PARIS REINFORCE

31/03/2020 (revised 22/03/2021)

D4.1 SOCIO-TECHNICAL INNOVATION SYSTEM MAPPING

WP4 – ROBUSTIFICATION & SOCIO-TECHNICAL ANALYSIS TOOLBOX

Version: 1.10R

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EC Summary Requirements

1. Changes with respect to the DoA

No changes with respect to the work described in the DoA. The deliverable was submitted on time (March 2020) and was slightly updated to include two case studies (Brazil, Argentina) additionally to DoA, in November 2020. The document at hand is the revised version (v1.10R) of deliverable D4.1. The deliverable has been revised in order to maximise the impact in terms of dissemination capacity to a broader audience, by introducing an additional section discussing key takeaways and highlighting potential convergences and divergences among case studies (Section 5).

2. Dissemination and uptake

This deliverable aims to serve as a resource for modellers to exploit in the first round of national modelling runs of the PARIS REINFORCE project, in work packages WP5 and WP6. Along with the modelling results, the sociotechnical analyses included in this deliverable will help to eventually develop robust, transformative policy pathways (Task 4.6). It can also be used by other researchers, policymakers and other stakeholder groups as a fully informed account of the sociotechnical context of selected sectors and countries—namely the Greek power sector, the iron and steel, cement and basic chemical sectors in Germany and the United Kingdom, the transport sector in Norway and Canada—that can help inform decarbonisation pathways or further research. The Greece case study has been published in T&F Energy Sources, Part B: Economics, Planning and Policy; the UK and Germany comparative case study in MDPI Energies; the Norway and Canada comparative case study in MDPI Sustainability, and the Brazil and Argentina is currently under review in Elsevier's Renewable & Sustainable Energy Reviews.

3. Short summary of results (<250 words)

The deliverable hosts several case studies, in different countries and sectors, based on different or combinations of Systems of Innovation frameworks. In Greece, an application of the Multi-Level Perspective aims to explore the factors establishing lignite as the mainstream energy resource, as well as the factors sustaining its dominance despite niche technologies and innovations challenging the regime. Drawing from the country's commitments to transform its energy system and the need to secure a transition that considers socioeconomic impacts on local economies, the analysis explores how the envisaged lignite phase-out can eventually be socially just, effective and sustainable. Furthermore, we review the evolution of the UK and German industries during the past three decades, focusing on three of the most energy-intensive and emitting industries: iron and steel, cement, and chemicals. In doing so, we explore and compare the structure and functions of the two systems, based on the building blocks of the Sectoral Innovation Systems framework, which we then integrate with a systems failure analysis, to capture existing and potential drivers of or barriers to diffusion of low- or zero-carbon industrial technologies. The comparisons drawn between the two countries, oriented on the systems failure framework, are complemented by references to factors like new or emerging non-European industrial economies as well as implications of Brexit volatility and overall orientation of the two systems. A similar approach is used to analyse and compare the Norwegian and Canadian transport sectors, exploring the potential of decarbonisation and the risks hindering it. A TIS/MLP approach is finally employed in the Brazilian and Argentinian transport sectors.

4. Evidence of accomplishment

This report, three publications and one manuscript currently under review.

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Preface

PARIS REINFORCE will develop a novel, demand-driven, IAM-oriented assessment framework for effectively supporting the design and assessment of climate policies in the European Union as well as in other major emitters and selected less emitting countries, in respect to the Paris Agreement. By engaging policymakers and scientists/modellers, PARIS REINFORCE will create the open-access and transparent data exchange platform I2AM PARIS, in order to support the effective implementation of Nationally Determined Contributions, the preparation of future action pledges, the development of 2050 decarbonisation strategies, and the reinforcement of the 2023 Global Stocktake. Finally, PARIS REINFORCE will introduce innovative integrative processes, in which IAMs are further coupled with well-established methodological frameworks, in order to improve the robustness of modelling outcomes against different types of uncertainties.

NTUA - National Technical University of Athens	GR
BC3 - Basque Centre for Climate Change	ES
Bruegel - Bruegel AISBL	BE
Cambridge - University of Cambridge	UK
CICERO - Cicero Senter Klimaforskning Stiftelse	NO
CMCC - Fondazione Centro Euro-Mediterraneo sui Cambiamenti Climatici	IT
E4SMA - Energy Engineering Economic Environment Systems Modeling and Analysis	IT
EPFL - École polytechnique fédérale de Lausanne	CH
Fraunhofer ISI - Fraunhofer Institute for Systems and Innovation Research	DE
Grantham - Imperial College of Science Technology and Medicine - Grantham Institute	UK
HOLISTIC - Holistic P.C.	GR
IEECP - Institute for European Energy and Climate Policy Stichting	NL
SEURECO - Société Européenne d'Economie SARL	FR
CDS/UnB - Centre for Sustainable Development of the University of Brasilia	BR
CUP - China University of Petroleum-Beijing	CN
IEF-RAS - Institute of Economic Forecasting – Russian Academy of Sciences	RU
IGES - Institute for Global Environmental Strategies	JP
TERI - The Energy and Resources Institute	IN

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Abbreviations

ANP	Agência Nacional do Petróleo, Gás Natural e Biocombustíveis (Brazilian National Agency for Petroleum, Natural Gas and Biofuels)
AS	Aksjeselskap (Stock-based company, the same as SA)
ASA	Allmennaksjeselskap (Public limited company)
ATAC	Air Transportation Association of Canada
BAT	Best Available Techniques
BDI	Bundesverband der Deutschen Industrie (Federation of German Industries)
BEIS	Business, Energy and Industrial Strategy
BEV	Battery Electric Vehicle
BF	Blast Furnace
BFI	Betriebsforschungsinstitut (Institute for Applied Research)
BImSchG	Bundes-Immissionsschutzgesetz (Federal Immission Control Act)
BMWi	Bundesministerium für Wirtschaft und Energie (Federal Ministry for Economic Affairs and Energy)
BOF	Basic Oxygen Furnace
CAA	Norwegian Civil Aviation Authority
CBI	Confederation of British Industry
CBIO	Brazil’s Carbon Credit
CCC	Climate Change Committee
CCME	Canadian Council of Ministers of Environment
CCS	Carbon, Capture and Storage
CCUS	Carbon Capture, Use and Storage
CEFIC	Conseil Européen des Fédérations de l'Industrie Chimique (European Chemical Industry Council)
CGS	Clean Growth Strategy
CIA	Central Intelligence Agency
CICERO	Centre for International Climate and Environmental Research
CNEP	Brazilian National Council for Energy Policy
CNG	Compressed Natural Gas
CO_2	Carbon Dioxide
CPP	Corporate Partnership Programme
CRA	Canada Revenue Agency
CRES	Center for Renewable Sources and Energy Saving

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CSP	Concentrated Solar Power
CUTA	Canadian Urban Transit Association
DIN	Deutsches Institut für Normung (German Institute for Standardisation)
DR	Direct Reduction
DRI	Direct Reduced Iron
DVT	Deutscher Verband Technisch-wissenschaftliche (German Association of Technical and Scientific Societies)
EAF	Electric Arc Furnace
EDGAR	Emissions Database for Global Atmospheric Research
EEA	European Economic Area/
EIA	US Energy Information Administration
EID	Energieintensive Industrien in Deutschland (Energy-Intensive Industries in Germany)
ENTSO-E	European Network of Transmission System Operators for Electricity
EPR	Environmental Permitting Regime
ESEPIE	Hellenic Association of Electricity Trading and Supply Companies
ESR	Effort Sharing Regulation
ETS	Emissions Trading System
EU	European Union
EV	Electric Vehicle
FCEV	Fuel Cell Electric Vehicle
FES	Normenausschuss Eisen und Stahl (the Committee for Iron and Steel Standardisation)
FMA	Freight Management Association of Canada
FOSTA	Forschungsvereinigung Stahlanwendung (Research Association for Steel Application)
GdE	Gas de Estado
GDP	Gross Domestic Product
gGmbH	gemeinnützige Gesellschaft mit beschränkter Haftung (non-profit Company with limited Liability)
GHG	Greenhouse Gases
GHGPPA	Greenhouse Gas Pollution Pricing Act
GTAI	Germany Trade & Invest
GVA	Gross Value Added
HAIPP	Hellenic Association of Independent Power Producers
HEDNO	Hellenic Electricity Distribution Network Operator
HELAPCO	Hellenic Association of Photovoltaic Companies

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HellasRES	Hellenic Association of Renewable Energy Producers
HTSO	Hellenic Transmission System Operator S.A.
IAPG	Argentinian Institute of Oil & Gas
IBP	Brazilian Petroleum, Gas and Biofuels Institute
IEA	International Energy Agency
IED	Industrial Emissions Directive
ILC	Industrial Life Cycle
Inc.	Incorporation
IPC	Industry Partnership and Commercialisation
IPCC	Intergovernmental Panel on Climate Change
IPTO	Independent Power Transmission Operator
ISER	Informationsstelle Edelstahl Rostfrei (Information Centre Stainless Steel)
IT	Information Technology
LAGIE	Operator of Electricity Market
LCA	Life Cycle Assessment
LCOE	Levelised Cost of Energy
LDV	Light-Duty Vehicle
MAPA	Ministério da Agricultura, Pecuária e Abastecimento do Brasil (Brazilian Ministry of Agriculture, Livestock, and Food Supply)
MDG	Millennium Development Goal
MLP	Multi-level Perspective
MLP	Multi-Level Perspective
MPA	Mineral Products Association
MPIE	Max-Planck-Institut für Eisenforschun (Max Plank Research Institute for Iron)
NAP	National Action Plan
NDC	Nationally Determined Contribution
NECP	National Energy and Climate Plan
NFI	New Flyer Industries
NIIPS	Non-Interconnected Island Power Systems
NIS	National Innovation Systems
NMA	Norwegian Maritime Authority
NPRA	Norwegian Public Roads Administration
NSB	Norges Statsbaner (Norwegian State Railways)
NSTIS	National, Sectoral and Technology Innovation System
OECD	Organisation for Economic Co-operation and Development

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OICA	Organisation Internationale des Constructeurs d'Automobiles (International Organization of Motor Vehicle Manufacturers)
OPEC	Organization of the Petroleum Exporting Countries
OVEG	National Energy Program from Vegetable Oils
PCF	Pan-Canadian Framework for Clean Growth and Climate Change
PHEV	Plug-in Hybrid Electric Vehicle
PNPB	Programa Nacional de Produção e uso do Biodiesel (Brazil's Biodiesel Production and Use Program)
PPC	Public Power Company
PÜZ	Prüfung, Überwachen und Zertifizieren (Testing, Monitoring and Certifying)
RAC	Railway Association of Canada
RAE	Regulatory Authority of Energy
RES	Renewable Energy Sources
RIS	Regional Innovation Systems
SDG	Sustainable Development Goal
SEI	Stockholm Environment Institut
SIS	Sectoral Innovation Systems
SMEs	Small and Medium Enterprises
SMR	Steam Methane Reforming
SNM	Strategic Niche Management
SPEF	Association of Photovoltaic Energy Producers
SR	Smelting Reduction
SSB	Statistisk sentralbyrå (Statistics Norway)
TA	Technische Anleitung (Technical Instructions)
TAC	Transportation Association of Canada
THE	High-Temperature Electrolysis
TIS	Technological Innovation Systems
TNERP	Transitional National Emission Reduction Plan
TØI	Transportøkonomisk institutt (Institute of Transport Economics)
UICPs	University-Industry Co-authored Publications
UK	United Kingdom
UN	United Nations
USA	United States of America
USDA	United States Department of Agriculture
USGS	United States Geological Survey

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VAT	Value Added Tax
VCI	Verband der Chemischen Industrie (German Chemical Industry Association)
VDEh	Verein Deutscher Eisenhüttenleute (Association of German Steel Manufacturers)
VDZ	Verein Deutscher Zementwerke (German Cement Works Association)
WCI	West Climate Incentive
WEC	Wave Energy Converter
WV Stahl	Wirtschaftsvereinigung Stahl (German Steel Federation)
YPF	Yacimientos Petroliferos Fiscales
ZERO	Zero Emissions Resource Organisation

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Contents

The PARIS REINFORCE project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under grant agreement No 820846.

The PARIS REINFORCE project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under grant agreement No 820846.

Table of Figures

Table of Tables

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1 Greek case study: a sustainable lignite phase-out

This case study has been published in Nikas, A., Neofytou, H., Karamaneas, A., Koasidis, K., & Psarras, J. (2020). Sustainable and socially just transition to a post-lignite era in Greece: a multi-level perspective. *Energy Sources, Part B: Economics, Planning, and Policy*, in press. https://doi.org/10.1080/15567249.2020.1769773

1.1 Introduction

In the last decades, more than 80% of global electricity generation originated from fossil fuels (IEA, 2018b), with coal being the backbone of power generation systems; while electricity accounts for a quarter of the global greenhouse gas (GHG) emissions (Tranberg et al., 2019). In EU countries, 21.5% of the electricity produced came from solid fuels (mainly lignite and coal), in 2016, which are responsible for the majority of power generation-related CO_2 emissions. Therefore, considering also the increasing energy demand, a strategy aiming to reduce GHG emissions should focus, among others, to decarbonise the electricity sector by phasing out fossil fuels and introducing greener alternatives.

In 2017, Greece was responsible for approximately 2.2% of CO_2 emissions from fossil fuels in EU countries (IEA, 2019a), even though its electricity production accounts for less than 0.2% of total EU generation (IEA 2019). This means that the operations of the power sector are highly emissions-intensive, contributing 623 g CO_2/kWh in 2016, compared to almost half (295.8 g CO_2/kWh) of the EU average (EEA, 2018), a significant contribution considering the country's socioeconomic share in the region. Latest statistics (IEA, 2017) show that Greece's electricity system is coal-intensive, with lignite accounting for 34% of total production, followed by natural gas (31%). Another significant aspect of the electricity system is that a number of islands are not interconnected with the mainland grid, thereby addressing their electricity needs via operation of oil (diesel)-fired plants. The country has a very long tradition of lignite extraction: the Greek lignite-mining industry is one of the sector's leaders in Europe, and longstanding experience in mining operations has introduced important achievements (Kavouridis, 2008). Heavy reliance on lignite can be largely attributed to the abundant indigenous reserves and thus energy security and low energy costs can be achieved.

On the other hand, lignite mining and combustion have many adverse impacts on health, not only for residents nearby extraction areas, but also for the total population. According to the World Health Organisation, seven million people died in 2012, as a result of exposure to air pollution (Dam et al.,2017). Lignite is considered one of the world's environmentally most hazardous fuel (Arapostathis and Fotopoulos, 2019). A diversity of scenarios and pathways are proposed towards mitigating the GHG emissions associated with power generation. This research aims to review historical development of the Greek electricity system towards assessing the potential for decarbonisation by gradually shutting down lignite plants and increasing capacity of renewable energy sources, in a progressive coal phase-out, based on the country's pledges and recently announced plans. Given its role in the country's economy and energy security, this would entail a smooth transition, including new policies and adoption of new technologies. The trajectory towards this transition is investigated through the historical development of the Greek electricity system by determining which landscape factors have affected this process and how new low-carbon technologies, or niches, have commenced to replace some of the incumbent polluting electricity generation methods of the regime. This is accomplished by implementing the Multi-Level Perspective (MLP) framework, as thoroughly described in Section 1.3.

Our aim is to help understand how a low-carbon transition of the Greek energy system to a sustainable post-lignite era can be achieved. This study presents several aspects of the Greek electricity system, divided into two time periods, 1990-2008, and 2009-2017, orienting on the mark of the economic recession in Greece, which caused

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significant changes in energy use. The analysis is based on the Multi-Level Perspective (Rip and Kemp, 1998; Geels, 2002) framework, with the aim to shed light on the technological transformations from a socio-technical perspective. As such, the analysis is divided into three levels, in respect to the regime (energy demand and supply, installed capacities, structure and actors), the landscape factors, and niche technologies (renewables, hydrogen, carbon capture and storage, etc.).

Aside from the introduction, this research is developed in six sections. Section 1.2 further delves into the background of the study, discussing the importance of a transition to a post-lignite era in Greece. Section 1.3 discusses the use of the MLP framework in this domain; while Section 1.4 presents the analysis of the Greek electricity system regime as well as the landscape factors affecting it, in two time periods. Section 1.5 one presents the considered niche technologies that can replace conventional power plants, followed by their main benefits. Section 1.6 section draws from the findings to discuss where we currently stand, what is the institutional response to the outlined challenges, how the latter can be just, and what the impact of the discussed lignite phase-out can be on sustainability. Finally, Section 1.7 summarises the conclusions, limitations, and prospects of our study.

1.2 Lignite and other conventional sources in Greece: a 'dirty' life cycle

1.2.1 The importance of a lignite phase-out

There are various arguments for closing and replacing the lignite power plants operating in Greece, by other technologies; these are mainly of economic, climate/environmental and societal/health reasons. Here, we start by examining major socioeconomic and environmental aspects associated with lignite use per life cycle stage (Table 1), drawing from the literature (Donnes et al., 2007; Georgakellos, 2010; Roinioti and Koroneos, 2019). For a lignite power plant, these stages consist of the construction of the plant; the mining, processing and transportation of the necessary fuel; and power generation. Across all stages, lignite use for power generation creates a large number of jobs, directly for electricity production, indirectly for the supporting processes outside the plant, and induced related to the jobs created locally due to increased spending of employees involved with plant; however, the environmental costs, calculated based on the produced emissions and an external cost of €35 per tonne of CO_2 equivalent (Kaplanović and Mijailović, 2012), of the employment benefits are significant. The Levelised Cost of Electricity (LCOE) of a lignite power plant, relevant for assessing its financial viability, equals to €55/MWh (Rionioti and Koroneos, 2019).

Table 1 Lignite power plant life cycle CO_2 emissions and external costs

Life Cycle Stages	CO_2 emissions (kg/MWh)	Climate Change External Cost (€/MWh)	Direct employment (Job-years/TWh)	Indirect employment (Job-years/TWh)	Induced employment (Job-years/TWh)	Total employment (Job-years/TWh)
Power Plant Construction	30.00	1.05	14.6	9.0	4.5	28.1
Lignite mining, processing & transportation	20.00	0.70	119.5	39.3	84.8	243.6
Power Generation	1,230.00	43.05	104.3	19.8	54.2	178.3
Total	1,280.00	44.80	238.4	68.1	143.5	450.0

Sources: (Donnes et al., 2007; Georgakellos, 2010; Roinioti and Koroneos, 2019)

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The continuous exploitation of lignite has resulted in the enlargement and depth increase (over 200 meters) of the lignite mines. This fact has rendered the mines quite unstable and difficult to manage. This phenomenon has resulted in several landslides during the last decade, some of which have occurred nearby some villages and settlements of Western Macedonia (Zevgolis et al., 2019). Similar incidents have occurred in Poland, another (hard) coal-dependent country, sometimes corroding nearby roads (Bednarczyk, 2017). Furthermore, coal excavation has been correlated with the increase of seismicity in regions close to coal mines (Mirek and Mirek, 2011).

The operation of lignite plants poses a threat to the climate, biodiversity and well-being, since their operational procedures (combustion of lignite) evoke emissions of noxious gases in the atmosphere. As such, the EU has intensified efforts to restrict these emissions through regulations. Directive 2010/75/EU (European Commission, 2010) established the targets for the emissions of SO_2, NO_x and dust for the conventional production sources. Sulfur dioxide is considered responsible for increased mortality caused by cardiovascular and respiratory problems (Wu et al., 2020), while nitrogen oxides, apart from health problems, are related to several environmental problems, such as acid rain, the formation of photochemical smog and the creation of fine particles (PM) (He et al., 2019). Furthermore, the combustion of lignite is intertwined with the emission of several pollutants aside from CO_2, SO_2 and NO_x. These pollutants are called polycyclic aromatic hydrocarbons (PAHs) and are considered toxic and mutagenic. They may also have carcinogenic effects on humans and various living organisms (Nádudvari et al., 2018). All the aforementioned emissions may cause externality costs, which can reach up to 5€/MWh in the case of the Western Macedonia lignite power plants (Papagiannis et al., 2014).

Carbon dioxide aside, and in accordance with the aforementioned directive, Greece developed the "Transitional National Emission Reduction Plan" (TNERP) with the Joint Ministerial Decision 34062/957/E103 – Official Government Gazette 1793/B/20.08.2015, setting progressive emission targets for lignite plants from 2016 to 2020 with the obligation to perform actions in order to achieve emissions reduction on a level of 200 mg/Nm^3 both for SO_2 and NO_x. Each plant was at liberty to reach this target by 2020 given that the total emissions followed the directions of TNERP. Towards this direction, the Greek Government has introduced a more ambitious version of its draft National Energy and Climate Plan (NECP), which mandates the shutdown of all lignite plants operating in Greece by 2028 at the latest, starting with old plants and shifting fuels in the most recently constructed one. This is a measure taken by the Greek Government in compliance with the EU's targets for GHG emissions reduction, which submitted its first Nationally Determined Contributions (NDC) for climate action following the Paris Agreement, setting a target of a 40% reduction in GHG emissions by 2030 in comparison with 1990 (Fragkos et al., 2018), with a view to increasing efforts in the upcoming 2020 update.

In 2018, the power plants of Amyntaio, Kardia, Agios Dimitrios, Melitis and Megalopoli released annual reports (Ministry of Energy 2018a; 2018b; 2018c; 2018d; 2018e; 2018f) regarding the environmental parameters of their operations, as obliged by the Ministry of Environment and Energy. The results regarding the average monthly emissions are presented on the following table.

Table 2 Average monthly emissions by power plant

Life Cycle Stages	SO_2 (mg/Nm^3)	NO_x (mg/Nm^3)	PM (mg/Nm^3)
Amyntaio	816	227	50
Kardia I	169	238	118
Kardia II	173	203	94
Kardia III	195	301	37
Kardia IV	305	209	39
Agios Dimitrios	276	257	17.6

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Melitis	200	130	1.2
Megalopoli A	154	111	2.5
Megalopoli B	100	128	10

Source: Ministry of Energy (2018a, 2018b, 2018c, 2018d, 2018e, 2018f)

In Figures 1(a-c), a comparison of the results with the targets is presented. For dust, the baseline was taken directly from the Directive since the TNERP does not establish a specific target.

