “The Four Generations of District Cooling - A Categorization of the Development in District Cooling from Origin to Future Prospect.” *Energy* 253 (August):124098. https://doi.org/10.1016/j.energy.2022.124098.

Owens, Brandon. 2014. “The Rise of Distributed Power.” General Electric. https://legacy-assets.eenews.net/open_files/assets/2014/02/25/document_gw_02.pdf.

Oxford English Dictionary. 2023. “Couple, v.” In . Oxford University Press. Oxford English Dictionary. https://doi.org/10.1093/OED/8431225069.

Perry, Martin K. 1989. “Chapter 4 Vertical Integration: Determinants and Effects.” In *Handbook of Industrial Organization*, 1:183–255. Elsevier. https://doi.org/10.1016/S1573-448X(89)01007-1.

Ramsebner, Jasmine, Reinhard Haas, Amela Ajanovic, and Martin Wietschel. 2021. “The Sector Coupling Concept: A Critical Review.” *WIREs Energy and Environment* 10 (4): e396. https://doi.org/10.1002/wene.396.

Ridjan, Iva, Brian Vad Mathiesen, and David Connolly. 2016. “Terminology Used for Renewable Liquid and Gaseous Fuels Based on the Conversion of Electricity: A Review.” *Journal of Cleaner Production* 112 (January):3709–20. https://doi.org/10.1016/j.jclepro.2015.05.117.

Rosenberg, Matt. 2020. “The Major Sectors of the Economy.” ThoughtCo. January 28, 2020. https://www.thoughtco.com/sectors-of-the-economy-1435795.

Sadeghian, Omid, Arman Oshnoei, Behnam Mohammadi-Ivatloo, and Vahid Vahidinasab. 2022. "Concept, Definition, Enabling Technologies, and Challenges of Energy Integration in Whole Energy Systems To Create Integrated Energy Systems." In *Whole Energy Systems*, edited by Vahid Vahidinasab and Behnam Mohammadi-Ivatloo, 1–21. Power Systems. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-87653-1_1.

Schreyer, Felix, Falko Ueckerdt, Robert Pietzcker, Renato Rodrigues, Marianna Rottoli, Silvia Madeddu, Michaja Pehl, Robin Hasse, and Gunnar Luderer. 2024. "Distinct Roles of Direct and Indirect Electrification in Pathways to a Renewables-Dominated European Energy System." *One Earth* 7 (2): 226–41. https://doi.org/10.1016/j.oneear.2024.01.015.

World Energy Council. 2024a. "World Energy Trilemma 2024: Evolving With Resilience And Justice." World Energy Trilemma Index 2024. Temple Chambers 3-7 Temple Avenue, London, EC4Y 0DA: World Energy Council 2024. https://trilemma.worldenergy.org; https://www.worldenergy.org/assets/downloads/World_Energy_Trilemma_2024_Full_Report.pdf?v=1713253987.

———. 2024b. "World Energy Trilemma Framework." World Energy Council 2024. 2024. https://www.worldenergy.org/transition-toolkit/world-energy-trilemma-framework.

List of Figures