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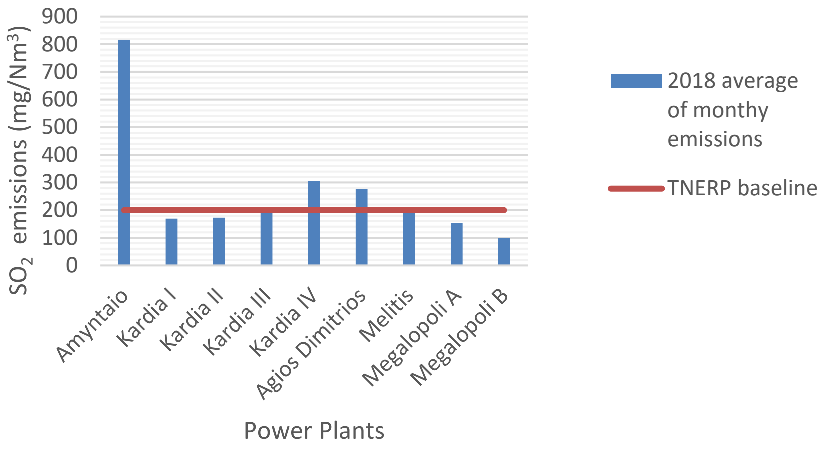
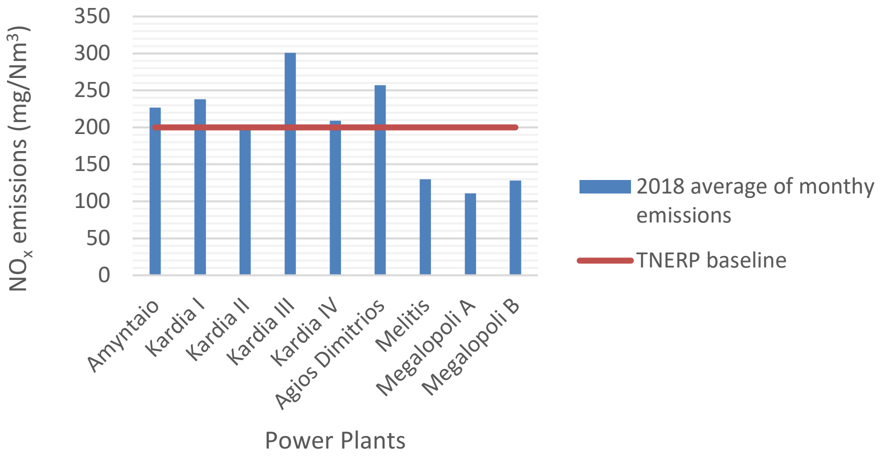
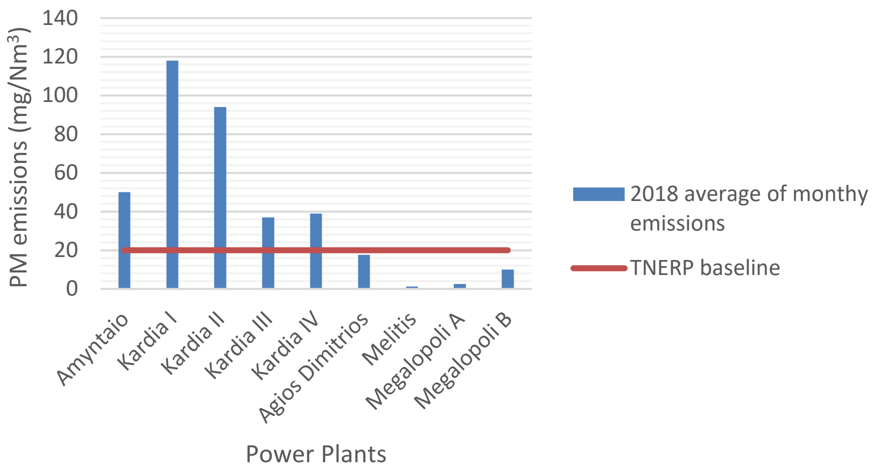


(a)



(b)



(c)

Figure 1 Monthly average SO_2 (a), NO_x (b) and dust (c) emissions for 2018

Source: Ministry of Energy (2018a, 2018b, 2018c, 2018d, 2018e, 2018f) and the 2015 TNERP; own elaboration

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Evidently, the power plants of Melitis and Megalopoli have already reached their targets. The units of Agios Dimitrios have not yet met their target, since the implementation of a dry flue-gas desulphurisation (dry FGD) process in not feasible for all units, therefore a wet-FGD process should be installed, but are expected to achieve it by 2020 according to the 2015 TNERP.

On the other hand, the plants located in Amyntaio and Kardia perform poorly because they operate on a limited basis, therefore they are not bound by the same targets as the other units. However, even though they are on limited operation, the emissions are rather high on the hours that they produce energy, so it is important for the phase-out of lignite to begin by further limiting the hours of production from these units.

Another important factor is that the TNERP is ending in 2020. Meanwhile, in 2012, the United Nations Rio+20 Summit recommended the adoption of the 2030 Agenda for Sustainable development, broken down into 17 Sustainable Development Goals (SDGs), as a pathway to sustainability towards 2030 (Griggs et al., 2013). These goals constitute an extension of the Millennium Development Goals (MDGs), from 2000 to 2015, in order to achieve social priorities worldwide (Sachs, 2012). Out of these goals, SDG12 set targets on production and consumption patterns, with emphasis on regulating the practices of private actors (Gupta and Vegelin, 2016). Even though actions have taken place, Greece is performing poorly in this respect, as presented in the Sustainable Development Report 2019 (Sachs et al., 2019), especially on the metrics of emissions regarding the production-based SO_2 emissions, the imported SO_2 emissions and the nitrogen production footprint. This indicates that, in order to achieve sustainability by 2030, more actions need to be implemented, especially focusing on the complete phase-out of lignite, since the mitigation of emissions, even through best available techniques (BAT), could only reach adequate levels of environmental protection (Cikankowitz, and Laforest, 2013).

1.2.2 Other fossil fuels

Diesel, a fossil fuel with high transportation capacity, is mainly used in the numerous islands not interconnected to the mainland grid. A major concern lies in the carbon footprint of diesel combustion for electricity generation. According to the literature (Georgakellos, 2006; 2010; 2012; Jungbluth, 2007), the CO_2 emissions traced in the different life cycle stages of oil use for power generation, along with their externality costs for climate change, are displayed in Table 3.

Table 3 Diesel power plant life cycle CO_2 emissions and external costs

Life Cycle Stages	CO_2 emissions (kg/MWh)	Climate Change External Cost (€/MWh)	Climate Change External Cost (%)
Power Plant Construction	1.65	0.06	0.20
Crude Oil extraction & Processing	7.00	0.24	0.83
Crude Oil Transportation	13.00	0.46	1.54
Crude Oil Refining	42.00	1.47	4.98
Fuel Oil Transportation	0.58	0.02	0.07
Power Generation	780.00	27.36	92.38
Total	844.23	29.55	100.00

Sources: (Georgakellos, 2006; 2010; 2012; Jungbluth, 2007)

Diesel combustion in the country's power generation mix is also associated with employment benefits (Kis et al.

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2017), as presented in Table 4. The LCOE of a diesel power plant is 76.28€/MWh (Strantzali et al., 2017).

Table 4 Jobs created by a diesel power plant

Life Cycle Stage	Job-years/ TWh
Materials extraction & beneficiation	5.4
Power Plant Manufacturing	6.48
Construction/Installation	21.6
Fuel Transportation	11.52
Operation	97.2
Maintenance	7.2
Total	149.4

Finally, natural gas is increasingly used for electricity generation in the country, which however exploits negligible amounts of its natural gas resources (Newman, 2013). Although it has been gaining ground as a cheap alternative to lignite and a potential solution for the intermittency of a wide-scale RES deployment, backed by its competitiveness for energy storage (Elliott, 2016), further increase of natural gas use could lead to Greece becoming heavily dependent on importing energy from other countries to cover the electricity demand, and therefore potentially vulnerable to economic and political pressure (Roupas et al., 2011; Antosiewicz et al., 2019). However, natural gas produces less emissions in comparison with lignite and fuel oil as shown in Table 5.

Table 5 Natural Gas power plant life cycle CO_2 emissions and external costs

Life Cycle Stages	CO_2 emissions (kg/MWh)	Climate Change External Cost (€/MWh)	Climate Change External Cost (%)
Power Plant Construction	1.81	0.06	0.45
Natural Gas extraction & Processing	1.51	0.05	0.37
Natural Gas Transportation	3.37	0.12	0.83
Power Generation	400.00	14	98.35
Total	406.69	14.34	100.00

Sources: (Bauer, 2008; Dones et al., 2007; Fritsche et al., 2009; Georgakellos, 2010; 2012; Hawkes, 2010)

Despite its large share in the national energy mix, natural gas (with an LCOE of €87/MWh) is associated with lower employment benefits (Roinioti and Koroneos, 2019), compared to lignite and diesel (Table 6).

Table 6 Jobs created from a natural gas power plant

Direct Employment Factors	Direct (Job-years/ TWh)	Indirect (Job-years/ TWh)	Induced (Job-years/ TWh)	Total (Job-years/ TWh)
Construction	4.0	2.5	1.2	7.7
Operation	51.3	9.7	26.0	87.0
Fuel extraction and transportation	-	-	-	
Total	55.3	12.2	27.2	94.7

Source: (Roinioti and Koroneos, 2019)

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From the previous tables, it is evident that total job years for lignite are significantly higher than those of natural gas and diesel further indicating a problem potentially arising from a lignite phase-out.

1.3 Methodological approach

The Multi-Level Perspective (MLP), originally developed by Rip and Kemp (1998) and further developed by Geels (2002), consists of an analytical framework to study sociotechnical transitions and understand innovation systems. The MLP focuses on the creation of qualitative scenarios to examine the interactions and dynamics between three different levels: the landscape (macro-level), the regime (meso-level) and the niches (micro-level) forming a nested hierarchy as seen on the following figure.

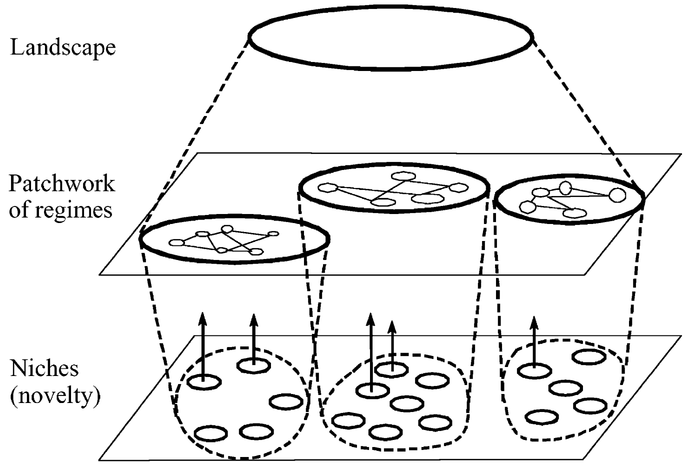

Figure 2 Multiple levels as a nested hierarchy

Source: Geels, 2002, p. 1261

On the micro-level, niches provide the environment for radical innovations to be created and developed (Schot, 1998), and progressively breach to the meso-level disturbing the balance of the socio-technical regime, an extension of the technological regime, established by Nelson and Winter (1982). Inside the socio-technical system, social groups, actors and practices or structures are interlinked (Geels, 2005b) determining the natural trajectories caused by the dynamic relationships following a specific set of rules. The meso-level is situated inside the exogenous environment of the macro-level, formed by the sociotechnical landscape, which influences the sociotechnical development on a wider aspect.

Even though the MLP focuses on the transition towards sustainable development (Geels, 2011), several studies deal with cases deriving from different sectors. Congdon et al. (1997) examined the small-area health and mortality of England and Wales; Where the MLP was used for the wider contextual effects between health and socioeconomic conditions. On a similar aspect of public health and personal hygiene, Geels (2005a) used the MLP for the transition in water supply as a process of co-evolution of technology and society. The necessity for coexistence and flexibility between the niches and the mainstream context is also stressed by Smith (2007), by analysing the green niches of eco-housing and organic food; the considerably low diffusion of these technologies is attributed to them being considered as radical niches requiring severe changes in the existing regime.

On the other hand, Geels (2005c) presented three historical case studies regarding the transport sector: the transition from propeller-piston engine aircrafts to turbojets in civil aviation, as an example of the technological substitution route following the landscape development of the Second World War; the transition from horse-drawn carriages to automobiles in land transportation, describing the wider transformation route as a result of problems in the regime; and finally the transition from sailing ships to steamships. The third case, also examined in Geels (2002) for the period of 1780-1900, presents an interesting example of interactions between the niche

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and the regime as the steam engines where initially used as an auxiliary device to sailing ships before their establishment as the dominant technology. This paradigm furthers the argument that effective diffusion of niches could happen by progressively changing and coexisting with the regime. Therefore, Nykvist and Whitmarsh (2008) expanded the niche concept to include numerous innovations driving the transition of the transport sector of the UK and Sweden. Specifically, since policy measures had little effect relative to the growth in demand, the transition of the existing regime towards sustainable mobility is based on three approaches: technological improvements of vehicles; sustainable models of travel, such as public transport; and travel planning with emphasis on the implementation of information and communications technologies. These approaches differ from a classical approach of the niche, such as the transition to a floating grain elevator in the port of Rotterdam in 1901 (Van Driel and Schot, 2005), where an innovative technology regarding cargo handling created pressure on the regime, even though there was no pressure from the socio-technical landscape for such a change. Necessity for such expansions in transport is due to the existence of multiple regimes, which in some cases contain local elements contributing to the fact that the automobility regime seems fairly stable in contrast to other sectors (Geels, 2012).

Even though the transport sector presents differences from other sectors, lessons learnt from examining such case studies could be used in the transition towards low-carbon economies. Indicatively, McDowall (2014) examined possible transition scenarios to a low-carbon economy on the UK, based on hydrogen energy, which could mainly be used in vehicles as hydrogen fuel cells.

Regarding the low-carbon transition, the MLP has been used in numerous case studies providing valuable theoretical insights. Similarly to the objectives of PARIS REINFORCE, Sluisveld et al. (2017) inserted the rich information provided by the qualitative narrative of the MLP to integrated assessment models (IAMs), to build a case study for Europe, examining the approach towards meeting the European Unions' 80% emission reduction objective for 2050. On the same axis, Geels et al. (2018) combined computer models with the MLP to create socio-technical scenarios of the UK electricity sector. The MLP approach helped explore problems of social acceptance and political feasibility in low-carbon transitions, further elaborating on the introduction of politics in the MLP from Geels (2014), who focused on the role of actors instead of green niches, concluding that the decline of existing fossil fuels in the regimes should be further considered and studied. Similarly, Rogge et al. (2020) also coupled quantitative modelling with the MLP to study the transition of the German electricity system towards renewable energy in accordance with the 80% emission reduction target by 2050. Drawing from the typologies of Geels and Schot (2007), the transition paths recognised included the technological substitution and wider regime transformations with the analysis focusing on solar photovoltaics (PV), onshore and offshore wind, bioenergy, and smart meters. A different approach was followed by Edsand (2017), who used another Systems of Innovation tool, the Technological Innovation System (TIS) (Carlsson and Stankiewicz, 1991), to explain the slow diffusion of wind energy in the electricity sector of Colombia. Since the TIS approach focuses on a specific technology, the MLP can be used to evaluate the broader context of the landscape and the regime, leading to an integrated framework (Markard and Truffer, 2008). Moallemi et al. (2017) also addressed limitations by creating a theoretical framework to explain the specific dynamics of the phase-in of renewable sources in the electricity system of India, by combining the MLP with the Multi-Pattern Approach (de Haan and Rotmans, 2011), a conceptual framework of driving forces of transformative change (Frantzeskaki, 2011), the actor-option framework (Yücel, 2010) and tools for Integrated Sustainability Assessment within the Methods and Tools for Integrated Sustainability Assessment (MATISSE) project (Weaver and Rotmans, 2006).

Verbong and Geels (2007) used the MLP approach in the Dutch electricity system to explain how the regime, analysed in three different periods, is undertaking a progressive transition driven by liberalisation and Europeanisation rather than the diffusion of niche technologies; since the implementation of renewable sources is low compared to other European countries, they suggested that add-on technology and adjustments on existing

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techniques of the regime could result in substantial environmental benefits. This observation leads to the conclusion that the MLP places significant focus on technological niches as the main locus for regime change in the transition process (Berkhout et al., 2004; Geels, 2011). However, as already stressed, effort could also be placed on the transformation of the regime and not just the niches (Geels, 2014) or by expanding the existing approach for the niches (Nykvist and Whitmarsh, 2008).

On this research, acknowledging the complexity of interactions between these three levels and between policies themselves (Oikonomou et al., 2012; Oikonomou et al., 2014), we build upon these ideas by using the MLP framework to study historical development of the transition of the Greek electricity system towards decarbonisation and sustainability considering the transformation of the existing regime driven by the phase-out of lignite, rather than simply focusing on the phase-in of renewable source niche technologies. We also delve into the landscape factors influencing the system, to determine how establishment of niche technologies depend on these factors. Landscape factors can hinder niche development, but they can also generate severe barriers for the continuation of the regime, creating a friendlier setting for the penetration of niche technologies (Köhler et al., 2019). The analysis of the progress that has been achieved so far will provide valuable insights into the main drivers and difficulties leading or hindering the transition, as well as shed light on pathways to be followed after the examined period to reach the envisaged targets in a socially just manner.

1.4 The Greek regime and landscape factors

A brief look at the events preceding the examined period, for which there is little data availability and consistency (Doukas et al., 2007), shows that the first power generation unit was installed in 1889 by a private company for lighting the centre of the city; while in 1918, 1929 and 1939 there were 21, 242 and 390 settlements respectively supplied with electrical power. In 1950, the Public Power Company (PPC) was established to render electricity widely available and supply all households; and the first lignite combustion power unit was installed in Aliveri, operated by PPC, thereby contributing to the 230MW of total installed capacity. In 1955, the first hydroelectric power plants were constructed near the rivers Agras, Ladonas and Louros; while a year later the transmission grid was 1,125km long, via 150kV lines (Papadopoulos, 2018), and the private company LIPTOL was established in Ptolemaida to exploit and utilise the lignite reserves for electricity production until 1959 (IENE, 2012), before gradually being merged with PPC—the merge was completed in 1975. In 1966, with PPC having already acquired the majority of private companies, new diesel units were constructed to cover the electricity needs in islands (including Crete), which were not interconnected with the mainland grid (Papadopoulos, 2018). The exploitation of another lignite reserve started in 1969 in Megalopolis (IENE, 2012), and later in 1980 the first wind farm was constructed in Kythnos island (Fotiadi, 2009).

1.4.1 The calm before the economic storm

1.4.1.1 Regime

1.4.1.1.1 Energy demand and supply

In the first 19-year period (1990-2008), electricity consumption in Greece was steadily increasing (Figure 3a), mainly due to economic development, population increase and temperature rise (Asimakopoulos et al., 2012). Consequently, electricity generation follows the same pattern (Figure 3b). In 2008, electricity consumption nearly doubled compared to 1990, while production increased by 82%. Electricity production from coal accounted for 72% of the total production at the beginning of this period, progressively decreasing to 52% at the end of the period, while the share of natural gas showed an increase from nearly zero to 22% (IEA, 2017). By 1990, twenty

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coal combustion units had been constructed, while one had already closed. During 1990-2008, three more units were constructed. The total installed capacity, excluding the closed plant, accounted for 4,776 MW. Figure 3c depicts the total installed capacity per year for each technology (conventional and RES) for both the interconnected and the non-interconnected system.

The first natural gas combustion plant was installed in Lavrio, Attica, in 1996, with a capacity of 174 MW (Kaldellis et al., 2005). The installation was an important milestone for the Greek energy sector, due to the exclusive dependence on lignite combustion during the preceding period. The use of natural gas partially undermines the energy independence of Greece, since Greece exploits negligible amounts of national resources (Newman, 2013) but produces less CO_2 emissions in comparison with the use of lignite. During this period, nine plants were installed with a total capacity of 2,794 MW of (LAGIE, 2019b).

Another important contributor to electricity production was hydro plants, which can be divided based on their capacity, to small and large plants. According to Law 3468/06, Art. 9, small hydro plants are considered renewable sources. During this period, large hydro plants accounted for 3,017 MW (TEE, 2016), and combined with the small units averaged a percentage of 8% of total production (IEA, 2017). Moreover, four diesel plants of 698 MW in total, operated to produce electricity (LAGIE, 2015).

A significant characteristic of the system was that 33 islands in the Aegean were not interconnected with the mainland system and thus 35 diesel units, of 1,367 MW totally, operated independently, to cover the local electricity needs (RAE, 2001). The non-interconnected island power systems (NIIPSs) comprise a significant part of the Greek economy and energy sector, accounting for 10% of electricity consumption and serving 15% of the nation's population (Hatziargyriou et al., 2017). The diesel plants, from both the interconnected and the non-interconnected system, accounted for 18% of the production, on average (IEA, 2017).

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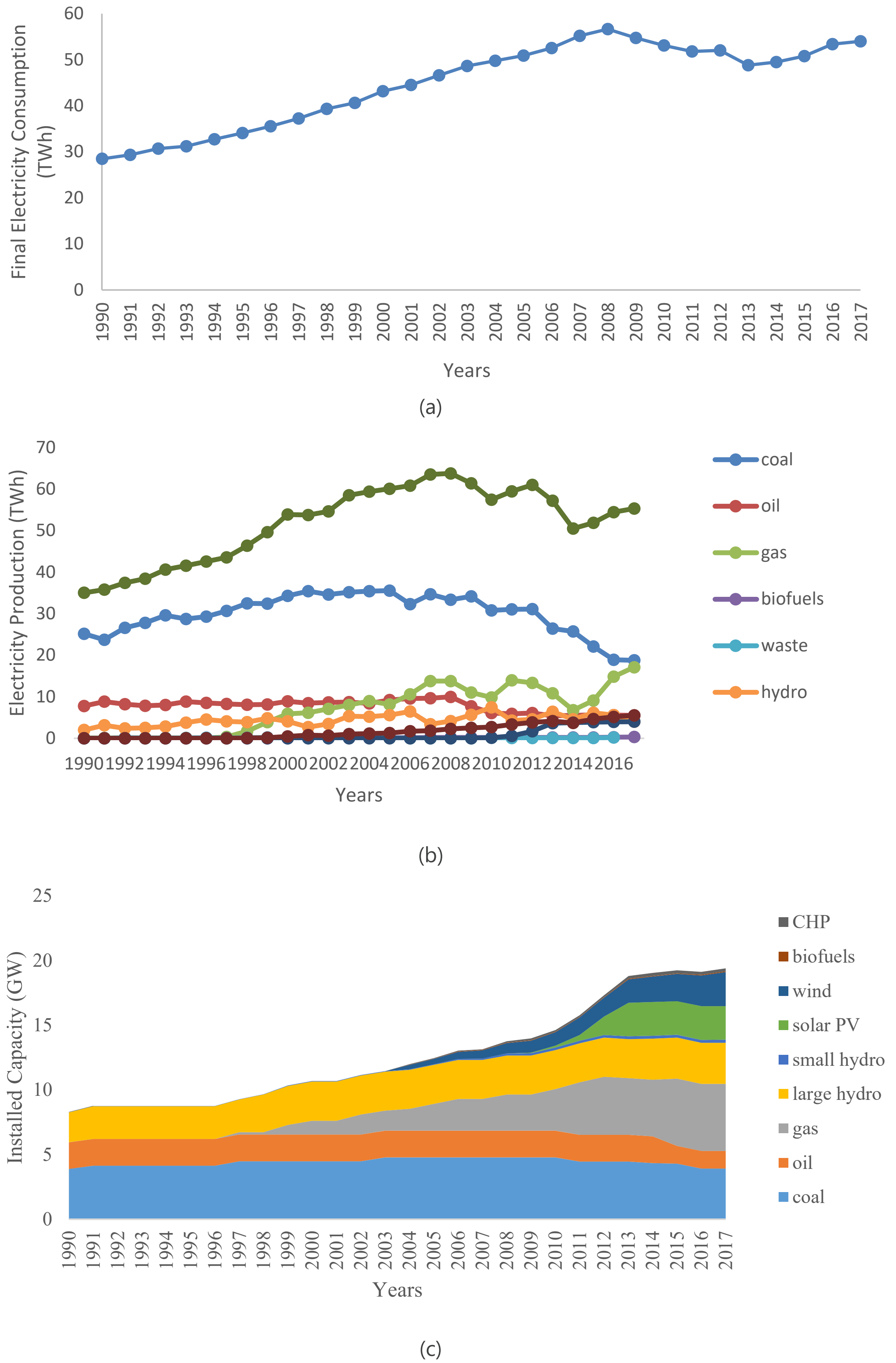

Figure 3 Electricity consumption (a), production (b) and total installed capacity (c) in Greece, 1990-2017

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Sources: IEA (2017), ADMIE (2019), Argyriadis and Bonataki (2006), LAGIE (2015), LAGIE (2019a, 2019b, 2019c), RAE (2013), RAE (2014), TEE (2008), TEE (2010); own elaboration

At the beginning of this period, liberalisation of the RES market took place in 1994 (Agoris et al., 2004). This was the first attempt of the Greek state to establish a greener energy mix. In 2006, Greek legislation integrated a framework for the penetration of PV parks into the power generation mix (Giannini et al., 2015). This was another act towards a greener electricity generation sector, especially for Greece, which is amongst the European countries with the highest amounts of solar radiation (Celik et al., 2009).

In 1999, an impressive growth of wind power was observed (Kaldellis, 2005), signifying the penetration of wind power into the electricity generation market and the start of large-scale renewable energy generation in Greece. Sequentially, energy independence was increased, mitigating the negative effect of introducing natural gas in the electricity sector. The share of wind farms accounted for 0.01% at the beginning of the period, rising to 3.5% in the end, showing a steady increase from the low early percentages (IEA, 2017). The total capacity of wind farms at the end of the period was 791 MW (LAGIE, 2019a). Small hydro plants had a capacity of 158 MW (LAGIE, 2019a), accounting, together with the large ones, to 8% of total production. It should also be noted that biofuels are another source to have contributed 0.3% of the electricity production in 2008 (IEA, 2017). The first biomass plant for electricity generation was constructed in 2001 (IEA, 2017), combusting agricultural waste for electricity generation rather discarding it, thereby contributing to more efficient waste management and emissions-free energy production.

PPC was the sole owner of the electricity transmission system in 2007. The system was composed by lines of a total length of 11,500 km, consisting of single-circuit lines of 66kV as well as single- and double-circuit lines of 150kV and 400kV (Lioutas et al., 2007). The 400kV lines aimed to transfer the energy produced in northern Greece towards the centre and south, where most of the electric load was concentrated (Orfanos et al., 2019). At the time, the Southern area of Peloponnese consisted mostly of 150kV lines, which transferred the energy produced by Megalopolis 1 and 2 (Lioutas et al., 2007).

1.4.1.1.2 Structure and actors

Actors

The main actor in the Greek electricity system for several years had been PPC, the biggest electric power producer and supplier in Greece, with over 7 million customers—today, the company is responsible for approximately 68% of the total installed capacity in Greece, consisting of conventional thermal and hydroelectric power plants and RES units. PPC was a monopoly until 2004, after which point each non-residential consumer could select their electricity supplier. The liberalisation of the electricity market was completed in 2007 when selection of supplier was extended to residential consumers (RAE, 2019a).

During this period, four new companies were established to supply electricity to the market: (a) Zenith, established in 2000; (b) Heron, established in 2001 and now operating two electric power stations (of total capacity of 600 MW) corresponding to 5% of the total installed capacity in Greece, and a strong presence in the retail electricity supply market with a market share of 3% since 2010; (c) PROTERGIA, established in 2001 with a current energy portfolio of over 1,200 MW, exceeding 13.5% of the country's installed thermal generation capacity; and (d) ELPEDISON, established towards the end of this first era (2006), operating a gas-fired power plant in Thessaloniki (400 MW) and later becoming a major alternative supplied with more than 50,000 active customers.

Other energy players (Doukas et al., 2008), not falling under the categories of suppliers or producers, also exist, with their main operations including the regulation, monitoring or support of the market and the relevant activities

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of the energy sector. Among them, the Regulatory Authority of Energy (RAE) and the Center for Renewable Sources and Energy Saving (CRES) are the most notable. RAE, founded in 1999, is an independent regulator for electricity and gas. Its primary responsibility is to oversee the domestic energy system, aiming to liberalise the electricity and gas markets. In addition, RAE has been entrusted with the task of consulting, monitoring and controlling the energy market in all sectors, such as the production of electricity from conventional fuels, renewable energy and gas, as well as assuming responsibilities related to the petroleum market. In particular, RAE monitors and oversees the operation of the domestic energy market; and studies, takes and communicates the necessary measures and/or makes recommendations to the competent bodies. Lastly, it monitors the level of transparency, including wholesale prices, and ensures that the energy-efficient companies comply with their transparency obligations. CRES is the national body for RES, rational energy use and energy saving, founded in September 1987 and enjoying financial and administrative autonomy. Its main purpose is to promote applications at national and international level, as well as to support all activities in the above areas, with a view to reducing the environmental burden on energy production and transport. CRES has a scientific staff of more than 120 scientists, experienced and specialised in the fields of its activity. During its operation, it has been active both as a research and technology centre for RES, developing applied research on new energy technologies and technically supporting the market for the penetration and implementation of new energy technologies; and as a national energy centre, studying energy planning, energy policy and energy saving issues, and developing the necessary infrastructure to support the implementation of RES investment programs.

Other organisations contributing to the effective operation of the electricity system include the Hellenic Association of Renewable Energy Producers (HellasRES), a non-profit company established in March 1997 comprising companies in the domain of constructing and operating RES projects and aiming to promote RES and coordinate actions towards common goals; and the Hellenic Association of Photovoltaic Companies (HELAPCO), a non-profit urban corporation founded in 2002 by the leading companies active in the production, trading, installation and maintenance of PV systems in Greece and aiming to develop a healthy and sustainable PV market, by establishing guaranteed selling prices for feed-in-tariffs and focusing on introducing incentives for home photovoltaics, simplifying licensing and creating green jobs.

Legislation

Laws are another important institutional part in any system, affecting its development and defining on a big scale its course. The main relevant regulations of this period are analysed with a focus on the contribution to the sustainable restructuring of the national energy system. According to Law 1468/1950 – Official Government Gazette 169/7.8.1950, the PPC took form in 1950 with exclusive privileges in the construction, operation and exploitation of hydro and thermal power plants, as well as in the transmission and distribution system. Half a century later, with Law 2773/1999 - Official Government Gazette A' 286/22.12.99, there was a first attempt to open the electricity production’s market to competition by allowing individuals to produce electricity from RES, combined heat and power (CHP) and conventional sources; while RAE was formed as an independent and autonomous administrative authority to regulate the energy system and PPC transformed into an Autonomous Society (S.A.).

One year later, continuing the effort to create an open market, Presidential Order 328/12.12.2000 established the Hellenic Transmission System Operator S.A. (HTSO) in order to operate and ensure the maintenance and development of the Electricity Transmission System. The company was owned by the state (51%) and the producers (49%).

The opening of the market expanded, from generation to supply, with Law 3175/2003 – Official Government Gazette A’ 207/29.08.2003, which amended paragraphs of Law 2773/1999 - Official Government Gazette A'

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286/22.12.1999, in order for any individual domestic client to be able to choose the source of consumed energy by 2007, while for non-domestic clients the option was available by 2004. This law was a response to the European Directive 2003/54/EC.

Law 3468/2006 - Official Government Gazette A' 129/27.6.2006 prioritised the injection of energy from renewable sources and independent producers, introducing net-metering. The law also defined a feed-in-tariff (FIT) scheme, according to the type and capacity of the installation. Different levels of targets were established varying from 73 €/MWh for on-shore wind turbines, to 450€/MWh for photovoltaic installations not exceeding 100kW$_p$, while these values were slightly increased for non-interconnected islands.

1.4.1.2 Landscape

The Greek electricity regime is a complex central component of the Greek energy sector; hence, it is affected by a wide variety of exogenous landscape factors, which are of technical, social, economic and political nature. It should be noted that, in this analysis, we acknowledge that boundaries between regime and landscape can be blurry at times (Upham et al., 2014): policy and regulations, in particular, can be viewed both as drivers of niche developments and as macro-level processes that relate to drivers of change originating within the regime or political settings of the landscape. Here, however, we consistently classify legislation as part of the Greek regime, and only highlight regulatory drivers of changes to the regime as landscape factors.

One of the main and initial factors that defined the Greek electricity system and the dominance of lignite was the abundant ***indigenous lignite reserves***, exploiting which minimised the need for imports and therefore boosted the country's energy security. At the time, Greece was the second largest lignite producer in the EU and fourth in the world, mining 70 Mt of lignite annually (Kavouridis, 2008). Lignite combustion was considered a very prosperous power generation option, especially after World War II and the Greek Civil War, both of which severely deteriorated the national economy in the 1940s; and decades later was still considered a driver of economic growth and energy security, despite its carbon and environmental footprint (Kolovos, 2006).

Lignite exploitation has also driven the ***structure of the energy transmission grid***. Most of the mainland grid was constructed so as for the generated electricity of the concentrated lignite plants to be easily transmitted to every city, town and settlement in the country, contributing to the technological lock-in of the country's power generation mix. The latter, combined with the part (15%) of the population being located on the non-interconnected islands (Spilanis, 1999), contributed to RES penetration in the Greek energy mix slowing down.

Later in this period, ***climate change*** started gaining cognitive ground as one of the major problems of the human society, and was therefore both socially and politically prioritised, with the aim to avoid its perilous consequences. It is noteworthy that a survey in 2002 showing 63% of people in Greece claiming to be very worried about climate change, showcasing the importance of climate change as a landscape factor in Greece (Markantonis & Bithas, 2009). In this direction, the electricity sector started showing efforts to turn to more sustainable energy resources, such as wind and solar power as well as to substituting coal with natural gas.

Another important factor was the ***EU policy framework*** in this direction, with the establishment of the emissions trading system (in 2005) towards the end of this first period (Neuhoff et al., 2006) and with the regulations and directives for carbon-intensive sectors (van der Gaast et al., 2013), with which the national framework struggled to harmonise. The impact of this measure was visible on the Greek electricity system, unexpectedly (Papadelis et al., 2013), from its first year of implementation. As shown in Figure 3.b electricity generation from lignite in 2006 decreased by 6% compared to 2005. In 2007, the EU also set its environmental targets for 2020, which included mitigation of GHG emissions by 20%, reduction of energy consumption by 20%, and 20% penetration of RES in the energy mix (Da Graça Carvalho, 2012).

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Another important milestone for the Greek electricity sector was the legislation of a national allocation plan in 2002 aiming for reducing GHG emissions by 25% for the period of 2008-2012 and increasing RES production share to 20%., by 2010, thereby ratifying the Kyoto agreement commitments (Chalvatzis and Hooper, 2009). However, according to the national allocation plan, electricity demand was expected to increase during the decade, which meant that the targets would not be reached.

The ***political agenda of the active governing party*** for a given period is also a crucial factor influencing progress of the electricity sector. In Greece, this period followed a short yet significant political uncertainty (in 1989-1990) but was marked by relative political stability, seeing two parties sequentially taking control. However, the political agenda of the governing parties, from the conservative New Democracy (1990-1993) to the centre-left Panhellenic Socialist Movement (1993-2004) and back to New Democracy (2004-2007), featured varying ideological orientation regarding the energy sector, climate change aspects and diplomatic ties with neighbouring countries, with different implications for the country's energy security (Doukas et al., 2011) and choice of energy imports.

In the middle of this period, in 1999, the Greek parliament legislated the ***liberalisation of the electricity generation sector*** (RAE, 2019a), which constituted another landscape factor that allowed private investors to construct and operate power plants (Iliadou, 2009). This eventually resulted in the construction of several natural gas plants by private investors, leading to the reduction of lignite combustion, and therefore to a greener energy mix.

In 2003, the Greek government also legislated the formation of a mandatory pool system for electricity generation and wholesale supply, serving the entire market of the mainland grid: all suppliers were obliged to purchase electricity from the pool and every electricity plant operated on a bid selection basis. In line with the limited non-residential liberalisation, industrial and commercial consumers became eligible to purchase energy from a supplier other than PPC; this was not the case for the non-interconnected islands. The option was provided to household consumers of the mainland grid three years later (Iliadou, 2009).

The power generation mix is usually affected by the ***imports dependency*** and the ***energy security*** of a country or region. Greece's natural gas supply was completely dependent on imports from the Russian Federation (via the Greek-Bulgarian border) and Algeria (in liquid form) (RAE, 2019b), making the country's power generation mix partially dependent on diplomatic relations with these countries. As such, Greece grew vulnerable to political and economic pressure, as such leverages have previously been used such in central and eastern European countries (Antosiewicz et al., 2019).

1.4.2 Post-recession developments (2009-2017)

The global financial crisis of 2008 affected several economies (Ivashina and Scharfstein, 2010) and the investment capability of many non-financial firms (Gao and Yun, 2009). Being among the countries hit hard by the recession (Nikas et al., 2019a), Greece entered a long-lasting financial crisis, which constituted a significant external factor affecting the electricity system (Doukas et al., 2014b) and marked a central point on the historical development of the system.

1.4.2.1 Regime

1.4.2.1.1 Energy demand and supply

After the emergence of the economic crisis in Greece, a reduction in energy consumption (Figure 3a) and production (Figure 3b) was observed. In 2009, consumption fell by 3.4% in just one year and then continued falling until 2013, reaching a 14% reduction compared to 2008. In 2014, there started a recovery in consumption, and in

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2017 it was only 5% lower than in 2008 (IEA, 2017). These impacts were reflected in electricity production as well; however, it is noteworthy that, after 2014, at which point more than half of the electricity produced came from lignite, the share of lignite in the power generation mix started shrinking. At the end of this period, in 2017, the share was as low as 34% (IEA, 2017), accompanied by a respective increase in the share of natural gas. This period was also characterised by no new coal combustion plants being constructed, with eight of them in fact shutting down. Thereafter, the remaining capacity was 3,912 MW (LAGIE, 2019b).

Covering the country's electricity needs emerging from the reduction of coal-based production required natural gas to gain ground, also reflected in five new gas plants being constructed as opposed to three old ones shutting down in this period, with gas having a total capacity of 5,188 MW in 2017 and a share of 31% of the electricity produced (LAGIE, 2015; Argyriadis and Botanaki, 2006). This positive trend, along with the decline of domestic lignite use, could eventually undermine Greece's energy independence (Newman, 2013), as discussed above. Large hydro plants accounted for 3,172 MW during this period (TEE, 2016). As for the diesel plants, there are still several units in the non-interconnected island system, accounting for 10% of total production in 2017, with only a few islands having replaced them with renewable sources. In the NIIPS, heavy fuel oil electricity generation constitutes 81.3%, wind 13.45% and solar PV 5.25% of the electricity produced in 2016 (Orfanos et al., 2019). This means that non-mainland electricity generation is heavily dependent on fuel imports, since Greece has in sufficient oil reserves (Tsirambides and Filippidis, 2012).

In 2011, the power generation mix changed drastically because of the sudden penetration of PV power plants into the grid (Kyritsis et al., 2017). This contributed to boosting energy independence reducing GHG emissions.

RES had started having a significant role after 2009, driven mainly by the increasing electricity generation from wind and solar. Small hydro plants kept having a steady contribution throughout this period, slightly higher than the previous one by around 10% (IEA, 2017). The capacity of small hydro plants (in the interconnected system) increased at 230 MW (46% higher than in 2008) (LAGIE, 2019a). Hydro plants also emerged in the non-interconnected system having a total capacity of 1.35 MW (LAGIE, 2019c). Electricity production from wind accounted for 10% at the end of 2017 with a total capacity of 2,300 MW in the interconnected (LAGIE, 2019a) and 323 MW in the non-interconnected system (LAGIE, 2019c). PVs featured an ascending trajectory, since in 2017 their contribution to electricity production had increased by 79% compared to 2009 (with a 7% share in total production). In the interconnected system, there were 2,445 MW of solar power in parks and on rooftops (LAGIE, 2019a); while in the non-interconnected system solar power only reached 160 MW (LAGIE, 2019c). At the end of 2017, biofuels contributed about 0.56% of the electricity produced, marking an increase of 62% compared to 2008 (IEA, 2017).

Regarding the electricity transmission system, in 2011, Law 4001/2011 transferred its management to the Greek Independent Power Transmission Operator (IPTO). Ever since, there have not been significant changes to the system, which spanned across 11,232 km by 2013. The majority of the grid was based on overhead lines of 150kV and 400kV, whereas 66kV lines were used for the connection with the island of Corfu (Greek Independent Power Transmission Operator, 2019). Moreover, according to the European Network of Transmission System Operators for Electricity (ENTSO-E), the Greek system was and remains interconnected via lines of 400kV with Albania, North Macedonia, Bulgaria and Turkey and via a DC line with Italy (European Network of Transmission System Operators for Electricity, 2019).

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Figure 4 Greek interconnected electric transmission grid in 2014

Source: ADMIE (2020)

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1.4.2.1.2 Structure and actors

Actors

Following electricity market liberalisation, nine private companies had been established since 2009 to provide electricity services. Table 7 presents the companies and the year of their establishment, with the previously introduced actors still in operation.

Table 7 Electricity suppliers (2009-2017)

Name	Year of establishment
GREEN	2009
VOLTERRA SA	2010
KEN	2010
EKO ABEE	2011
WATT & VOLT	2011
CORAL ENERGY SA	2012
VOLTON HELLENIC ENERGY SA	2016
ELTA	2017
Natural Gas Hellenic Power Company	2017

An important event of this period is two PPC departments becoming autonomous and starting operating independently. IPTO, established in 2010, is responsible for the management, operation, development and maintenance of the electricity transmission system and its interconnections. Its aim is to ensure the country's electricity supply in an adequate, safe, efficient and reliable manner as well as the functions of the electricity market, related to the transactions taking place in accordance with the principles of transparency, equality and free competition. Alongside IPTO, the Hellenic Electricity Distribution Network Operator (HEDNO) also become independent in 2010 and is responsible for the distribution network, aiming to operate, maintain and develop the electricity distribution network in Greece and to ensure transparent and impartial access to consumers and to all users of the network in general.

As in the previous period, there were actors not falling under the categories of suppliers or producers, but operating in order to regulate, monitor or support the market and relevant activities of the energy sector. Apart from the already established organisations, four new ones were established in this period. The most notable one is the Operator of the Electricity Market (LAGIE), established in 2012, the main activities of which consist of carrying out the daily energy planning, maintaining a special register of market participants, providing participants with information on their market participation and conducting cash settlement arrangements

Moreover, the Association of Photovoltaic Energy Producers (SPEF), established in March 2009, aims to protect the interests of photovoltaic energy producers, by solving problems related to the production of electricity from PV stations and systems, coordinating the establishment and operation of PV parks in the country, representing its members in authorities and the media, and assisting climate change mitigation and environmental protection actions.

The Hellenic Association of Independent Power Producers (HAIPP) was an initiative of the largest private electricity companies, which have already invested €1.5 billion in six modern gas-fired power plants. The goal of the association is to promote the production and distribution of environmentally friendly electricity, as well as the liberalisation of the market for all primary energy commodities, the development of independent electric power companies with modern production facilities and effective selling mechanisms to the consumer, and the creation

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of new jobs.

Finally, the Hellenic Association of Electricity Trading and Supply Companies (ESEPIE) was established in 2015, mainly aiming to assist further development of the Greek electricity market, achieve a constructive cooperation with the government and all market institutions, and promote further market liberalisation.

Legislation

A pricing methodology for PV electricity was established by Law 3734/2009 - Official Government Gazette 8A/28.1.2009, which introduced a considerable decrease of feed-in tariffs (FITs) from 2009 to 2014 and a formula for the years after 2015, emphasising the average system marginal price (SMP) of the previous year. The general FITs, excluding PV, were redefined by Article 5 of Law 3851/2010 - Official Government Gazette A 85/4.6.2010, which also set a national target for the share of renewable energy sources in the gross electricity consumption to at least 20% by 2020.

Law 4001/2011 - Official Government Gazette 179 A/22.08.2011, in compliance with Directive 2009/72/EC, changed the format of the energy market introducing the ownership unbundling of the transmission and distribution networks from supply and generation by creating independent authorities for the operation, transmission and distribution of energy. The activities of HTSO split between IPTO, which manages the transmission system, and LAGIE, for all other operations. HEDNO was also formed with the responsibility to manage the distribution network.

Article 143B of Law 4203/2013 235- Official Government Gazette A/01.11.2013 established the transition tax of security supply causing an additional burden to PV installations. Due to the recession and low FIT rates, many RES investments became non-viable, leading in turn to a decrease of newly installed PV capacity. Law 4254/2014, Article 1 (par. 13) once again redefined FITs, establishing the limit of 200MWp per year to be compensated by the existing FIT scheme until 2020.

With Law 4342/2015 – Official Government Gazette A' 143/09.11.201, Directive 2012/27/EU was integrated, setting the general target of and defining a roadmap for 20% energy efficiency (Forouli et al., 2019).

Law 4336/2015 - Official Government Gazette 94/A/14.8.2015 set a target for the energy market that no company should produce more than 50% of the annual electricity production and imports.

The compensation system based on FITs was replaced, via Law 4414/2016 - Official Government Gazette A' 149/09.08.2016, by the Feed-in-Premium system, where a differential increase based on the type of the installation was calculated on top of the market price. Law 4425/2016 - Official Government Gazette 185/30.09.2016 reorganised the energy market by regulating the establishment and operations of the Energy Exchange, after the implementation of Law 4389/2016 A' 94/27.05.2016, which introduced PPC's obligation to sell energy to competitors at below-cost prices in order to limit the company's dominance and strengthen the competitive market.

Ministerial Decision YAPE/A/F1/oik. 175067/ 2017- Official Government Gazette 1547B/5.5.2017 amended Law 3468/2006 - Official Government Gazette A' 129/27.6.2006 regarding net-metering, by allowing virtual net-metering for production on a different installation from consumption, defining contracts for individual producers.

Directive 2012/27/EU was amended by the Energy Efficiency Directive (2018/2002), which established new targets for 2030, also obliging energy companies to help their customers achieve 1.5% energy efficiency on an annual basis, but this had not yet been incorporated in the national framework by the end of this period.

Finally, Ministerial Decision 204/27.12.2017 established the National Energy and Climate Committee with a main objective to create a National Energy and Climate Plan (NECP).

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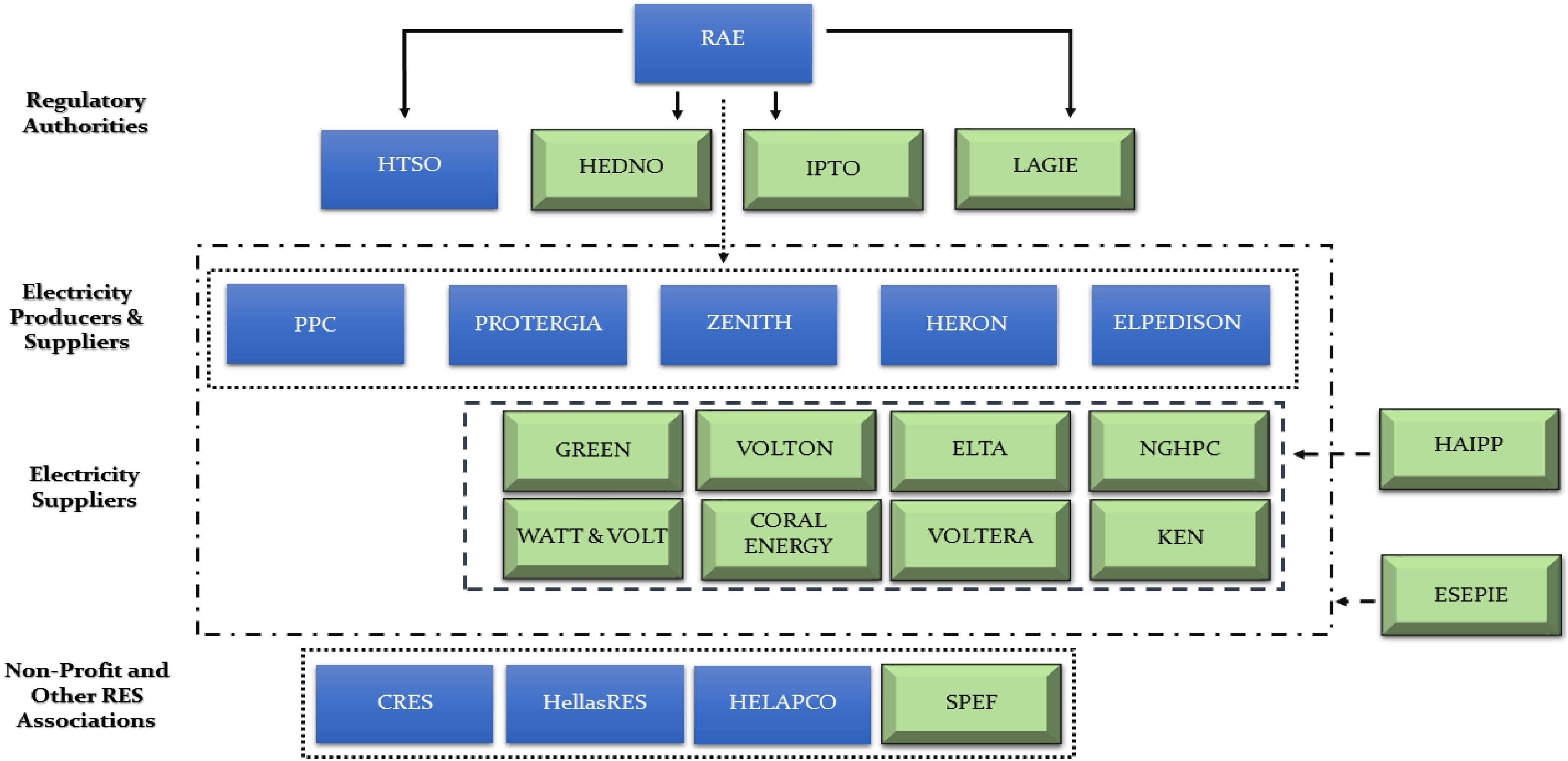

Figure 5 Actors of the Greek Electricity System for Phases I and II

Blue background and white letters: Actors involved in Phases I and II, Green Background and black letters: Actors involved only in Phase II

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1.4.2.2 Landscape

Most of the external factors described in the first period also apply here.

The starting point of the second period of the analysis is the beginning of the ***financial crisis*** in Greece, which started in the fall of 2009 (Gibson et al., 2012), as a debt crisis rather than a fiscal one, leading to the reduction of electricity consumption, as well as the belated payment of electricity bills, causing liquidity problems for PPC (Azam et al., 2016). The financial crisis, which had a grave impact on the Greek economy and society, has also affected the electricity generation sector (Doukas et al., 2014a), since energy demand in Greek industry and households has been significantly reduced during this period. Moreover, due to financial hardship, many households have not been able to participate in energy saving investments (Spiliotis et al., 2020).

In comparison with most European countries, the financial crisis in Greece gravely affected the fiscal agenda of the previous governments in almost every aspect of political action. The most evident example of this phenomenon was the implementation of the three ***Memoranda of Understanding (MoU)*** between the national government and the EU, the International Monetary Fund and the European Central Bank, which established various measures in order for the Greek economy to achieve a government budget surplus, imposing austerity measures (Koukiadaki and Kretsos, 2012) and affecting many public and private sectors, including the energy and electricity sector. For example, the MoU proposed the partial privatisation and liberalisation of several public companies, including PPC (Hatalis, 2012). The liberalisation was completed in 2011 with the establishment of HEDNO and IPTO (Danias et al., 2013). In 2012 and following little—if any—improvement of the country's economy, the second MoU led to the abatement of RES investments, suspending the improvement of the national energy mix, and to the legislation of various measures that were deemed to render renewable energy investments less profitable (Eleftheriadis and Anagnostopoulou, 2015). According to the third MoU, signed in 2015 towards legislating fiscal measures for further confronting the debt crisis (Kotroyannos et al., 2017), in order for the liberisation of the energy system to be completed, no company should produce and import more than 50% of Greece's electricity until 2020, while PPC was obliged to auction some of its productive power plants (Konstantinidis and Vlachou, 2016).

In 2009, two conflicting events occurred: on the one hand, the government set a ***National Renewable Energy Action Plan*** (NREAP) as part of the European Union's effort to reduce GHG emissions by 2020 (Sakellaridis et al., 2011) but, on the other, PPC investigated the scenario of constructing three new lignite plants, a) Ptolemaida V, b) Meliti II and c) Agios Dimitrios VI, increasing the dominating presence of lignite in the Greek energy mix.

Another important factor affecting energy policy lies in ***social protest movements***. This was especially true in Greece, where, despite the growing concern of climate change and voices against exploitation of lignite, there were several communities that strongly oppose the installation of wind plants (Botetzagias et al., 2015). This not-in-my-backyard opposition was mainly reflected in claims that wind turbines create visual nuisance and deteriorate the natural beauty of the landscape, further coupled with concerns over ecosystem disturbance and overall interventions necessary for the installation stage of a wind plant.

In the course of the period 2012-2014, there were various legislations undermining the rapid growth of RES investments, and especially investments in PV installations. For instance, there was an immediate freeze of licensing procedures regarding new PV plants; a new tax was legislated, in 2013, which passed part of the RES installation cost to electricity consumers; while two consecutive decreases on FIT schemes, in 2014, contributed to halting PV installation growth (Giannini et al., 2015; Papadelis et al., 2016).

In 2013, the ***EU ETS*** entered its third, more radical phase, during which an EU-wide cap was set, and the electricity generation sector was required to buy all of its emissions allowances (Bel and Joseph, 2015), in a push for

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renewables.

In 2015 and 2016, the ground-breaking Paris Agreement was signed by 195 nations, during and little after the ***21st Conference of the Parties*** (COP-21) to the United Nations Framework Convention on Climate Change (UNFCCC), the most notable outcome of which was a commitment to take action towards limiting the Earth's temperature increase to well below 2˚C compared with pre-industrial levels (Falkner, 2016).

In 2016, PPC also came to an agreement with China Machinery Engineering Corporation for the construction of a second lignite plant in the region of Meliti in Western Macedonia, the Meliti II plant (Tzogopoulos, 2017). This agreement gave rise to doubts about how determined the Greek government was to actually deliver on its energy and climate commitments (Nikas et al., 2018b). It is, however, noteworthy that the development progress of this plant is in a premature phase (Nikas et al., 2018).

In the following year, the EU proceeded to the foundation of the Platform on Coal Regions in Transition, in order to assist lignite-dependent countries to shut down their lignite plants without creating turbulence to local economies relying on lignite mining and exploitation (Collins, 2019). In Greece, this venture pertains to the regions of Western Macedonia and Megalopolis, which dispose lignite mines and plants.

1.5 Niche: renewable and emerging technologies

In Greece, lignite constituted and still constitutes the most important indigenous energy source, significantly contributing to the development of the energy sector. It has affected economic development, given its competitive costs compared to other imported fuels and the jobs created in mining and electricity generation. Regions around mines, which are urban and less developed, have gradually attracted more people and helped the areas thrive (Kordas, 2006). Aside from the development of local societies, the financial benefit of local lignite utilisation can also be reflected in the electricity prices, which indicatively in 2005 were 52% lower than the European average, and the circumvention of exchange losses (Kaldellis et al., 2009). The truth is that, besides the huge environmental impacts of lignite extraction and combustion, there are significant employment benefits derived from the operation and construction of fire plants, especially in the less developed areas with increased unemployment rate (Tourkolias et al., 2009).

Empirical research shows that lignite mining is intertwined with socio-economic benefits, contributing to economic growth and employment (Badera and Kocoń, 2014); even if this causality is not always bidirectional, there are concerns over closing extraction mines negatively impacting lives at the local scale and the contributions of miners, their families and people employed in related services in local populations (Gurgul, 2011). This is especially true for local economies in Greece: an indicative example is that of Megalopolis, where population remained in stagnation until the underground reserves were discovered in the 1970s, an event followed by unprecedented economic growth for the city (Kaldellis et al., 2012).

Replacement of lignite fire plants should therefore be realised by means of investments that counterbalance losses in development and economy. RES installations should allow for replacing carbon-intensive energy sources, mainly drawing from their potential to reduce GHG emissions and lead to associated energy savings, but also to create new, green work opportunities to mitigate the significant decrease in mining and other traditional jobs (Witajewski et al., 2019). The plan to phase-out lignite plants and fossil fuels overall, which still constitute the backbone of the world's energy system, includes the transition to climate- and environment-friendly technologies like RES.

Electricity production in the Mediterranean region is predominated by fossil fuels, even though the renewable energy potential is very large and currently insufficiently exploited. However, lately, Mediterranean countries increased their efforts to develop strategies that include the exploitation of this potential. Installation of large-

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scale RES features several advantages, such as meeting the rising electricity demand at a lower cost, sustaining long-term economic growth, reducing energy bills in importing countries, creating new job opportunities, enhancing the quality of the environment, and encouraging energy exchange cooperation between the Mediterranean countries and the EU (Belaïd and Zrelli, 2019). In the following sections, such renewable energy choices are considered from the perspective of their life cycle performance, thereby enabling a comparison with conventional sources, and highlighting their relative advantages. Apart from conventional and most commonly considered RES sources (e.g. wind, solar, biomass and hydro), three younger technologies are also considered, which are not yet widely implemented.

1.5.1 Wind

Wind energy has been used for hundreds of years in various forms, with the first usage of windmills in Europe spotted as early as during the Middle Ages (Wailes, 1956). However, the use of wind energy for electricity generation constitutes a relatively new technology, first developed in the 1980s, performing rapid growth worldwide in the last decade (Enevoldsen and Xydis, 2019).

There are two types of wind technologies for electricity generation: onshore, which are usually installed at high altitude, such as mountain tops, in order to maximise the obtained energy; and offshore, which are installed in the sea, avoiding obstacles to wind flow. The latter are in fact the newest application of wind energy technology, since they were introduced as recently as during the last decade (Vagiona and Kamilakis, 2018), and are mainly installed in Northwest Europe (Lacal Arantegui and Jäger-Waldau, 2018), in the North, Irish and Baltic Sea (Pantusa and Tomasicchio, 2019). Given that Greece has no offshore wind parks to date, the environmental and financial analysis of wind energy plants takes into consideration only onshore wind parks existing in Greece. Regarding the environmental and social impact of an onshore wind park in Greece, the CO_2 emissions and external costs (Georgakellos, 2012) and jobs sustained (Roinioti and Koroneos, 2019), including those associated with the manufacturing (Tourkolias and Mirasgedis, 2011), per life cycle stage are presented in Table 8. Every year, there are new park installations in Greece (Kaldellis and Apostolou, 2018).

Table 8 Wind park life cycle CO_2 emissions and external costs

Life Cycle Stages	CO_2 emissions (kg/MWh)	Climate Change External Cost (€/MWh)	Direct employment (Job-years/ TWh)	Indirect employment (Job-years/ TWh)	Induced employment (Job-years/ TWh)	Total employment (Job-years/ TWh)
Power Plant Construction	8.20	0.29	160.3	88.2	66.3	314.8
Power Generation	0	0	136.9	61.6	74.7	273.2
Total	8.20	0.29	297.2	149.8	141.0	588.0

Source: (Georgakellos, 2012; Roinioti and Koroneos, 2019)

The LCOE value for onshore wind parks in Greece in favourable sites can be lower than the 60 €/MWh of April 2019 auction bids (New Climate Institute, 2019) which is significantly lower than the LCOE of a biomass power plant or a natural gas plant.

Again, there are no offshore wind parks in Greece, despite the country's rich yet underexploited shoreline. Therefore, it is important to examine the effect of this technology in Greece, since offshore winds are more efficient and less stochastic, and their installations feature reduced noise and visual pollution (Vagiona and Kamilakis, 2018). Greece may be considered a suitable host of offshore wind parks, since the Aegean Sea is characterised by strong

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winds throughout the year and low variance of wind speed and direction (Soukissian et al., 2017).

Another promising choice for increasing penetration of wind energy in the country is the construction of hybrid power stations, which combine the installation of wind turbines and the construction of an energy storage system. Today, there are two such applications in Greece, and few worldwide, due to current maturity of storage technologies (Katsaprakakis, 2016) and lack of effective financing frameworks rendering them viable and competitive (Vasilakos, 2020). These include a wind turbine of 900kW, a PV installation of 160 kWel and a system of batteries with a total capacity of 3MW, in the island of Tilos (part of the Dodecanese island complex); and a wind park of 2.7 MW capacity with two hydroelectric turbines, in the island of Ikaria, exploiting both the wind and the hydro potential of the island. Furthermore, there is a 2 MW water pumping system at the lower reservoir of the hydro storage plant, for the surplus of wind energy to be stored (Kaldellis, 2020).

1.5.2 Solar

Another widely exploited renewable source, solar power is exploited mainly by PV panels, and is relatively new, with broad application starting in 2008 in Europe, which had a pioneering role in its growth. Although Greece is considered an attractive solar market choice (Stavrakas et al., 2019) and, along with the broader Mediterranean region, is characterised by sunny weather (De Felice et al., 2018), PV technology become belatedly widespread in the country, in comparison with the rest of Europe, mainly after 2011 (Lacal Arantegui and Jäger-Waldau, 2018).

Another technique for generating solar-based electricity is concentrated solar power (CSP), which depends on the thermal power of the sun. This technology is used almost exclusively in Spain and in the USA (with a combined share of 98% of worldwide installations). Despite its weather conditions and solar radiation (Kabir et al., 2018), Greece has no CSP plants (Achkari and El Fadar, 2020); the technology has low yield in Greece, except for southern locations (Zafeiratou and Spataru, 2015). Nonetheless, a significant share of Greek households exploit the sun's energy in order to produce hot water for household usages (Martinopoulos and Tsalikis, 2018), with the country accounting for 0.7% of the world's solar water heating collectors, which is equivalent to the share of Japan and Italy (Ge et al., 2018), countries with far larger populations. It is important to mention that there are two CSP plants under development. The first is situated in the island of Crete, in the south. The second, however, will be constructed in Florina, in the northern part of Greece that is heavily dependent on lignite (Fernández et al., 2019), showing that the region, despite lacking ideal conditions, can also host some CSP plants. Neither CSP plant is operative yet.

Since solar-based electricity generation in Greece is only related to the PV technology, the environmental and sociotechnical analysis focuses strictly on this technology. Regarding the environmental and social impact of photovoltaics in Greece, the CO_2 emissions and external costs (Varun et al., 2009; Georgakellos, 2012) and jobs (Roinioti and Koroneos, 2019), including those associated with manufactruring (Tourkolias and Mirasgedis, 2011), per life cycle stage are presented in Table 9.

Table 9 Large-scale PV park life cycle CO_2 emissions and external costs

Life Cycle Stages	CO_2 emissions (kg/MWh)	Climate Change External Cost (€/MWh)	Direct employment (Job-years/ TWh)	Indirect employment (Job-years/ TWh)	Induced employment (Job-years/ TWh)	Total employment (Job-years/ TWh)
Power Plant Construction	104.00	3.64	612.2	333.7	255.6	1201.5
Power Generation	0	0	146.8	56.4	98	301.2

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Total	104.00	3.64	759.0	389.4	353.6	1502.7

Source: (Varun et al., 2009; Georgakellos, 2012; Roinioti and Koroneos, 2019)

PV power plants create the highest number of jobs per TWh for their construction and operation, with the LCOE of PV plants being lower than 70 €/MWh, with the starting level of auctioning in July 2019 at 0.69 €/kWh (Jäger-Waldau, 2019). PV power plants also feature some potential to contribute to mitigating job losses in a low-carbon transition to a lignite-free power generation mix.

Furthermore, a lot of PV panels are already installed on house rooftops, creating the opportunity for a net-metering framework and decentralised generation framework (Stavrakas and Flamos, 2020; Michas et al., 2020). In the net-metering framework, PV energy produced is injected to the electricity grid, counterbalancing a household's consumption on the basis that, if the consumption accounts to a larger quantity, only the difference needs to be paid, otherwise the household is compensated for the surplus injected to the grid. This compensation has a duration of three years, meaning that the surplus of the generated electricity is time-barred after a period of three years. Consequently, PV panels should not surpass a certain amount of capacity in order for the annual production of electricity to be equal or lower than the annual consumption (Jager-Waldau et al., 2018). An important legislation, introduced in January of 2018, tried to combine PV systems with the operation of energy communities, in which a number of households can install a PV system and use the produced energy taking advantage of a net-metering mechanism.

Another potential for the Greek electricity generation sector may lie in the construction of CSP plants: Greece and Spain feature the highest amount of solar radiation, which makes them two of the most favourable European countries for installing such plants (Kabir et al., 2018). And although Spain is a pioneer in the construction of CSP plants, Greece has none (Shouman, 2018).

1.5.3 Biomass

Biomass is one of the least exploited forms of RES in Greece. Biomass power plants in Greece have a capacity of 56.5 MW and are of three different types of plants depending the type of biofuel they use. In each category, biofuel is some kind of agriculture residue depending on the local agricultural activity. For example, orange tree pruning biomass-fired power plants can be found only in the prefectures of Laconia and Argolis. The other two types orient on the agricultural residue of the olive tree, using either the pruning or the dried pressed olive kernel, to generate energy (Sagani et al., 2019).

Apart from a light footprint, biomass power plants are also deemed quite significant for waste management, since proper removal and disposal of agriculture waste can be a rigorous challenge for many agricultural prefectures of Greece. Consequently, construction of biomass-fired power plants contributes not only to clean energy production, but also to the preservation of the local environment, since agricultural waste is successfully handled and disposed.

Despite these advantages, the total amount of CO_2 emissions that a biomass plant produces during its life cycle need to be evaluated. According to Jungmeier et al. (1998), Nikolaou and Diakoulaki (2003), Evans et al. (2010), CIEMAT (2004) and Sebastián et al. (2011), emissions per life cycle stage are displayed in Table 10, along with the jobs created (Roinioti and Koroneos, 2019). The total carbon footprint of a biomass-fired plant is evidently substantial; however, this source's LCOE is estimated at 93 €/MWh, which may be considered financially viable, especially regarding the number of jobs created.

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Table 10 Biomass power plant life cycle CO_2 emissions and external costs

<table>
<tr><th>Life Cycle Stages</th><th>COCO_2 emissions (kg/MWh)</th><th>Climate Change External Cost (€/MWh)</th><th>Direct employment (Job-years/ TWh)</th><th>Indirect employment (Job-years/ TWh)</th><th>Induced employment (Job-years/ TWh)</th><th>Total employment (Job-years/ TWh)</th></tr>
<tr><td>Power Plant Construction</td><td>38.50</td><td>1.35</td><td>116.3</td><td>57.0</td><td>45.0</td><td>218.3</td></tr>
<tr><td>Biomass Production</td><td>72.50</td><td>2.54</td><td rowspan="3">363.2</td><td rowspan="3">130.8</td><td rowspan="3">136.5</td><td rowspan="3">630.5</td></tr>
<tr><td>Biomass Transportation</td><td>13.70</td><td>0.48</td></tr>
<tr><td>Power Generation</td><td>0</td><td>0</td></tr>
<tr><td>Total</td><td>124.70</td><td>4.37</td><td>479.5</td><td>187.8</td><td>181.5</td><td>848.8</td></tr>
</table>

Sources: (Jungmeier et al., 1998; Nikolaou and Diakoulaki, 2003; Evans et al., 2010; CIEMAT, 2004; Sebastián et al., 2011; Roinioti and Koroneos, 2019)

Biomass can also be co-fired in lignite plants (Drosatos et al., 2020), reducing overall CO_2 emissions.

1.5.4 Hydro

Hydro power plants use falling or fast running water to generate emissions-free electricity. They are separated in two major categories, based on their capacity and requirements: small hydroelectric plants (up to 10MW), usually located on rivers and requiring little or no water storage and therefore no dam construction (Arribas et al., 2019); and plants of higher capacity, usually requiring the construction of a dam of a height of 100 or more meters (Efstratiadis, 2019). Although the process of producing electricity from hydro power is emissions-free, the construction of hydro plants is not (Biska and Oikonomou, 2006; WSA, 2011; Korre and Durucan, 2009; Kellenberger et al., 2007; Georgakellos, 2012), as reflected in Table 11; still, its overall carbon footprint may be considered negligible, compared to other power generation options. Because of the different construction costs of each category of hydroelectric plant, the LCOE fluctuates from 80€/MWh for small hydroelectric plants to 132 €/MWh for larger plants (Roinioti and Koroneos, 2019).

Table 11 Hydro plant life cycle CO_2 emissions and external costs

Life Cycle Stages	CO_2 emissions (kg/MWh)	Climate Change External Cost (€/MWh)	Direct employment (Job-years/ TWh)	Indirect employment (Job-years/ TWh)	Induced employment (Job-years/ TWh)	Total employment (Job-years/ TWh)
Power Plant Construction	2.51	0.09	83.3	39.5	31.5	154.3
Power Generation	0	0	95.4	40.2	54.1	189.7
Total	2.51	0.09	178.7	79.7	85.6	344

Sources: (Biska and Oikonomou, 2006; WSA, 2011; Korre and Durucan, 2009; Kellenberger et al., 2007; Georgakellos, 2012)

Although the life cycle CO_2 emissions of a hydropower plant are insignificant, it is important to mention that their construction may have various adverse environmental impacts. The reservoir created by the dam replaces a usually vast land area which might have been the habitat of many species of flora and fauna, or even an agricultural area.

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Therefore, the formation of a reservoir may threaten the lives of several animals and plants or even the crop yield of a region (World Commission on Dams, 2000). Furthermore, dam construction may affect the quality of the river's water flowing towards the dam. Last but not least, the formation of the reservoir may erode the soil in some cases (Botelho et al., 2017; de Lima Andrade and dos Santos, 2015). Nevertheless, it is noteworthy that all of the above are dependent on the topology and biodiversity of each region; the construction of a hydro plant must take into account many environmental factors, in order for it to be considered completely environment-friendly.

Although hydropower constitutes a considerable component of the Greek electricity mix, accounting for 13.1% of the total electricity generated (Roinioti and Koroneos, 2019), a significant margin exists for new hydroelectric installations: only 31% of Greece's hydroelectric potential is exploited (Efstratiadis, 2019); while a few large hydro plants are already under construction in Mesochora and Sykia, with a cumulative power capacity of 280 MW (Efstratiadis, 2019).

1.5.5 Other Potential Choices

1.5.5.1 CCS

The Greek electricity sector is heavily dependent on the combustion of fossil fuels and especially on lignite, resulting in large GHG emissions. Therefore, an interesting method for reducing CO_2 emissions could lie in the use of the carbon, capture and storage (CCS) technology: the pre-combustion capture, the post-combustion capture and oxyfuel. The most commonly-held one is the post-combustion capture. An important aspect of this option lies in the storage method. Generally, there are three ways of storing carbon: ocean storage, geological storage and mineral carbonation. For Greece the first method is not very prosperous, since most electricity plants are situated in landlocked areas, far from the sea (Kelektsoglou, 2018).

There exist few sites studied for the construction of geological storage CCS plants: Prinos, in the region of Kavala; Pentalofos and Eptachori, in Northwestern Greece; the Evros region, in the north east; Pentalofos and Tsotili, in Northwestern Greece; and Vourinos in Western Macedonia. However, this option is considered to have several environmental risks (Tasianas et al., 2016; Koukouzas et al., 2018; Vatalis et al., 2012).

Mineral carbonation is considered more prosperous, since Greece disposes abundant geological forms capable of this procedure. Some of these forms include basaltic rocks found in the Pindos mountain range (Saccani and Photiades, 2004), basalt found in numerous Greek islands, (Mortazavi and Sparks, 2004; Stouraiti et al., 2017, Bachmann et al., 2012), and ultramafic rocks found in Central Greece (Magganas and Koutsovitis, 2015; Koutsovitis, 2012).

1.5.5.2 Ocean Energy

There are various forms of exploiting the energy of oceans and seas, such as tidal energy, wave energy, ocean thermal conversion and salinity gradients. In Greece, according to (Nikolaidis et al., 2019), only tidal, current and wave energy can be used sufficiently.

Wave energy is one of the most abundant, frequent, periodic and easily predictable sources of energy; hence it could be considered as a competent alternative to the combustion of fossil fuels for electricity generation (Melikoglu, 2018). Nowadays, there is no policy in Greece for the exploitation of wave energy since it is considered a country with low potential, in comparison with other regions of the Mediterranean basin. However, there are sites that may be considered worthy of wave energy investments, with the use of proper equipment, with most promising candidates including the islands of Crete, Naxos and Euboia (Lavidas, 2019).

Construction of wave energy converter plants can also contribute to the creation of hundreds of new jobs in

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Greece, since there are plenty of potential sites such investments. Nevertheless, it should be stressed that the capital cost for these plants is still much higher compared to the cost of other RES plants, but is predicted to drop by 2030, when the technology is expected to mature (Lavidas, 2019).

Current and tidal energy applications are not thoroughly studied in Greece. Although there is significant current activity in the south coast of Crete (Nikolaidis et al., 2019), the most studied and known example in the country is the Evoikos Gulf (Tsirogiannis et al., 2019).

1.5.5.3 Hydrogen

Another interesting option lately investigated is the use of hydrogen as an energy storage method, especially for renewable electricity generation plants. Given most Greek islands not being interconnected to the mainland grid, storage of renewable energy is necessary to fully exploit the maximum capacity of RES plants (Apostolou and Enevoldsen, 2019). This is mainly important for the insular regions of Greece because of the oil-based electricity generation, which is quite expensive, compared to the cost of electricity generation in the mainland (Kavadias et al., 2019), and since oil combustion produces significant amounts of CO_2 emissions.

A common application of the combination of hydrogen storage and RES electricity generation is related to the exploitation of wind energy. In order to maximise the availability of a wind park, the construction of a hydrogen storage and electricity generation unit is installed. Hydrogen electricity generation is accomplished with the use of fuel cells, operating in two distinct modes: if the wind park generates electricity that cannot be absorbed by the grid, the abundant energy is used to produce hydrogen, which can be stored and then used by the fuel cells to generate the necessary amounts of electricity for the grid, when the amount of wind power is not sufficient (Apostolou and Enevoldsen, 2019); this technology, along with other alternatives like batteries and compressed air energy storage (Zafeiratou and Spataru, 2019) as well as refurbishing existing turbines and using hydrogen as a fuel, can be considered for the islands' energy future.

Hydrogen use can be coupled with various power generation technologies, without significant methodological differences. The construction of fuel cell electricity generation plants might therefore be a promising solution for the country's electricity generation sector, allowing further exploitation of the high solar and wind potential.

1.6 Discussion

1.6.1 Where are we now?

Taking a closer look at the developments in the country's energy system, many reasons can be found explaining the transitions that occurred during the last 27 years as well as the transitions that must be realised in the upcoming years, aiming to ensure sustainable development in the country.

In the first period, increasing energy demand is observed due to the country's economic development at that time. The dominant energy source was lignite, with PPC being the main actor, as the owner of the indigenous reserves and responsible for their exploitation.; On top of that, oil-based electricity generation to meet the demands of non-interconnected islands is heavily dependent on fuel imports, since Greece has no sufficient oil reserves (Tsirambides and Filippidis, 2012). The fact that island remained non-interconnected, among other factors (Zafeiratou and Spataru, 2017), also slowed down penetration of RES in the energy mix.

Among the first transition attempts were the liberalisation of RES in 1994 (Agoris et al., 2004) and the liberalisation of the electricity generation sector in 1999 by allowing private investors to construct and operate power plants (Iliadou, 2009). In the same year, a first increase of natural gas is observed and so are the first wind farms (Fig. 6).

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This increase of natural gas is mainly driven by private investors—most gas plants do not belong to PPC—showcasing that liberalization of the electricity sector is an important driver towards use of cleaner fuels in comparison with the lignite regime, dominating the power system at that time. In 2006, the Greek legislation integrated a legal framework for the penetration of PV parks into the power generation (Giannini et al., 2015), resulting in the start of a remarkable boom of solar power in 2009 (Fig. 7), when electricity production from lignite dropped for the first time. All these developments led to a greener energy mix. Earlier, in 2007, the liberalisation of the electricity market was completed, with the opening of the market expanding to the supply of electricity and not just production, in order for any individual domestic client to be able to choose their supplier by 2007— for non-domestic clients the option had been made available since 2004. Around the same time, the injection of energy produced from renewable sources and independent producers was prioritised; while FITs were established for different types and capacity; altogether marking the rise of competition in this domain.

Two intertwined factors to significantly contribute to the transition and gradual reduction of lignite plants' operation were EU policies and directives, and the developments of the EU ETS, triggered by the necessity to address climate change. Climate action drove EC directives, leading to the establishment of and further changes to the EU ETS. These policies had a significant effect on the destabilisation of the lignite-based regime, since a year after the launch of the EU ETS, in 2006, there was a drop in electricity generation from lignite, the most pollutant source, by 9%.

The recession in Greece, starting towards the end of 2009 (Gibson et al., 2012), as well as the implementation of the three Memoranda of Understanding led to the reduction of electricity consumption, needs and therefore generation (Fig. 5, 6). In 2010, total electricity production was reduced by 6% while production from lignite dropped by almost 10% as a result of the crisis, coupled with European and national emission regulations At the same time, among the repercussions of the crisis, households and businesses were discouraged from investing in RES installations and energy saving measures.

Since 2012, electricity generation from lignite has declined, and until 2017 it has dropped by almost 40%. This is mainly due to the ETS, which in 2013 entered its third phase, and the age of most of the country's inefficient lignite plants, producing more emissions. However, electricity demand has been increasing between 2013 and 2017, reaching an overall increase of 10%, and is mainly addressed by solar power that rose in 2012 and 2013 and then by wind and hydro.

Another important factor that contributed to the transformation of the market, in this period, is the establishment of the organisations responsible for its regulation, monitoring and support as well as for protecting the interests of relevant stakeholders. Some external factors, including regulations, enhanced the environment for the development of RES, for instance through the enactment of targets for green energy, energy efficiency, emissions reductions. Others, on the other hand, such as the cut of FITs and the transition tax of security of supply, halted RES penetration, with PV capacity indicatively remaining virtually the same since 2013. The negative effect of the latter was reinforced by the continued recession and societal opposition to installation of wind turbines, which remains strong in 2020.

Law 4513/2018 - Official Government Gazette A 9/23.01.2018 cultivated the conditions for the implementation of energy cooperatives in the energy system, boosting energy democracy and enabling local authorities to participate in the production of energy. It should be also noted that, in 2018, two new private suppliers entered the market and the first interconnection with some of the NIIPS (Cyclades) was occurred.

Despite the tendency for more RES installations and the augmented GHG emission prices, in 2013, PPC made a controversial move and announced the construction of a new lignite plant in Ptolemaida (Roumpos and Papacosta, 2013), to further exploit the low-quality, domestic lignite (Kaldellis and Kapsali, 2014). Today, there still are

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discussions on operating this plant using natural gas instead of lignite. Moreover, the entire lignite power plant stock of the country is expected to start shutting down in 2021, a process currently expected to speed up, given two major events of 2019. First, in response to the European Commission press release IP/18/386, Law 4533/2018 - Official Government Gazette A΄75/27.04.2018 planned the sale of two lignite units with the mining rights, in order to limit PPC's monopoly, with the proposed measures being accepted from the Commission (press release IP/18/3401); while PPC appeared endeavoring to auction some of its lignite plants to private investors in order to reduce its debt (Naftemporiki, 2019). Second, the Prime Minister of Greece, when representing the country in the UN Summit for Climate Change in September 2019, announced the country's determination to phase out all of its lignite plants until 2028, in order to achieve its emission abatement targets (WWF, 2019). However, as discussed in Section 1.4, progress of the phase-out of lignite has been limited over the 37-year period examined, mainly due to the financial crisis. The small period remaining until 2028 requires that radical transformations take place to reach the desired target, potentially giving rise to social imbalances.

Regarding total CO_2 emissions, and as presented in the tables above, through their life cycle, hydro plants present the lowest value followed by wind and solar, whereas lignite appears to be the worst option. As far as the social impact is concerned, the technology providing the largest number of jobs per unit of energy produced is solar followed by biomass and wind. However, the labour intensity of RES technologies is usually associated with manufacturing processes that are rarely performed domestically (Cameron and Van Der Zwaan, 2015). In order to fully exploit this employment potential, Greece needs to invest on developing RES technologies and equipment which could increase the local added value of regions affected by the phase-out of lignite. Also, this does not take into account the labour skills required for each type of plant. The importance of a well-prepared and sustainable coal phase-out is strongly explained by the comparisons below.

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Table 12 Conventional sources and RES life cycle CO_2 emissions

Life Cycle Stages	CO_2 emissions (kg/MWh)						
	Lignite	**Diesel**	**Natural Gas**	**Wind**	**Solar**	**Biomass**	**Hydro**
Power Plant Construction	30.00	1.65	1.81	8.20	104.00	38.50	2.51
Mining/extraction, processing & transportation	20.00	20.58	4.88	-	-	72.50	-
Refining	-	42.00	-	-	-	-	-
Power Generation	1,230.00	780.00	400,00	0	0	0	0
Total	**1,280.00**	**844.23**	**406.69**	**8.20**	**104.00**	**124.70**	**2.51**

Table 13 Conventional sources and RES life cycle external costs

Life Cycle Stages	Climate Change External Cost (€/MWh)						
	Lignite	**Diesel**	**Natural Gas**	**Wind**	**Solar**	**Biomass**	**Hydro**
Power Plant Construction	1,05	0.06	0.06	0.29	3,64	1,35	0.09
Mining/extraction, processing & transportation	0.7	0.72	0.17	-	-	1.64	-
Refining	-	1,47	-	-	-	-	-
Fuel oil transportation	-	0.02	-	-	-	-	-
Power Generation	43,05	27,3	14,00	0.00	0.00	2,54	0.00
Total	**44,8**	**29,55**	**14,23**	**0.29**	**3,64**	**4,36**	**0.09**

Table 14 Total jobs created by conventional sources and RES

	Job-years/TWh						
	Lignite	**Diesel**	**Natural Gas**	**Wind**	**Solar**	**Biomass**	**Hydro**
Total of Direct, Indirect and Induced Employment	450	149	95	588	1,503	849	344

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From a socio-technical perspective, developments so far—including the establishment and reinforcement of the lignite regime—were driven by the landscape; niche innovations, as reflected in the country's delayed and negligible diffusion of renewables, failed to create pressure on the regime. And it is again meso-level actors, like climate change and respective regulations, incentives and subsidies, currently attempting to challenge this regime.

However, from the end of the first period a more positive conclusion can be drawn, since a partial lignite phase-out started taking place. Lignite combustion has been reduced by almost 50% in just twelve years, from 2005 to 2017 (Figure 3.b). A large increase of RES generation is also observed, especially after the beginning of the second period. This phenomenon demonstrates that landscape factors like EU policy and national regulations, driven by climate change, have set serious challenges to the existing regime, leading towards a gradual lignite phase-out. At the same time, landscape factors have also created favorable conditions, e.g. legislation of financing schemes, for the phase-in of niche technologies such as wind and solar PV energy generation, which are progressively becoming part of the regime.

With the gradually increasing role of RES in the system, new technological breakthroughs, including negative RES installation cost trends, batteries maturing as well as advancements in emerging technologies (such as hydrogen and CCS), it is interesting to see whether micro-level technological innovations alone will be enough to overcome or transform incumbent landscape factors, like social opposition and employment concerns, and how co-existing with the regime—oil until grid interconnections, lignite until 2028, and gas until new niches render it an unnecessary evil of RES intermittency—will play out.

1.6.2 A new Energy and Climate Plan: a just transition?

In December 2019, the Greek Government published a revised version of its initially drafted National Energy and Climate Plan (NECP). This plan was under public consultation until the 16th of December 2019. This revised version featured more ambitious targets towards the mitigation of climate change, with implications for almost every economic sector and aspect of the Greek society. Among others, it aims to reduce energy consumption by promoting energy efficiency measures for the household sector; achieve rapid penetration of electric cars in the transportation sector; and proceed in the longer run to interconnecting the majority of the Greek islands to the mainland electricity grid. Most importantly, the plan appears to focus on a complete lignite phase-out until 2028, while the emission target for 2030 is 42% reduction compared to 1990. This measure might also have positive effects on the Greek economy, since the high cost of emission rights rises the price of electricity generation. Again, national legislation acts as an important landscape driver of lignite phase-out.

Aside from the benefits of the transition from lignite to "cleaner" energy sources, there are also adverse effects that must be considered. This transition, as promoted by the country's NECP, and the associated shutdown of various lignite plants may give rise to job losses and overburden local economies, which are heavily dependent on the operation of these power plants, in turn leading to the desolation of entire towns. Consequently, the transition to greener energy systems should be realised while ensuring there will be new job opportunities for the citizens as well as exploiting the lignite sites in innovative ways. A just, low-carbon transition should entail investments in clean sectors and technologies, respect human life and labour rights; be based on social dialogue among all affected; draw on socioeconomic impact assessments; and support local communities affected but removed from the decarbonisation agenda (Doukas et al., 2018).

In this direction and in addition to the outlined activities, local civil societies of the lignite regions (Florina, Amyntaio, Ptolemaida and Megalopolis) should be supported by the Greek Government, since the shutdown of the lignite plants is expected to severely impact employment and local economies. Towards achieving a just

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transition and in line with several SDG dimensions, resources from the EU Just Transition Fund should be made available accordingly, in order for these communities to transform their economic and development model and to maintain social cohesion.

Citizen engagement can help understand how the low-carbon transition can be "just", building on recent analyses of the importance of social dialogue to achieve procedural and distributional justice (Gambhir et al., 2018) and gender equality (Sorman et al., 2020) in such transitions. The European Union has established the Platform on Coal Regions in Transition in order to support the nations that are heavily dependent on the use of coal. This platform assists communication among national, regional and local stakeholders regarding the modernisation of the economy of these regions. This modernisation focuses on a clean energy transition, which also takes into account social fairness. In this way, people who used to work in the lignite sector can obtain new skills and become capable of working in the "greener" economies. The platform was established in December 2017 to aid the interchange of efficacious ideas and frameworks and to propose schemes and actions towards the direction of the transition process. Since its introduction, the Platform meets every three months with the presence of hundreds of stakeholders that represent business and civil society institutions, local authorities and governments (Energy - European Commission, 2018). In Greece, Western Macedonia has joined the platform and receives assistance for relevant issues.

Finally, aside from climate and energy justice issues, major concerns over the country's revised NECP lie in the insufficient description of the investments required for accomplishing its targets; and in its limited consideration of the current electricity grid not being able to accommodate the ambitious increase of RES penetration in the country's energy mix, without significant and costly maintenance and expansion activities. Furthermore, as observed in Section 1.4, natural gas has been gaining ground more rapidly than renewables; growing dependence on natural gas to make up for cuts on lignite combustion can be considered as a delignitisation pathway but not as a decarbonization way forward, especially since natural gas has been gaining ground more rapidly than renewables. This showcases that mapping the NECP in the MLP is not as straightforward, as it does not secure the country will not lock into a transition fuel regime instead of a sustainable decarbonization pathway.

Impacts on sustainability Two main concerns of human society are the socioeconomic development and the mitigation of climate change. Towards this direction, in 2015, the UN set 17 Sustainable Development Goals (SDGs) defined by 169 targets. These goals act as a successor of the Millennium Development Goals (MDGs) and emphasise inter alia the development of every country with respect to the environment, in order to avoid any further impacts of climate change (Allen, et al., 2016). These seventeen goals can be separated in four main categories (van Soest et al., 2019): efficient and sustainable resource use (SDGs 2,6,7,12); preservation of the environment (SDGs 13,14,15); human and economic development (SDGs 1,3,4,5,8,10); and good governance and infrastructure (SDGs 9,11,16,17).

In this report, the impact of an environment-friendly energy transition, based on a wide-scale coal phase-out, on the SDGs was reflected in the analysis of its innovation structural elements. As a major event for the Greek economy, a coal phase-out will potentially affect almost every aspect of the country's development, infrastructure and governance. According to Nguyen et al. (2019), the provision of clean energy, which is the main goal of an energy transition, may result in economic growth in various regions; given Greece's high RES potential (Arabatzis, et al., 2017), an energy transition may be beneficial for its economy and contribute to its recovery from the ongoing recession.

A transition orbiting on a coal phase-out in parallel with technologies driven by climate action is a major step

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towards affordable, reliable and modern energy (Swain and Karimu, 2019); this is especially true for an economy heavily locked into lignite combustion, like Greece. Investments in renewable energies could prove to be a significant factor towards economic growth (Koçak and Şarkgüneşi, 2017). For Greece, this could mean that clean energy investments should attract economy-wide investments and contribute to sustainable economic growth, as well as better employment opportunities and activity rate, as pinpointed by recent modelling studies (Nikas et al., 2018b); similar studies in the literature show that this can be the case for economies that are even more coal-dependent (Antosiewicz et al., 2019), where renewables can secure new job opportunities. The impact on local economies, hitherto revolving around lignite-fired electricity generation, however, is expected to be severe: empirical evidence suggests that miners' adaptability to different sectoral employment requirements can be very slow (Autor, 2016).

Clean energy, economic growth and productive employment aside, the envisaged transition could lead to cleaner energy use from industries as well, thereby contributing to mitigating CO_2 emissions per unit of value added. It also features significant potential as a key factor for sustainable city transformations: substituting biomass combustion for lignite use, may contribute to better waste management at the local level (Moustakas et al., 2019), in which Greece currently performs very poorly compared to other EU Member States (Noll et al., 2019). Cleaner energy alternatives will also promote responsible use of the planet's resources and abatement of the national expenditure on fossil fuels.

Last but not least, gradually shutting down coal and mitigating emissions of various pollutants not only is directly intertwined with climate action features significant health co-benefits: polluted air provokes respiratory and cardiovascular problems, and a coal phase-out may help confront these issues at the local level (Samara et al., 2018).

1.7 Concluding remarks

This research aims to map the Greek electricity system from a socio-technical perspective, in order to understand how a low-carbon transition to a sustainable post-lignite era can be achieved through the phase-out of lignite, rather than simply focusing on the phase-in of renewable source niche technologies. This report presents several aspects of the Greek electricity system, with the 2008 economic crisis as a reference timepoint; by implementing the Multi-Level Perspective framework, the interactions and dynamics between three different levels are examined: the regime, the landscape and the niches of the electricity system.

Regime analysis of the coal-intensive Greek electricity system showed that, for many years, the exploitation of lignite contributed to the country's socioeconomic growth. Electricity demand had been increasing until the emergence of the 2008 financial crisis. Climate change and respective EU policies, as well as the development of laws regarding the operation and management of the electricity system, including inter alia market liberalisation, contributed to the decrease of lignite utilisation for electricity generation, and to the parallel increase of renewables in the power generation mix; but an unstable regulatory framework driven by commitments to austerity-oriented reforms halted the pace of RES penetration (Nikas et al., 2019a). The latter is deemed insufficient considering the national targets for environmental protection and climate action (Forouli et al., 2019). Coal phase-out should be implemented with at-scale deployment of existing and new niche technologies that can at the same time mitigate the negative impacts on employment and therefore also boost regional development. Such technologies were also analysed, and their impacts on several sectors were assessed to be overall positive.

The drafted and then revised Greek National Energy and Climate Plan (NECP) includes ambitious targets for climate change mitigation, with implications for almost every economic sector and aspect of the Greek society. Our research highlights that local civil societies in the lignite regions should be facilitated to transform their economic

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and development model, in order to maintain social cohesion; this support will provisionally enable achieving a just transition, in consideration of requirements for procedural and distributional justice across different income groups, labour and gender (Sari et al., 2017). Moreover, in order to address potential adverse effects of such a transition (Nikas et al., 2019b), focus should be given in the country's performance across all sustainability dimensions, emphasising the country's development with respect to the environment, in order to avoid any further impacts of global environmental change. In careful consideration of the factors that boosted lignite as a major energy source in Greece as well as hindered attempted transformations in the past, as analysed in this research, the energy transition can prove beneficial for the country's economy and contribute to its recovery from the long-lasting socioeconomic impacts of the economic crisis.

Our research can be enhanced by integrating the employed MLP framework with different Systems of Innovation tools, like Technological Innovation Systems (TIS) (Carlsson and Stankiewicz 1991), which have also been used in studies of low-carbon transitions (e.g. Edsand 2017); acknowledging the explicit technological focus of this framework, the MLP can be used to evaluate the broader context of landscape and regime, leading to an effectively integrated framework (Markard and Truffer 2008). Another prospect should be to expand the analysis to the entire water-land-food-energy-climate nexus, so as to enable the interconnection of all systems and provide a more thorough analysis of the existing regime's transformation towards sustainability, considering all dimensions of the SDG spectrum. Furthermore, we have outlined how citizen engagement is crucial in sound, acceptable and effective policymaking, but the same can be said for science. This can also be the case in future work of our sociotechnical analysis, where stakeholders' tacit knowledge sheds light in certain qualitative aspects of a transition that are hard to identify through quantitative models (Nikas et al., 2017; Lieu et al., 2018). At last, another prospect, in the same direction, could be to couple these insights with models and stress-test how these can help define modeling assumptions and scenarios or vice versa (Rogge et al., 2020; van Sluisveld et al., 2020).

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2 UK and Germany case study: industrial transitions

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2.1 Introduction

Being responsible for the production of all goods used in people's lives, industry is one of the most vital aspects of an economy. Its processes, however, are associated with high amounts of energy used and especially fossil fuel combustion, thereby resulting in high greenhouse gas (GHG) emissions. According to IPCC (2014), industry accounts for 30% of worldwide direct and indirect emissions, while direct and industrial process-related CO_2 emissions account for almost 60% of the total industrial share. Industry in Europe has been a major emitter, accounting for more than 20% of the total emissions, including indirect emissions, out of which more than 25% are related to process emissions (Åhman and Nilsson, 2015). Hence, the decarbonisation of EU industry is central towards a low-carbon economy (Gerres et al., 2019). Among the most energy-intensive industrial sectors and therefore highest contributions to industrial GHGs are iron and steel, cement and basic chemicals.

Indicatively, 4% to 7%[1] of global industrial CO_2 emissions derive from the iron and steel industry (Pardo and Moya, 2013; Stefana et al., 2019), highlighting the importance of alternative production technologies for this sector and the economy overall. However, large-scale transitions in iron and steel encounter many challenges and barriers since investing in the relevant technological innovations is not only considered to be expensive, but also quite risky (Karakaya et al., 2018), due to possible production failures that may damage a company's market share (Wesseling et al., 2017). Considering the cost of innovations and this specific industry having gone through various sociotechnical shifts that established dominant processes, it may inevitably feature technological lock-ins hindering economy-wide energy transitions (Flichy, 2008).

Cement production has also played an important role in the economic growth of developed countries (Mokhtar and Nasooti, 2020). Accounting for almost 15% of global industrial energy demand, activities of this sector are broadly regarded as energy-intensive (Avami and Sattari, 2007). CO_2 emissions are driven by processes associated with raw materials, not depending on the combusted fuel. These process emissions account for approximately 50% of total cement industry GHG emissions, and 5% of global CO_2 emissions (Markewitz et al., 2019). Therefore, significant transformations are required in the cement industry as well.

The chemical and petrochemical industry is another important contributor to industrial GHG emissions (7% globally), accounting for 10% of global total final energy consumption. Encompassing a very diverse range of products, the sector lies in the boundaries between energy- and non-energy-intensive (Griffin et al., 2018).

This research focuses on the industrial sectors of Germany and the United Kingdom (UK), two countries with significant emissions (Global Carbon Atlas, 2018), but with a different composition. Germany shows a stable industry, where iron and steel plays an important role and supplies other sectors like the automotive industry (Stahl, 2020d). Compared to Germany, the UK shows a significant shift from these energy-intensive industries

1 This range seems to reflect the consensus in various sources. Different installations behave differently regarding CO_2 emissions despite using the same technologies (e.g. fuel quality), making it difficult to calculate a percentage.

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towards services (Allen, 1988; Cunningham and James, 2009). These different compositions may provide insights into the elements of each system that promote or hinder decarbonisation pathways.

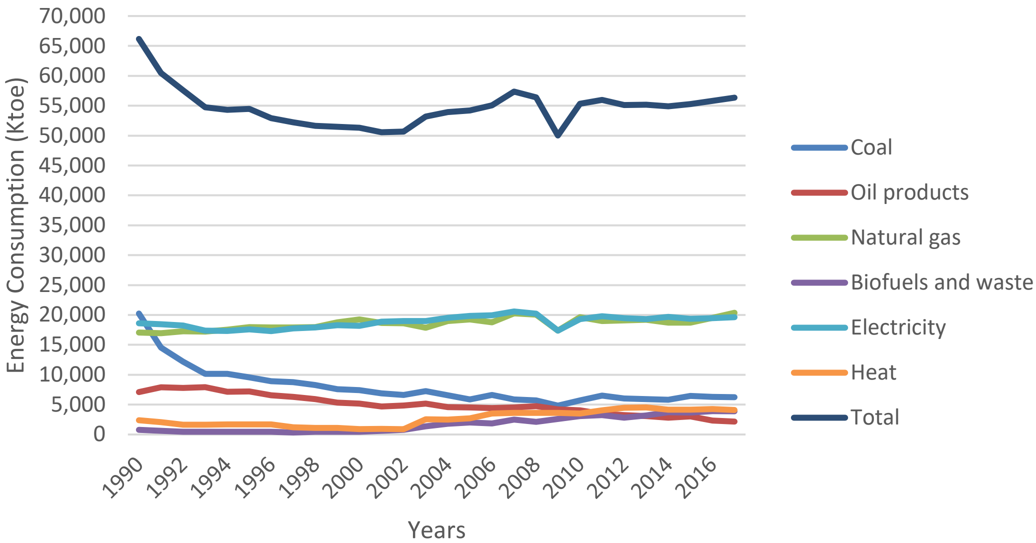
Innovation, whether technological or organisational (Edquist et al., 2001), usually lies at the core of sociotechnical change, showing a systemic nature (Fagerberg et al., 2005). Applying Systems of Innovation frameworks allows a holistic and interdisciplinary perspective (Song et al., 2020) that captures the role of actors, networks, institutions and learning processes in the diffusion of innovation (Edquist, 2005). We choose the Sectoral Innovation System (SIS) framework (Malerba, 2004) as a basis of our methodological approach, which enables us to examine the multidimensional dynamics (Malerba, 2002) of the industrial sector, aiming to identify the role of different actors in driving the transition towards carbon lock-out in energy intensive industries (Bosman et al., 2018). This comparison is further elaborated with the use of the system failure (SF) framework (Woolthius et al., 2005), which investigates potential barriers to the diffusion of a specific technology; in this case low-carbon industrial processes, which are essential towards the mitigation of climate change.

The aim of this research is to map the industrial systems of Germany and the UK, focusing mainly on iron and steel, cement and chemicals, from a low-carbon transition perspective, while examining barriers that could hinder the use and diffusion of sustainable industrial technologies, building on and coupling the SIS and SF frameworks.

2.2 Context of the case study

2.2.1 Background

Germany and the UK are among the world's top 10 and 20 CO_2 emitters, respectively (Global Carbon Atlas, 2018). Focusing on industry, from 1990 until 2017, it accounts approximately for 24% of final energy consumption in Germany and 21% in the UK (IEA, 2019b). Figures 6a-b provide the energy sources that the German and UK's industry are using for their operations. Evidently, in both countries, natural gas and electricity have the highest contributions, while coal shows a decreasing trend since 1990.



(a) Germany

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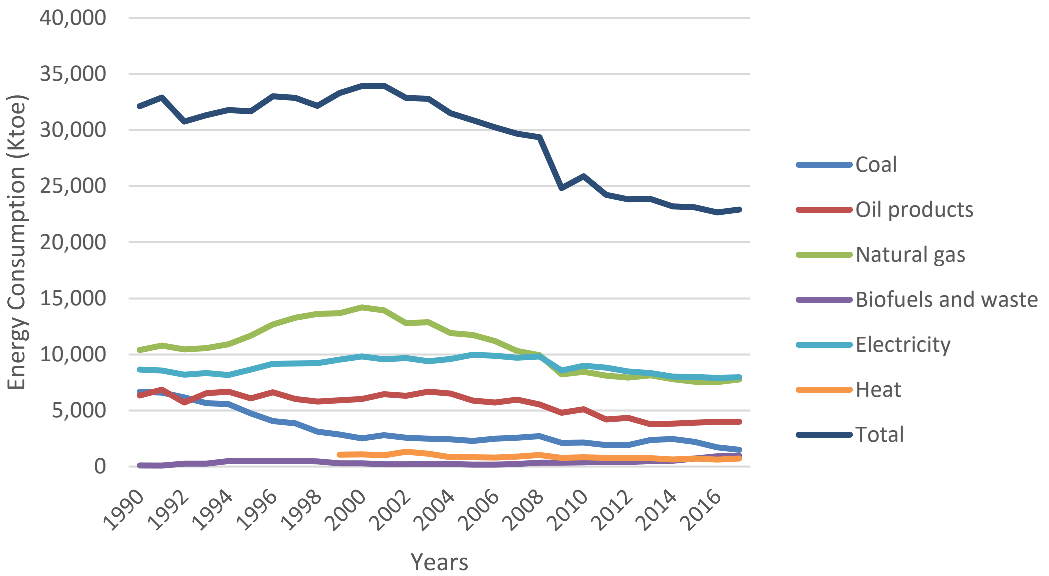

(b) UK

Figure 6 Industrial energy consumption per energy source in a) Germany, and b) the UK

Source: IEA (2019b), own elaboration

As far as total industrial GHG emissions are concerned, Germany reduced CO_2 by 23% in 2017, compared to 1990 levels, while the UK achieved a 35% reduction in the same period. However, this could be partially attributed to the fact that the UK shifted away from industry showing decreased direct emissions, while Germany's industrial share remained stable (IEA, 2019b), despite post-unification industrial downturn in Eastern Germany. Specifically, industrial CO_2 emissions contribute to the national footprint of each country with 13% and 10% for Germany and the UK respectively (IEA, 2019b). It is important to mention that the UK Government published its Clean Growth Strategy (CGS) in October 2017, setting out ambitious goals and proposals regarding pathways up to 2032. UK's Industrial Strategy was also published in November 2017, including a Clean Growth Grand Challenge targeted at assisting UK industry to benefit from the global shift to a low-carbon economy. The CGS stipulates investments of about €115 million for industrial decarbonisation and carbon capture, use and storage (CCUS). Similarly in Germany, the Federal Government's Energy Concept, published in 2010, set the goal of achieving a drop in GHG emissions of at least 55% by 2030, compared to the baseline year (1990)—this target corresponds to a 49-51% cut in industry. Considering also that industry is partly driven by the EU Emissions Trading System (ETS), a cost-effective scheme for the adoption of new technologies to address climate change (Zeng and Zhu, 2019), and that carbon prices are expected to rise within the next few years in line with ratcheting up climate policy stringency, efforts towards industrial decarbonisation should be intensified so that the two countries can retain competitiveness.

In both countries, basic metals, including iron and steel, showed the largest energy consumption in 2017, followed by chemicals; next were non-metallic minerals, including cement (IEA, 2019b). In Germany, there is almost stable energy consumption in all sectors, except for a drop in 2009 related to the global recession, with consumption, however, returning to previous levels the next year. On the contrary, UK's industrial consumption has been constantly decreasing since 2000, marking an overall reduction of almost 47%. This can be attributed to the country experiencing a long-term transition from manufacturing towards services, which is evident from iron and steel production decreasing in the last 25 years (Worldsteel, 2020), while production of cement has dropped by

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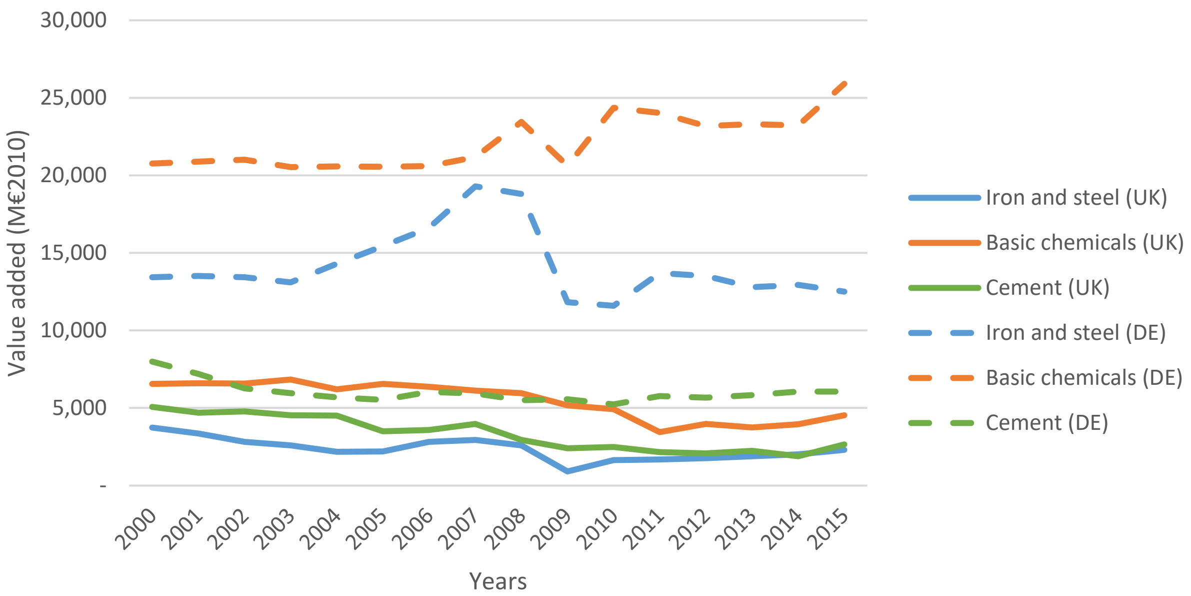
50% (British Geological Survey, 2014).

For a clear distinction between activity effects and technological progress in the evolution of the total CO_2 emissions of an industrial sector, it is useful to decompose the total emissions into the specific CO_2 emissions per economic output (CO_2 intensity) and the economic activity (Kaya, 1997). We note that CO_2 intensity is driven by the specific energy consumption and fuel mix, covering both energy efficiency improvements and the switch to cleaner fuels (Wachsmuth and Duscha, 2019). In the following, we present an evaluation of both factors based on the JRC-IDEES database (Mantzos et al., 2018), which covers the period 2000 – 2015. Results are summarised in Figure 7.

Between 2000 and 2015, UK's economic activity in the iron and steel, basic chemicals and cement sectors experienced mainly a downturn with some relaxation in the most recent years. The same applies to the German cement sector, while basic chemicals saw substantial economic growth apart from a modest downturn during the 2009 economic crisis. The economic activity of the German iron and steel sector increased strongly until a severe drop in 2009 and stabilised at its starting point afterwards.

During the same period, CO_2 intensity of the cement sector in Germany kept roughly constant, while it started out lower in the UK but increased to a similar level. In the UK iron and steel sector, energy intensity saw high upward dynamics, in particular during the economic crisis, but returned to its starting levels afterwards. CO_2 intensity remained substantially lower in the German iron and steel sector throughout the period. Finally, CO_2 intensity of the basic chemicals sector in the UK started out twice as high as in Germany but decreased by a quarter, while the German CO_2 intensity did not change markedly.

In summary, we see that there has been little progress in decarbonising the energy-intensive industries in Germany and the UK recently. Recent emission reductions mainly result from reduced activity; An exception lies in the UK basic chemicals industry, where CO_2 intensity substantially reduced. In contrast, cement CO_2 intensity even increased.



(a) Value added per sector

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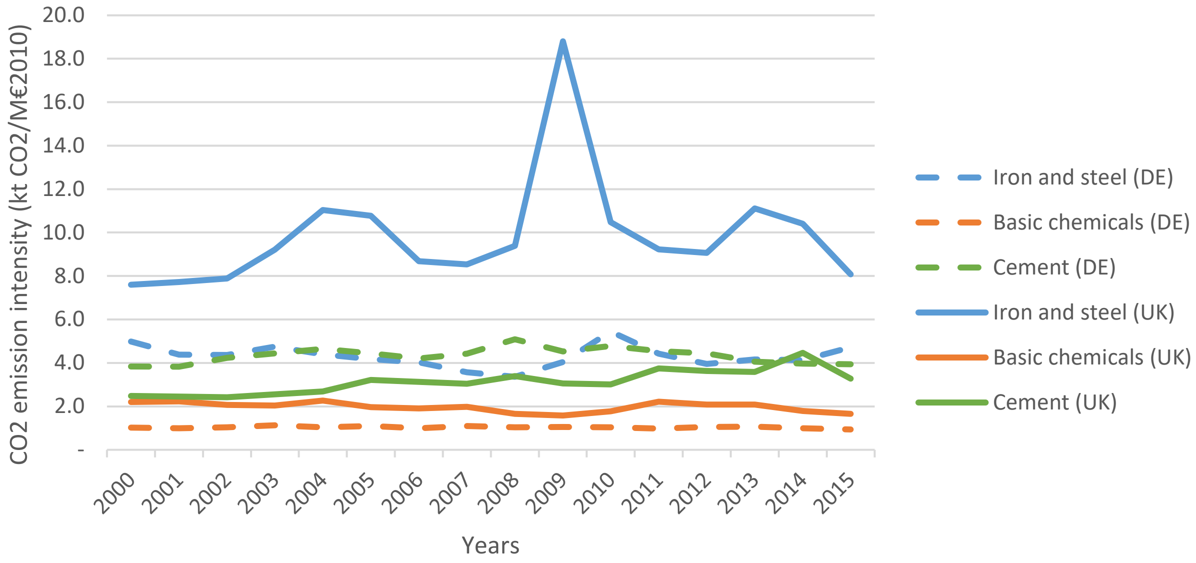

(b) CO_2 intensity (CO_2 emissions per value added) per sector

Figure 7 Value added and CO_2 intensity of energy-intensive industries in Germany (DE) and the UK (UK)

Source: JRC-IDEES database (Mantzos et al., 2018); own elaboration

Germany is considered a great economic power, in Europe and otherwise, having the highest GDP in the region and the 4th largest GDP globally (Marçal et al., 2020), accounting for €43,000 per capita (Trading Economics, 2020b). The country's economy is mainly based on the services sector (62% of GDP), followed by the industrial sector (27% of GDP) (Statista, 2018). It is also important to mention that Germany ranks 6th (among 130 countries) in the Green Economy Perception Index 20182, which records performance across four key dimensions: leadership and climate change; efficiency; markets and investment; and the environment. (Tamanini et al., 2014). The UK also has a strong economy, featuring the second highest GDP in Europe and the 6th worldwide, accounting for €39,000 per capita. The UK economy relies more on services (71% of GDP) and less on industry (18% of GDP) (Statista, 2018), compared to Germany. In the Green Economy Perception Index 2018, the UK ranks 11th. Our study is further motivated by these two countries spending 3% and 1.6 % of their GDP respectively in public and private Research and Development (R&D) (OECD, 2017a).

2.2.2 Production processes

This subsection describes the procedures followed to produce iron and steel as well as cement, in order to better perceive the operation of the system and the dominant technologies. Chemicals' production processes have been omitted, since every chemical product derives from a different and highly differentiated procedure, so this report elaborates the subsector from a broader perspective.

[2] https://www.greengrowthknowledge.org/resource/2018-global-green-economy-index-ggei

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2.2.2.1 Steelmaking Production

Routes

Production of steel is currently based on two main routes: the primary method of Blast Furnace/Basic Oxygen Furnace (BF-BOF), which produces steel directly from iron ores and the Electric Arc Furnace (EAF), which produces steel taking advantage of scrap. According to the World Steel Association (2020a), 70.7% of the total steel production is based on the BF-BOF route, while 28.9% is based on the EAF route. As of 2018, the EU relied substantially more on the EAF route than the global average, producing 41.7% of crude steel via this method, while BF-BOF accounted for 51.3% (Eurofer, 2019). Direct Reduced Iron (DRI) and Smelting Iron (Corex and Finex methods) could be fed to the EAF process, accounting for 5%, with a small number of power plants existing globally (Arens et al., 2012).

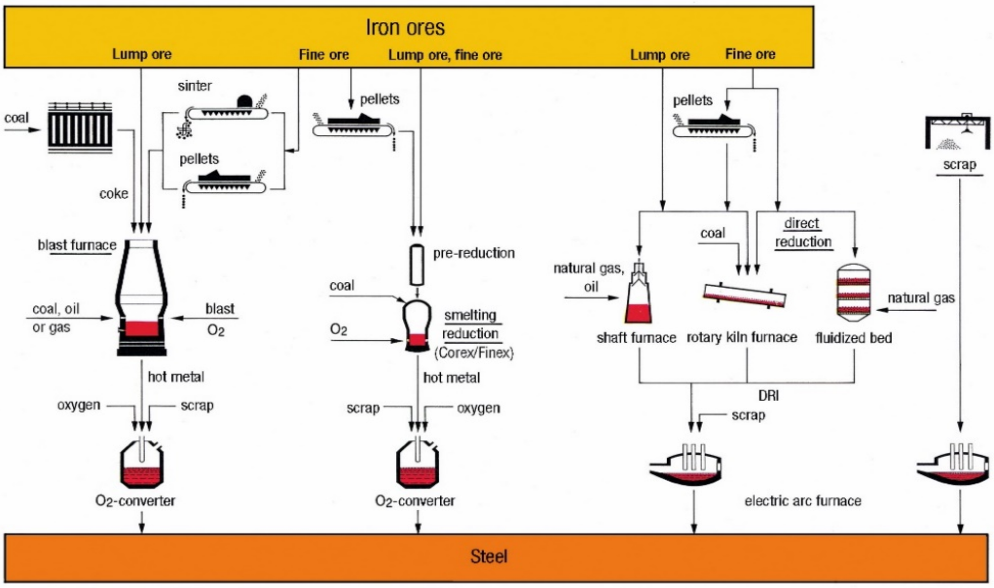

Figure 8 Steelmaking Processes

Source: (Stahl, 2020c)

<u>Blast Furnace-Basic Oxygen Furnace</u>

Via the BF-BOF route, iron ores are sintered and pelletised to prepare the iron oxide raw materials, while hard coal is carbonised in high temperatures in the coke ovens, in order to be converted into coke, a strong carbonaceous material (Razzaq et al., 2013).

These materials are then fed from the top of the blast furnace. Specifically, the iron-bearing materials (iron ore lumps, sinter, pellets) and the reducing agents (coke), plus additive materials like limestone and auxiliary reducing agents (oil, gas, etc.), are blasted via tuyeres with hot air enriched with oxygen, in order to reduce iron oxides to create the hot metal (pig iron) (Geerdes at al., 2015). A simplified basic chemical process of this procedure is described in the equation below:

$$Fe_2O_3 + 3C0 \rightarrow 2Fe + 3CO_2$$

where the hot air reacts with the reducing agents to create carbon monoxide, which in turn assists on reducing iron oxide to pig iron. As seen from the equation, a by-product of the chemical reactions is CO_2, leading to the conclusion that the blast furnace section of the process is an important contributor of carbon-based emissions. Even though partial usage of coke could be replaced by other hydrocarbons creating less emissions, an amount

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of coke should always be used to maintain the operation of the BF (Roudier et al., 2013).

At the bottom of the blast furnace the iron pig is separated from the slag.

The decarburisation of the hot metal to less than 1% (depending on the final product), along with the removal of impurities takes place through exothermic reactions (therefore not requiring additional energy for heating) in the basic oxygen furnace (Oster, 1982).

Electric Arc Furnace and alternative iron making processes

Contrary to the BF-BOF, which produces steel directly from iron ores, the EAF route uses recycled steel scrap since steel is considered an easily recycled material (World Steel Association, 2020a). Even though EAF requires significant amounts of electricity, the process is more efficient than the BF-BOF requiring almost one-third of the amount of energy required by the latter (Arens et al., 2012).

DRI can also be used for the iron ore reduction, an important process, since the availability of scrap otherwise limits the EAF route (Kopfle and Hunter, 2008). Since the DRI process uses natural gas instead of coke, it can lead to significantly lower CO_2 emissions (Orth et al., 2007).

The production of hot metal from iron ore can be achieved without coke through Smelting Reduction (SR) as an alternative to the BF, thus avoiding the environmental impacts of coke ovens and sinter plants by using non-coke coal reducing agents (Anameric and Kawatra, 2008). However, the higher fuel consumption of processes like Corex and Finex act as a barrier to the popularisation of these techniques (Xiaoguang et al., 2008).

Environmental issues

According to the Best Available Techniques report of the European Commission (Roudier et al., 2013), the processes of iron and steel production lead to emissions of off-gases and solid waste through most of the necessary steps. Coal and coke handling play a significant role in these emissions, however raw material handling and transportation or energy required for the operation of the facilities and heating of the equipment could also contribute.

Environmental harm also derives from the slag created in the BF, BOF and EAF, which is usually collected and then used as a construction material or in road building (Yüksel, 2017; Proctor at el., 2000).

2.2.2.2 Cement Production

Cement is considered one of the most significant materials in the world, since it is essential for the building sector. It is the main ingredient for producing concrete, which is a blend of inert mineral aggregates (e.g. crushed stones, gravel, sand and cement) (Worrell, 2014). The most commonly used type of cement is Portland Cement, which accounts for approximately 90% of global production. Other types of cement are also produced by the same procedure, but they are characterised by different ingredient mixes. For example, White Portland Cement (WPC) contains much less Fe_2O_3 than normal gray Portland Cement (Hurley and Pritchard, 2005).

Cement production consists of four steps: mining and quarrying, kiln feed preparation, clinker production (pyroprocessing) and finish grinding. The basic ingredient used for manufacturing cement is calcium carbonate ($CaCO_3$), obtained by limestone or chalk (Hannant, Venkata Siva and Rama Sreekanth, 2018), which are usually mined from a quarry near the cement plant (Worrell, 2014). There are also other minerals mined for producing cement such as clay and shale, which are used for generating other ingredients necessary for the cement mix. Afterwards, these materials are crushed and combined (sometimes including iron ore and other minerals) to create the required mineral mixture.

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The next step entails the preparation of the blend fed to the kiln, which may be a dry or wet process. On the dry process the mixture is ground into powder of relatively small pieces to be further dried, in order to reach the desired moisture level (0.5%). On the wet process, raw materials are ground and combined with water. This procedure is preferred if the moisture of the initial blend is higher than 20%. In both cases, the product of this step is called "raw meal" (Worrell, 2014), which is delivered to a rotating kiln, where it is heated in very high temperatures (800-1450ºC). During pyroprocessing in kiln a variety of chemical reactions occur, such as the evaporation of free water and the calcination of the calcium carbonate. These reactions take place in four zones, all characterised by high temperatures. The most important of these steps is the decomposition of calcium carbonate (Oliveira et al., 2019) because of the high temperature during the process:

$$CaCO_3 \rightarrow CaO + CO_2$$

The rest of the reactions result in the enrichment of calcium oxide to produce clinker, which is the main ingredient of cement. This material must be cooled before being blended with the required additives for producing cement. It should be mentioned that heating the kiln requires significant amounts of energy derived usually from fossil fuel combustion.

The last stage of cement production is grinding: clinker is combined with various additives (such as gypsum) to adjust its properties, which are also dependent on the energy consumed during the grinding process, since high quality product requires higher amount of energy used. The whole process for cement production is depicted on the following figure.

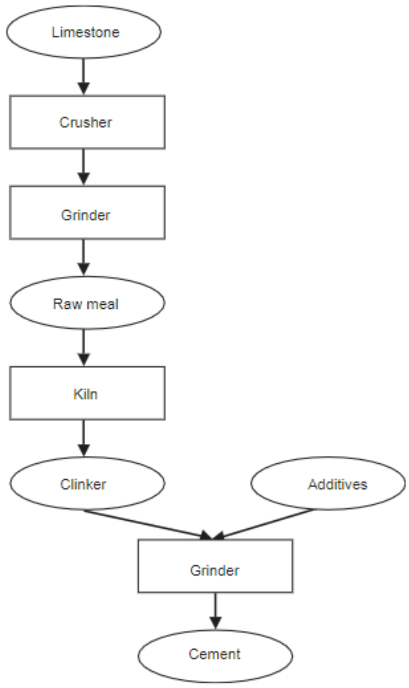

Figure 9 Cement Production

Source: (Worrell, 2014)

2.3 Methodology

The notion of innovation systems has been at the core of systemic analysis of dynamic interactions between actors, networks and processes to trigger technological change (Hekkert et al., 2007), as part of the evolutionary theories of economic and technological growth (Nelson and Winter, 1982; Nelson and Nelson, 2002). During this process,

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technical, scientific, social, economic and political considerations influence innovation as a collective entity, leading to transformation through technological development (Callon, 1987). Within literature, there have been a variety of different concepts of innovation systems developed, each focusing on different levels of analysis, like national (NIS) (Freeman, 1987; Lundvall 1992; Nelson, 1993), regional (RIS) (Asheim and Isaksen, 1997; Cooke et al., 1997; Cooke, 2001), sectoral (SIS) (Breschi and Malerba, 1997; Malerba 2002; Malerba, 2004; Malerba, 2005) and technological (TIS) (Carlsson and Stankiewicz, 1991) innovation systems. These approaches, depending on their focus, analyse innovation processes through different but increasingly blurred boundaries (Binz and Truffer, 2017). As Bergek et al. (2008) suggest, TIS can be used to examine the diffusion of technological innovation with both geographical and sectoral focus, even though they are considered fundamentally international and multi-sectoral; Nikas et al. (2017) integrated TIS with system maps, a framework to capture the different dynamics present in the systems of innovation, as an extension of "market maps" (Albu et al., 2015). Markard and Truffer (2008) also differ from the distinct boundaries of the different systems, in order to create an integrated framework that establishes the connection between NIS, SIS and TIS, while also connecting them with the multi-level perspective (MLP) (Rip and Kemp, 1998; Geels, 2002), an analytical framework to understand sociotechnical transitions, in order to capture the benefits of such an approach in the analysis of the transition towards radical innovation. Similarly, Chung (2012) also built upon the idea of a unified innovation system by using a National, Social and Technical Innovation System (NSTIS), a configuration of the three innovation systems, for the biotechnological sector of Taiwan—Asheim et al. (2011) illustrate how the different innovation systems relate to each other.

The SIS, in particular, has been implemented in various case studies of different sectors and industries, like power generation (Rogge and Hoffmann, 2010), buildings (Siva et al., 2017), capital goods (Kim and Lee, 2008), natural resources (Sæther et al., 2011), facilities management (Andersen et al., 2014), photovoltaics (Balaguer and Marinova, 2016), food (Chunhavuthiyanon and Intarakumnerd, 2014) and housing (Faber and Hoppe, 2013). Decarbonisation of energy-intensive industries has also received significant attention in literature. Lechtenböhmer et al. (2016) examined electrification of basic materials production in the EU across multiple sectors, in an approach similar to Åhman et al.'s (2012) study of industrial transitions in Sweden. Gerres et al. (2019) also examined decarbonisation on a European level, mainly focusing on technologies like carbon capture and storage. Application of SIS in decarbonisation of energy-intensive industries was first attempted by Wesseling and Van der Vooren (2017), who solemnly focused on the Dutch cement sector and the corresponding clean cement innovations; and concluded that a systemic approach is necessary for understanding the diffusion of clean technologies, even though the notion is not sufficiently addressed in the literature. Building upon this idea, this study focuses on the sectoral innovation systems of the broader industrial sector in the national context of both the UK and Germany. A central point of our analysis lies in the examination of specific technologies related to the decarbonisation of the energy-intensive industries of iron and steel, cement, and chemicals, intending to find the elements of each system that mostly affect the diffusion of such innovations.

Our analysis is performed based on the four blocks identified by Malerba (2004): 'actors and networks', 'institutions', 'demand', and 'knowledge, learning processes and technologies'. Initially, the industrial primary and secondary actors in the two countries are mapped. However, the co-existence of these actors individually does not ensure effective diffusion of innovation (Markusen, 2000). It is through cooperation and established networks between the key players of an industry, public authorities and research institutions that innovation can be shared and cultivated (Esparcia, 2014). Via institutional analysis, national policies affecting the industry and setting a path towards decarbonisation are identified, along with European initiatives towards the same direction, like the ETS (Napp et al., 2014). Demand also plays a key role in the market, not only as a consuming agent, but also in the adoption of new technologies and the improvement of end products (Klepper and Malerba, 2010). This is especially the case for the industrial sector, where the customer base comprises other large agents like the automotive industry (Turnbull et al., 1992; Mazur et al., 2015b). The block of knowledge, learning processes and technologies plays a fundamental role in the innovation system, describing the existing knowledge base and the technologies currently dominating the industrial sectors, but also explaining the opportunity conditions leading to the rise of innovative processes (Malerba and Orsenigo, 1997). Knowledge transfer inside the block allows the examination of the technological diffusion pathways in the system.

The UK and German sectoral innovation systems are then fed into a comparative analysis, where barriers to entry for the diffusion of decarbonisation technologies can be drawn from the systemic perspective, potentially leading to carbon lock-in (Unruch, 2000) and subsequently to failure of the system to adapt to new technologies and policies (Zhang and Liang, 2012), thus failing to meet emission targets. The analysis is performed based on the four types of innovation systems' failures identified by the SF (Woolthuis et al., 2005): 'institutional', 'infrastructural', 'capabilities' and 'interactions'. Introducing the SF approach in the comparative analysis allows us to deviate from a strictly structural comparison, derived from the individual case studies, thereby enhancing our perception on the ability of the two systems to manage innovation. The connection of the aforementioned types of failures with the building blocks of the SIS enables integration of the two theories, not only through the evident correspondence of the institutional level, but also through the relationship between the interactions and networks, as well as through the inclusion of demand inside the capabilities failure (Zhang and Liang, 2012). These types of failures are directly correlated with barriers extensively identified in literature on energy-intensive industries (Janipour et al., 2020; Åhman et al., 2017; Bataille et al., 2018; Dewald and Achternbosch, 2016; Luiten and Blok, 2003; Wesseling et al., 2017). The conceptual framework is represented in Figure 10.

Our main research question examined in this study orients on the ways in which the UK and German industrial sectors are formed from a sectoral systemic approach, with regard to how decarbonisation technologies are diffused within and across the innovation system. Drawing from the structural properties of the systems, specific barriers that may act as bottlenecks in the diffusion of innovation are also identified, potentially leading to system failures in coping with sustainability transitions.

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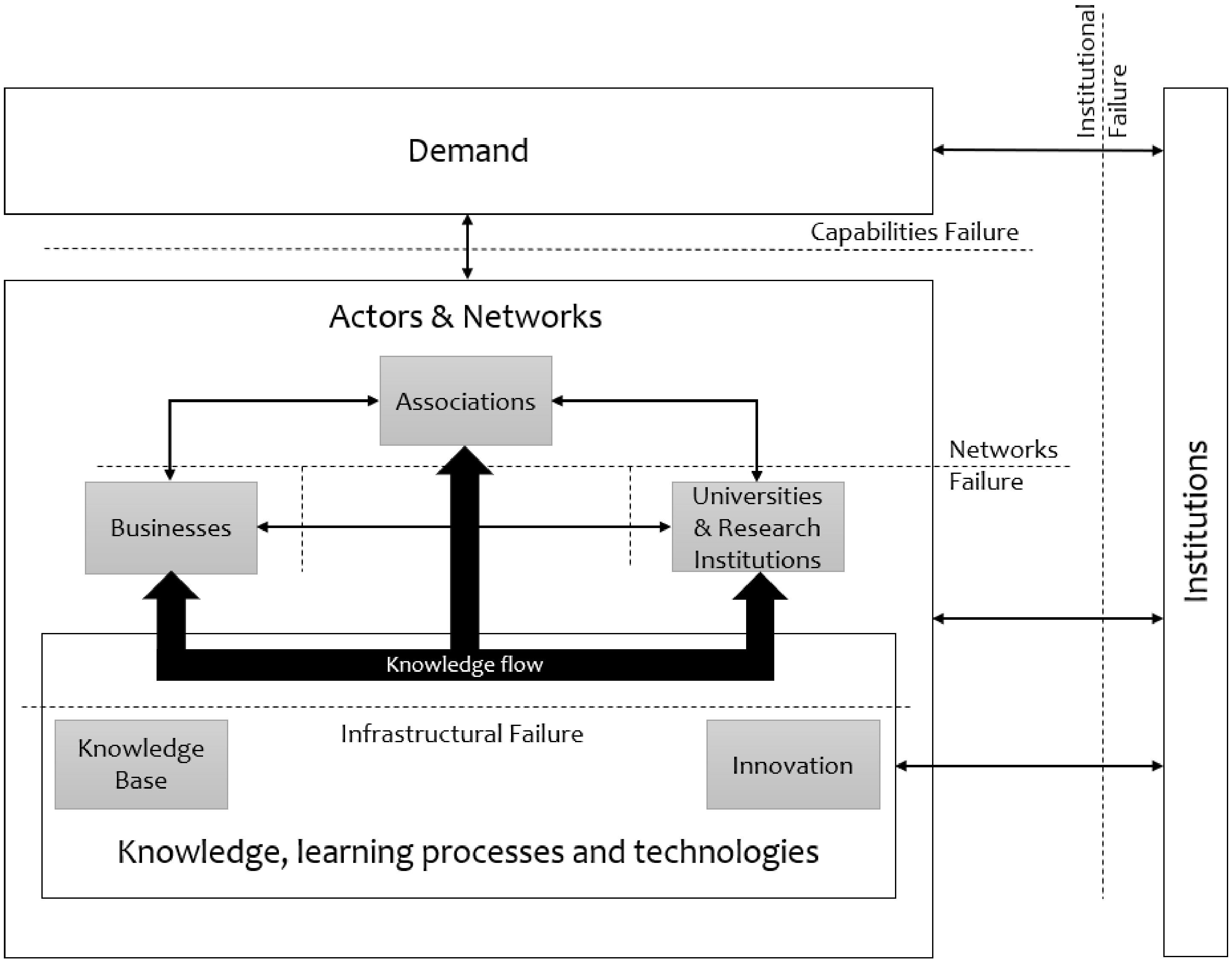

Figure 10 Theoretical approach for the integration of the SIS and the system failure framework

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2.4 The German industrial SIS

The Industrial Revolution in Germany began in the mid-19th century. The German state governments rapidly developed a rail system to minimise distances in the country. The railroad lowered the costs of regional trade, making it feasible to serve distant markets from central locations, while also providing an incentive for manufacturers to concentrate production in central areas and around coal fields. In the Ruhr Valley, coalfields were fully developed, assisting Germany to become the foremost coal producer in Europe. The concentration of accessible coal deposits in central Germany explains the higher rates of industrial employment in coal-rich regions like the Ruhr area, compared to other areas in Germany that lost traditional manufacturing centres (Gutberlet, 2013). Moreover, a steel industry developed, and the stimulus of coal and steel development expanded the banking and capital markets available in the country. This triggered growth of other industries like the chemical and electrical sectors, both developed in the latter part of the 19th century, with the chemical industry of Germany becoming the most advanced in the world. In other words, the new coal-using technologies of the industrial revolution were progressively invented over the course of the 18th century and were then progressively improved and increasingly adopted during the following two centuries (Fernihough and O'Rourke, 2014).

2.4.1 Actors and Networks

The German industrial sector comprises a complete network of interconnected actors where knowledge and innovation diffuse.

On a macro-level, the Federation of German Industries (BDI) is the umbrella network of at least 35 different associations operating in the industrial sector. Since a quarter of the GDP of Germany derives from industrial products, BDI represents the interests of a variety of sectors in the political decision-making process, showcasing the impact of industry on society (BDI, 2016). Similarly, the Energy-Intensive Industries in Germany (EID) interest group focuses on representing the country's energy-intensive industries, accounting for 15% of the manufacturing workforce, by also promoting the importance of sustainability and energy efficiency as part of the necessary, for the local value chains, operations of the different sectors (EID, 2020). Research-wise, the German Association of Technical and Scientific Societies (DVT) provides policy recommendations towards scientific progress on technical issues from the 17,000 different organisations currently in their network (DVT, 2020). Financially, Germany Trade & Invest (GTAI) focuses on connecting domestic businesses with the global market to trigger investments, but also assists foreign enterprises setting up in Germany.

These activities are supported by the Federal Ministry for Economic Affairs and Energy (BMWi), the lead authority on industrial policy regulation and a key player in financing R&D activities. This is of vital importance for sub-sectors like the chemical industry, who mainly comprise small and medium enterprises (SMEs) and rely on public investment and tax reductions to finance R&D operations, as stated by the German Chemical Industry Association (VCI) (2020). The ministry also supports universities and non-academic research organisations like the Fraunhofer Society and the Leibniz Association.

Regarding iron and steel, the German Steel Federation (WV Stahl) is a significant political influencer affecting not only the national steel industry but also the global market, having ties with the World Steel Association and Eurofer. It focuses on creating an effective political economic environment for the German enterprises to be competitive; as such, it operates as an umbrella organisation that assists numerous autonomous institutes on performing key activities for the steel sector. Specifically, the VDEh Steel Institute, the former Association of German Steel Manufacturers, constitutes a network of institutions focusing on the promotion of technical-scientific and technical-economic innovations, as well as standards in collaboration with the Committee for Iron

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and Steel Standardisation (FES) and the German Institute for Standardisation (DIN) (DIN, 2020). The VDEh Institute for Applied Research (BFI), the Research Association for Steel Application (FOSTA) and the Information Center Stainless Steel (ISER) focus on producing applied research throughout the entire production process. An interesting public-private collaboration is the Max-Planck-Institut für Eisenforschung GmbH (MPIE), an autonomous research institute, equally financed by VDEh and the Max Planck Society for the Advancement of Science, a non-governmental association of German research institutes, ensuring that applied research produces results useful not only on a strictly scientific knowledge base, but also market-wise, to promote competitiveness of products (Stahl, 2020a).

Regarding the private sector, manufacturing companies like ThyssenKrupp, ArcelorMittal Bremen and Salzgitter AG play an important role in maintaining iron and steel production, since their operations are both local and global, with exports being a key activity. However, the existence of large multinational companies creates competitive instabilities on the system, as was the case in 2019 when Germany's cartel authority fined ThyssenKrupp and Salzgitter, alongside Austria's Voestalpine, for price fixing after agreeing to specific surcharges (Schuetze and Seythal, 2019). The private sector also contributes to the iron and steel sub-system from an innovation perspective; Siemens VAI was in fact the lead research body to establish the COREX and FINEX alternative ironmaking processes (Hasanbeigi et al., 2014).

The cement industry is more diversely structured, compared to the steel sector: contrary to the majority of the manufacturing operations coming from key steel players, cement is produced not only by large-, like HeidelbergCement, but also by medium-sized companies (VDZ, 2020b). On an institutional level, a key actor is the German Cement Works Association (VDZ) representing the interests of at least 16 companies of the cement industry producing €2.8 billion of sales (VDZ, 2020c). Like VW Stahl, VDZ operates a network of organisations with a focus on research; it represents the German cement manufacturers, by promoting diffusion of knowledge, technology and research with regard to production and environmental management. These activities are further elaborated from the Research Institute and Environmental Measuring Body for effective monitoring of production plants. These bodies' independence from VDZ ensures credibility of research results. Two bodies also focus on the certification process, PÜZ and FIZ-Zert, which are responsible for product certification according to standards and certification of GHG emissions respectively. Conveying the findings to companies, authorities, universities and the public is a key element of the described network.

The German chemical industry has a completely different structure due to the vast plethora of products produced. A main aspect of the subsector is the high share of SMEs, representing 90% of total workforce, that take advantage of increased innovation needs to formulate research-driven business models (Schmidt and Minssen, 2007). VCI is the main association in the chemical industry representing more than 1,700 companies, which are organised in thirty different sector groups and associations depending on their area of operation (Kahl and Desel, 2003), further proving the structural complexity of the sector. This diversity leads to difficulties in establishing chemistry-specific research organisations, so apart from SMEs and large companies most of the sector's research is powered by institutes like the Max Planck Society, Fraunhofer-Gesellschaft, Helmholtz Association and the Leibniz Association (GTAI, 2019).

2.4.2 Institutions

On a policy level, Germany faces a dual challenge maintaining the role of a major industrial nation, while also implementing actions to effectively deal with climate change. This twofold problem is further presented in the efforts of industrial lobbying associations to block regulatory interventions and reforms or downgrade policies to voluntary actions (Markussen and Svendsen, 2005). These efforts are further assisted by the industrial mentality of

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the German society (Liebmann and Kuder, 2012), as local influence may oppose initiatives affecting the regional added value of the industrial sector, thus leading to more conservative approaches that do not threaten their interests (Wesseling and Van der Vooren, 2016).

However, Germany has been keen on dealing with climate change at least since 1991, when a first version of feed in tariffs was introduced, with the Electricity Feed-In Law obliging utilities to buy energy from renewable energy sources (RES) on premium prices, thus ensuring grid access to RES-based energy (IEA, 2013). Parallelly generation from RES was also encouraged through the Renewable Energy Act (Lauber and Jacobsson, 2016), introduced in 2000 and later revised in 2014 and 2017, setting a target for RES production of at least 80 percent by 2050 (BMWi, 2017). As part of a complete strategy, the Energy Concept (Energiekonzept) was introduced in 2010 setting the target of 80-95% GHG emissions reduction by 2050 (BMWi, 2010), while at the same time the Energy Transition (Energiewende) aimed at a nuclear power phaseout and further cut on fossil fuels (Renn and Marshall, 2016).

For these targets to be achieved, strict regulations needed to take place. In as early as 1964, the German air pollution control regulation was legislated in the form of the Technical instructions of air quality control (TA Luft) setting the first limits regarding air quality standards, while in 1974 the Federal Immission Control Act – BimSchG set out general principles on harmful environmental practices (Hartung, 1986). The TA Luft has since been revised on many occasions, targeting for stricter limits for air pollutants, leading to its 2014 revision in order to incorporate the Industrial Emissions Directive (IED) into national legislation (Drotloff, 2014). The directive aims to oblige installations to operate according to the Best Available Techniques (BAT), creating legally binding conclusions that define new emission limits (Roudier et al., 2013). This was especially important for Germany, since almost 10,000 of the total 45,000 permits issued under the IPPC Directive—a previous version of IED—regarded German installations (Conti et al., 2015; European Commission, 2014).

Combined with the IED, energy-intensive installations are bound to fulfil emission targets according to the EU ETS, requiring them to acquire tradable allowances to cover their GHG emissions (Rogge and Hoffmann, 2010). The implementation of the EU ETS poses certain dangers for the industrial sector as it increases the value at stake. Specifically, cement and the iron and steel sub-sectors are prone to danger since 60% and 25% of the gross value added by these sectors respectively could be at stake (Graichen et al., 2008). To protect these sectors, the EU ETS framework included a progressive transition to auctioning, through free allowances. These allowances were meant to steadily decrease until 2020, when the majority would have been auctioned; however, to prevent the emergence of carbon leakage (Naegele and Zaklan, 2019), free allowances were continued with a decreased proportion (European Commission, 2020a).

These changes led to increased costs for system actors and need to be taken into consideration during the following periods, since major companies have already expressed interest in implementing actions for emission cuts requesting policy support, but are susceptible to proceed due to a lack of viable business plans (Wehrmann, 2020). Answering to those requests, on February 2019 BMWi (2020) published a draft of the National Industry Strategy 2030, which aims at strengthening the competitiveness of the entire industrial sector in Germany, while also promoting innovation as a key factor of a viable market economy. However, this draft is still in an open discussion process, mainly due to the strong criticism received for overestimations and the centralisation introduced (Kiel Institute of World Economics, 2019; American Institute for Contemporary German Studies, 2019).

2.4.3 Demand

In 2019, the German industrial sector experienced signs of recession that were reflected in lower production

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volumes (Federal Statistical Office of Germany, 2019). Major challenges faced by the automotive industry (Canzler, 2020) were partially responsible for the observed downturn (Arnold, 2019), since the importance of the sector is reflected not only in the final output, but also in the individual products consumed for the car-making process. In fact, this outlines two major effects that demand has on the industrial system; a direct impact of demand in terms of growth or decline in absolute numbers, and an indirect influence that consumers and their preferences could have in the diffusion of knowledge and innovation (Malerba and Pisano, 2019).

The effect that different sectors have on the system is further observed in Figure 11.

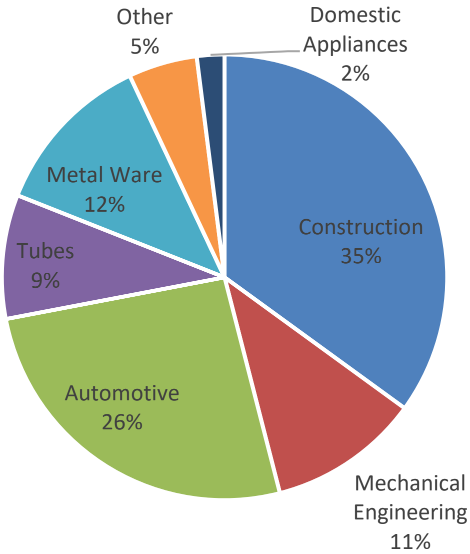

Figure 11 Sector shares of steel consumption in Germany in 2017

Source: (Stahl, 2020b)

Hummen and Ostertag (2015) compared historical data regarding steel consumption in Germany for the period 2000-2010 showing that sectoral shares remain steady, with construction, mechanical engineering and road vehicles being important consumers.

The German iron and steel industry was responsible for the production of 43 million tonnes of crude steel in 2014 (Stahl, 2020d). Major consumers were the construction and the automotive industry, combining to more than half of total production (Figure 10). An important aspect of iron and steel demand lies in exports, with 13.3 million tonnes of steel being exported in 2017 to top steel markets like France and Poland (International Trade Administration, 2017). Germany is also considered one of the top five wind markets (Global Wind Energy Council, 2018); steel demand for wind turbine manufacturing could therefore lead to green energy production over a turbine's lifetime surpassing the energy required for the steelmaking process (World Steel Association, 2015).

As with iron and steel, the cement industry is also largely affected by the nature of the consumers of the final product. Specifically, from data provided by VDZ (2020a) at least 30% of the total cement consumption is driven by the construction sector, even though consumption is relatively small compared to a total production of over 30 million tonnes (Supino et al., 2016). This leads to significant exports alleviating risks through geographic diversification (VDZ, 2020a).

The chemical industry, with a 2018 turnover of around €200 billion (CEFIC, 2020a), is another sector heavily dependent on trading and exports, since the latter surpassed €90 billion in the same year, with Germany registering the highest trade surplus of the European member states (Eurostat, 2019). The sector also plays the role of a facilitator for other industries, since 90% of the chemical products are used as input in multiple industrial

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procedures (Keller, 2020). Consequently, the challenges of the automotive industry naturally affected the chemical sector, experiencing signs of crisis despite the boost of the pharmaceutical sector (Alkousaa and Martin, 2019; Stephan, 2019).

Decarbonisation policies affect not only these sub-sectors, but their consumers as well. Subsequently, these sectors also affect the described system, as problems in demand are then transferred as challenges to our sectors. Especially for the German industry where the automotive sector is a significant driver of economic progress (Kädtler and Sperling, 2020), consumers' technological needs have the potential to steer research and innovation towards more efficient techniques.

2.4.4 Knowledge, learning processes and technologies

2.4.4.1 Knowledge base

The technological regime of the industrial sector comprises different knowledge bases regarding the individual sub-sectors, although industries related to iron and steel, cement and chemicals are commonly regarded as energy-intensive (Fischedick et al., 2014; Khurana et al., 2002; Luis and Van der Bruggen, 2014), with industrial energy efficiency and new practices receiving increasing attention on a policy and research level (Thollander and Ottosson, 2010).

Regarding the German status quo of the iron and steel sector, traditional production routes dominate the steelmaking process. The BF-BOF route is responsible for generating almost 70% of the total production, with the remaining 30% mostly being produced by the EAF route and to a smaller extent from a single DRI plant (Arens et al., 2017). Between 1991 and 2007, the steel sector progressively increased the percentage of EAF production, leading to a decline of specific energy consumption (Arens et al., 2012), a transition with high importance since the iron and steel industry accounts for 4% of the country's GHG emissions (Arens et al., 2017). This is also reflected in the relatively low CO_2 intensity of the iron and steel industry in Germany (cf. Section 2.2.1).

Accounting for 2.9% of Germany's GHG emissions (Brunke and Blesl, 2014), the processes for cement production play a key role in industrial energy consumption. After reunification, progress has been made in efficiency through significant reduction of the clinker ratio in cement produced to 73% in 2011 (Supino et al., 2016). Similarly, Usón et al. (2013) observed a substitution of fossil fuels by alternative fuels, like meat and bone animal meal, sewage sludge and biomass, to a rate of almost 60%.

In the chemical sector, dominant processes greatly vary, due to the diversification of the final products. The sector accounts for 19% of the total energy consumption of industry, while the majority of that is attributed to ethylene, chlorine, carbon black, ammonia, methanol, and polymers (Bühler et al., 2018). Specifically, ammonia synthesis is still based on the Haber-Bosch process that was invented in 1908 from the German chemists Fritz Haber and Carl Bosch (Erisman et al., 2008), and even though it is considered an energy-intensive process (Kuntke et al., 2012) the agricultural usefulness of the final product (Hawkesford, 2014) outweighs the negative effects. Similarly, ethylene production from cracking naphtha, which is the basic material used in Germany (VCI, 2012), is also considered an energy-intensive process (Ghanta et al., 2014).

2.4.4.2 Innovation

Evidently, the borders of the German industrial system are relatively strict, given the endurance of certain processes as dominant drivers of production through time. Therefore, structural adjustments must be made, in order for the sector to be able to cope with the increased necessity for industrial decarbonisation (Lechtenböhmer et al., 2016).

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In fact, most installations already tried to deal with the environmental impact of their operations, in the form of applying BAT (Roudier et al., 2013; Schorcht et al., 2013; Falcke et al., 2017). However, further improvements of energy efficiency through BAT technologies are subject to limitations regarding long-term targets (Fischedick et al., 2014; Arens et al., 2017). A shift to a less CO_2-intensive production route compared to traditional routes was attempted when ArcelorMittal opened the first DRI plant in Hamburg. The DRI process had the ability to create high quality iron that could be used in EAF due to the increasing need for scrap (Kopfle and Hunter, 2008). However, the fact that DRI is considered an expensive process (Arens et al., 2017) limited further diffusion of the process. As a result, reaching the ambitious targets of the German policy requires breakthrough innovations, strategically crossing the boundaries of the individual sub-sectors (Gassmann et al., 2010), while maintaining financial viability.

One such promising technology is carbon capture and storage (CCS), since industrial installations in Germany are forming localised clusters, which is ideal for implementing CCS (Leeson et al., 2017). This is especially true for extensive CO_2 emission reduction in the iron and steel, cement and chemical industries (Dütschke et al., 2016). CCS projects are still at an early stage in Germany, with mostly pilot implementations, usually producing mixed reactions from the public, mainly due to the risks of living nearby storage sites (Dütschke, 2011). Public misconceptions also exist in the use of alternative sources for chemical production (Lee, 2019). Since public acceptance is a major driver of change, such projects should also focus on cultivating a positive public perception.

Another promising technology is the use of low-carbon hydrogen electrolysed from RES, i.e. green hydrogen. This could benefit the iron and steel industry, as hydrogen can be used as a reduction agent to directly reduce iron ore, but also for ammonia production, which is already based on hydrogen (Forsberg, 2007). The private sector appears interested in the diffusion of hydrogen-based technologies. Salzgitter launched the Green Industrial Hydrogen (GrInHy) project in 2016, aiming to develop a High-Temperature Electrolyser (HTE) (Schwarze et al., 2017; Vogl et al., 2018). On the same axis, ArcelorMittal has also been developing a hydrogen strategy, focusing on an experimental project on the DRI plant in Hamburg (ArcelorMittal, 2019), which will further reduce plant's GHG emissions. These examples prove that the industrial sector is keen on hydrogen to deeply cut emissions, with multiple stakeholders in Germany requesting a hydrogen strategy from the national government combined with efforts towards a "European Hydrogen Strategy" (Amelang, 2020).

2.5 The UK industrial SIS

The UK, between approximately 1770 to 1850, was the first country to undergo an industrial revolution, of which the most important component was iron and steel production. Despite significant lack of scientific knowledge, the revolution was achieved by means of empirical methods. Several successful innovators developed spectacular patents for steel production, even though they had no industrial background (Spear, 2019). Industrial innovations also increased as the UK was endowed with extensive cheap coal supplies, which provided cheap energy and a lucrative export trade. These factors (innovations and the cheap coal supplies) led to the rapid development of engineering, railways, construction, shipbuilding, etc. Historically, during the 1600, England's iron production was around 20,000 tons/year, a value that did not vary much until after 1750, with the Shropshire coalfield being an iron making centre since the 16^{th} century. In 1767, the first iron rails were used and, in 1781, the first cast iron bridge was built by Abraham Darby III. Rapid growth was a stimulus for the implementation of new methods in industry (e.g. the Cranage brothers of Coalbrookdale patented the use of coke in a reverberatory furnace to forge wrought iron) (Spear, 2014).

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2.5.1 Actors and Networks

Energy-intensive industries are also capital-intensive, since construction of manufacturing plants requires significant investments. Therefore, these sub-sectors are generally characterised by a small number of incumbent firms. For example, there are only seven cement production firms (The Global Cement Report, 2020) and five primary and secondary iron and steel producing companies operating in the UK (MAKEUK, 2020b). There are also several midstream enterprises that process iron and steel or cement in order to produce components for a diverse variety of industrial applications. This means that the prices of raw materials used by midstream firms are considerably affected by the few upstream companies (Dobson and Waterson, 2007). Nevertheless, these few upstream corporations are also dependent on the midstream level firms, since these account for a significant fraction of their sales. To exemplify this, a drop in the number of buildings constructed may also result in a drop of the cement industry's production output. Moreover, some of the upstream industries that operate in the UK economy are multi-national firms, the headquarters of which are located in other countries, such as Tata Steel, which is an Indian enterprise (Services, 2020). In fact, the structure of the iron and steel industry has undergone significant restructuring from the privatisation of 1988 (Kim et al., 2016) to the mergers and acquisitions thoughtout the 2000s, as is the case with Tata Steel, who acquired Corus, a former merge between British Steel and Hoogovens from the Netherlands (Sourisseau, 2018). The same phenomenon is also present in the chemical industry, where global reshaping led to the establishment of companies like AstraZeneca and GlaxoSmithKline, as a result of mergers between different companies and Zeneca and Glaxo Wellcome respectively (Burgess et al., 2002).

In contrast, the chemicals sector employs more than 400,000 workers (Greenaway and Yu, 2004) and comprises firms with strong diversity, like a significant number of SMEs (Lampadarios, 2016). This is mainly due to this industry manufacturing a broad spectrum of products for a wide scope of uses. However, despite the plethora of the chemical industries, the dependency between different levels of firms is still vital for the sub-sector.

One of the most prominent UK associations regarding industry and associated businesses is the Confederation of British Industry (CBI), counting about 190,000 members that in turn employ around seven million people— almost one-third of the UK private sector total workforce (CBI, 2020). Its main purpose is the promotion of UK businesses by applying pressure to the government, whenever business interests are compromised, creating networks with other businesses and generating information via statistical and policy analysis. In this direction, the association facilitates knowledge transfer between businesses, enabling adoption of best available practices. CBI has launched campaigns supporting the transition towards a low-carbon economy by organising consultation events for firms. It should be noted that its actions are not limited within UK borders, holding offices in other countries, including Belgium, China, India and the Unites States of America (CBI, 2020).

There also exist various associations comprising corporations specialising in specific industrial sub-sectors. Some of the most important associations are related to the three industries, such as "MAKE UK", a federation consisting of various manufacturing and technology-based firms in the UK, including producers of iron and steel products, the main purpose of which is the provision of advice and expertise on climate, environment and employment among others (MAKEUK, 2020a). A similar trade association providing advice to industrial actors is the Mineral Products Association (MPA), consisting of businesses that operate in or produce cement, sand, asphalt and other products (MPA, 2020). Finally, the Chemical Industries Association represents energy-intensive firms that produce chemical and pharmaceutical goods (Chemicals Industries Association, 2020).

The UK is considered among countries with the most highly ranked universities in the world, having four of the world's top twenty universities (The World University Rankings, 2020) according to some rankings; top engineering universities include the University of Cambridge, the University of Oxford and Imperial College London. The

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country is therefore a pioneer in technological research, having produced 14% of the most highly cited publications (Department for Business, Energy & Industrial Strategy, 2019), which is closely linked to industry attracting significant investments in research (Her Majesty's Treasury, 2020). University-Industry Co-authored Publications (UICPs) reflect productive research cooperation between industrial firms and universities. Moreover, the country hosts many University-Industry Cross Researchers, i.e. researchers with one or more university affiliations and one or more industry affiliations, over the years (Centre for Global Higher Education, 2017).

Indicatively, Imperial College London has established the Corporate Partnership Programme (CPP), the aim of which is students' interaction with companies. An example of this interaction is "Industrial Placements", which help graduates find a job in industry. Furthermore, the university has an Industry Partnership and Commercialisation (IPC) team responsible for creating synergies between researchers and industries towards developing new industrial technologies. Finally, one of the main targets of the engineering faculty's research strategy is "the transition to a sustainable zero-pollution economy" (Imperial College London, 2020).

One third of the engineering research budget of the University of Cambridge comes from collaborations with various industrial corporations, and the engineering faculty's research programme is tailored to problems occurring within industry. The university's department of engineering has built long-term collaborations with companies on cutting-edge research in cooperation with private firms (University of Cambridge, 2020).

The University of Oxford engages with industry via provision of consulting services to various industries, and via forming spin-out companies, with a dynamic nature that facilitates capitalisation of university research on real-world applications, and boosts the impact of the university's research (University of Oxford, 2020).

Apart from research carried out in its universities, the UK government funds a variety of research programs and initiatives, such as the Industrial Strategy Challenge Fund, as part of the government's Industrial Strategy supporting various organisations and projects across the country as well as aiming to increase industrial productivity and contribute to decarbonisation (UK Research and Innovation, 2020).

The Department for Business, Energy and Industrial Strategy (BEIS) plays a significant role in formulating transition pathways for the industrial sector, aiming inter alia to ensure a low-cost and clean UK energy system. Its responsibilities include climate policy, science and research, company law, corporate governance, energy, innovation and many other aspects interwoven with sustainable industrial growth and transition (Department of Business, Energy and Industrial Strategy, 2020).

Responsibilities of the Ministry of State for Universities, Science, Research and Innovation include the reform of university education, science and research, innovation and technology. The ministry, jointly administered by the Department for Education and BEIS, can stimulate universities to further engage on environmental research applied in the industrial sector, by reforming university education (Minister of State for Universities, Science, Research and Innovation, 2020).

Finally, the Department for Environment, Food and Rural Affairs also targets sustainable development, which is directly connected with the use of "cleaner" and less energy-intensive technologies; an important action of this department is the formation of policies towards a cleaner and healthier environment (Department for Environment Food & Rural Affairs, 2020).

Last but not least, the Committee on Climate Change, a non-governmental public organisation, aims to advise the government towards achieving GHG cuts and adapting to climate change. For example, the government's target to reach net zero emissions was set after advice provided by this committee (Committee on Climate Change, 2019). The committee, lying behind the government's net zero emissions targets, assesses and reports progress of the nation's transition to a cleaner economy on an annual basis. Regarding the industrial sector in particular,

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the committee has supported the UK government in introducing Industrial Decarbonisation and Energy Efficiency Roadmaps and relative research programmes (Committee on Climate Change, 2020).

2.5.2 Institutions

The UK was an EU member state until January 31, 2020. Analysis of the environmental legislation is broken down into two categories, the national and the European (commonly shared with Germany), with obligations towards the latter being subject to negotiations and agreements in progress.

In 2008, the UK legislated an integrated environmental permitting regime (EPR), in which a vast variety of industrial enterprises must obtain an environmental permit to operate. These permits are divided in three parts: the first refers to industries producing heavy land, water and air emissions; the second to industries characterised by mild such emissions; and the third to industries producing only air emissions (Eden District Council, 2020). Consequently, industrial plants are obliged to remain within the permit's emissions limits and upgrade production plans accordingly, in order to remain operational.

Another important example of UK legislation is the revised Climate Act, which was proposed and voted in 2019 (Legislation UK, 2020) and made the UK one of the first nations set to achieve net zero emissions by 2050. This regulation is expected to affect every aspect of UK economy and especially industry, which is characterised by energy- and resource-intensive processes. In particular, industrial sub-sectors like iron and steel, cement and chemicals should be radically transformed in order to become emission-free until 2050.

As an ex-member state of the European Union, the UK was obliged to implement European legislation across a variety of political, economic and social aspects. One of the most crucial factors of EU policy is the environmental policy focusing on the mitigation of emissions and climate change. Like Germany, these policies include the IED and BAT limits for each industrial sector (European Commission, 2020b) and the EU ETS setting increasingly stricter limits for companies and industries to reduce their carbon footprint (Climate Action - European Commission, 2020a).

Existent EU legislation will remain in force until the end of 2020 (Thomson Reuters Practical Law, 2020), in order for the UK to achieve a smooth transition towards complete legislative and authoritative autonomy. After 2020, the UK government will be free to form their own environmental policies and amend the already existing limits set by the EU. Nevertheless, if the UK decides to remain in the European Economic Area (EEA), it can still participate in the EU ETS, in order to limit its emissions, similarly to Norway and Iceland, which never joined the EU (Climate Action - European Commission, 2020b).

2.5.3 Demand

For the UK, industry has been the country's powerhouse during the last two and a half centuries. The UK has been the land of the (first) industrial revolution, in which machines were first introduced and used. This boosted the country's economy and real wages (Trew, 2014) and was the cornerstone of the rapid development of many other sectors, such as engineering, shipbuilding and railways (Spear, 2019), which made the UK one of the largest economies of the world until today.

Iron and steel are materials used in a variety of applications and industries. In the UK, the largest amounts are used in the construction sector, followed by the manufacturing industry, including vehicles and mechanical equipment (University of Cambridge, 2016). Some of the most popular UK automotive enterprises using iron and steel are MINI Cooper, Rolls-Royce and Bentley.

In the last 25 years, although the national GDP increases almost every year, the manufacturing sector GDP has

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been showing little if any change, in contrast to sectors like services that have doubled their GDP in the same period (Trading Economics, 2020c). This indicates that the UK economic model is shifting towards a new era that promotes the production of services over goods. This may in turn result in reduction of iron and steel demand and production, which has been steadily decreasing in the country during the last 25 years (Worldsteel, 2020).

Cement is widely used in the building sector for manufacturing beams, floors, wall blocks, and so on. It can also be used for the construction of infrastructure, such as bridges, tunnels and railways (Shanks et al., 2019). Contrary to the manufacturing sector, the construction sector's GDP has risen almost by 20% since 1990 (Trading Economics, 2020c). Nevertheless, in the same period, production of cement in the UK has dropped by 50% (British Geological Survey, 2014), and increasing demand is met by imports.

Chemicals and pharmaceuticals constitute the second largest UK industry (CEFIC, 2020b). Most common products include plastics and polymers, such as polycarbonate and polyethylene (Singh, 2012), with renowned firms established in the UK, such as INEOS and LyondellBasell (Chemical & Engineering News, 2020). Furthermore, some of the most profitable pharma industries are also situated in the UK, e.g. GlaxoSmithKline and AstraZeneca. Contrary to the iron and steel and concrete industries, production of chemicals has remained steady during the last twenty years (The manufacturers' organisation, 2019), whereas its Gross Value Added (GVA) has increased by almost 40% since 1996 (The manufacturers' organisation, 2018). This indicates that UK chemical products are still competitive, despite products from countries like China being cheaper because of lower wages and production costs. Another important factor of the chemicals' market demand is that around 24% of total production is directly supplied to households (The manufacturers' organisation, 2019), which may hesitate to try products from unfamiliar firms.

Since the beginning of the 1990s, the global economy has entered a new era; US, EU and Japanese industrial dominance has started to lose grip, with several "new" industrial powerhouses emerging, including Mexico, Indonesia, India and China. In particular, China has quickly become one of the biggest economies in the world (Trading Economics, 2020a), mainly because of its rapid industrial development in almost every industrial sector, and its industrial GDP has increased by 140 times since 1992, making the country a significant exporter worldwide, with exports estimated around 2.1 trillion dollars for the year 2017 (CIA, 2020). China's iron and steel as well as cement production has increased twenty-fold times (Trading Economics, 2020a), and cater more than 50% of the total worldwide demand of these products (World Steel Association, 2020b; USGS, 2020). The UK, among other countries, has started to depend on imports from China or other emerging countries rather than their own industry; and domestic production has been facing a significant downfall.

2.5.4 Knowledge, learning processes and technologies

Industry is a very broad sector, with activities varying from producing everyday items (e.g. furniture) to manufacturing cutting-edge technology equipment (e.g. medical apparatus). Therefore, it is characterised by a plethora of applied techniques and technologies in the different sub-sectors.

2.5.4.1 Knowledge base

In the UK iron and steel industry, the dominant technology is the blast furnace method, which requires great amounts of fossil fuels and especially coal, accounting for 70% of total energy required in the sector; EAF accounts only for 2.5% of total sectoral energy demand (Griffin and Hammond, 2019a)—this is also reflected in only 17% of the country's total production coming from EAF (Millward-Hopkins et al., 2018), which is historically attributed to the difficulties in importing scrap (Langley, 1986). This therefore makes it the most polluting industrial sub-sector, accounting for 25% of industrial GHG emissions (Griffin and Hammond, 2019b). The comparably lower

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share of EAF is also one key factor for the CO_2 intensity in the UK being higher than in Germany (cf. Section 2.2.1).

The technological setting for the cement industry is similar. There are two types of production processes, one based on the exploitation of raw materials (basically limestone) by heating them at extremely high temperatures using various types of fuels; and another using electricity to transform already produced (or used) cement to other types. Regarding the first technology, not requiring the use of already produced cement, the UK has been among pioneers in fuels alternative to coke and petcoke: in 2014, the energy mix of this process consisted of 60% coal/petcoke, 18% biomass and 22% non-biomass waste (WSP et al., 2015a). The cement sub-sector is considered another major polluting industry, accounting for 8% of the UK industrial emissions (Griffin and Hammond, 2019b).

In contrast with the two sectors, the chemicals industry is characterised by an extended number of processes, producing a wide range of products from plastics to medicines. These processes may be thermal or chemical, such as steam cracking, which is fundamental to produce plastics, and polymerisation for the manufacturing of polymers. Many fuels are used in these procedures, such as naphtha, oil gas, butane, etc. (Griffin et al., 2018). Therefore, the chemicals industry is considered a major pollutant accounting for 19% of the UK industry's total GHG emissions (Griffin and Hammond, 2019b).

2.5.4.2 Innovation

Because of the wide variety of technologies used in industry, there are numerous existing techniques and technologies that can replace the currently dominant ones, aiming to reduce emissions and help mitigate climate change. Some of these technologies can be applied only to specific sub-sectors and others are characterised by a broader scope of applications. This means that their use may have a much greater impact on emissions abatement, especially if they are adopted in the entire industrial sector. Specifically, the UK's roadmap to industrial decarbonisation until 2050 (WSP et al., 2015b) identified cross-sectoral technologies. For the sectors of iron and steel, cement and chemicals the most important are the implementation of BAT, fuel switching, like hydrogen or biomass, CCS and energy efficiency.

Modification of all industrial plants in line with BAT comes as a first step towards a "greener" industry, contributing to increasing plants' energy efficiency and reducing production of various air pollutants (Mirasgedis et al., 2008). For example, in the iron and steel industry, adaptation to BAT can result in reducing energy consumption by 1GJ per tonne of steel produced in the European OECD countries, including the UK (He and Wang, 2017). A common BAT application is heat recovery in several stages of the iron and steel production process, such as blast furnace and sintering (Griffin and Hammond, 2019a). In the UK, BAT use was encouraged by EU legislation (since the UK was a member-state until January 31, 2020) and driven by motivation to achieve net-zero emission targets by 2050.

Apart from BAT application, achieving a net-zero emission industry requires the adoption of cutting-edge technologies. An effective technology for the high emitting industrial sector is CCS. For example, in the cement industry, the calcination process accounts for 60% of all GHG emissions, with the remaining 40% being caused by the combustion of fossil fuels (Cormos and Cormos, 2017). The former emits CO_2 regardless of the type of fuel used for heat production; as such, CCS is essential for the 2050 target and, as a relatively new technology, it requires more research, with universities and other research institutes to play an important role, like the carbon capture pilot plant opened by the chemical engineering department in 2012, which is considered one the of the most advanced worldwide (Imperial College London, 2020).

As already discussed, a significant amount of industrial emissions is caused by fossil fuel combustion in various heat production processes, such as the operation of the blast furnace in iron and steel factories. A very promising

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solution can be found in the use of low-carbon hydrogen since its combustion produces little to no CO_2 emissions, depending on the hydrogen technology. The UK is considered an important stakeholder in hydrogen research and production; most of its hydrogen plants use the steam methane reforming (SMR) process (Stockford et al., 2015), which results in the production of CO_2 emissions (Stenberg et al., 2018). A noteworthy example is the use of hydrogen in the Cornwall-based Goonhilly Earth Station that develops antennae in collaboration with the European Space Agency and was funded by the Industrial Strategy Challenge Fund (UK Research and Innovation, 2020). The use of hydrogen for a transition towards an emissions-free industry requires the promotion of green hydrogen plants and the use of CCS in SMR installations, with implications for the UK hydrogen industry.

2.6 Comparative Analysis

The industrial sector has globally locked-into extensive use of fossil fuels, driven by dominance of well-established energy-intensive processes (Unruh, 2002) that act as a barrier to the implementation of green technologies (Brown et al., 2008). Such barriers disrupt the diffusion of innovation in a system and delay the adoption of carbon-neutral techniques and the transition towards sustainability (Lehmann et al., 2012). Here, we compare the industrial innovation systems of the UK and Germany with the aim to identify existing barriers, by focusing on the energy intensive sub-sectors of iron and steel, cement, and chemicals. We study the ability of these barriers to cause system failures for each country, by examining the specific features of each innovation system. A visual representation of the SIS for the two countries accompanied with the corresponding failures is provided in Figure 12, while Table 15 summarises the strengths and threats faced by each sector as elaborated below.

There is strong correlation between the SF failures identified and SIS building blocks. Institutions play an equal role in both frameworks, while the connection between the interactions in the SF framework, on the one hand, and the actors and networks from the SIS, on the other, is evident. Concerning capabilities and demand, a non-exclusive connection is outlined, on the basis that the lack of capability on the part of an actor to provide a green product or technology in regular prices could face unwillingness for purchase on the side of demand (Zhang and Liang, 2012). Therefore, demand can be included in the failures of capabilities. Finally, infrastructural failures also include, apart from obvious infrastructural installations like roads, the difficulty to combine specific technologies, thereby indirectly including the aspect of how knowledge base and innovations are technologically formed.

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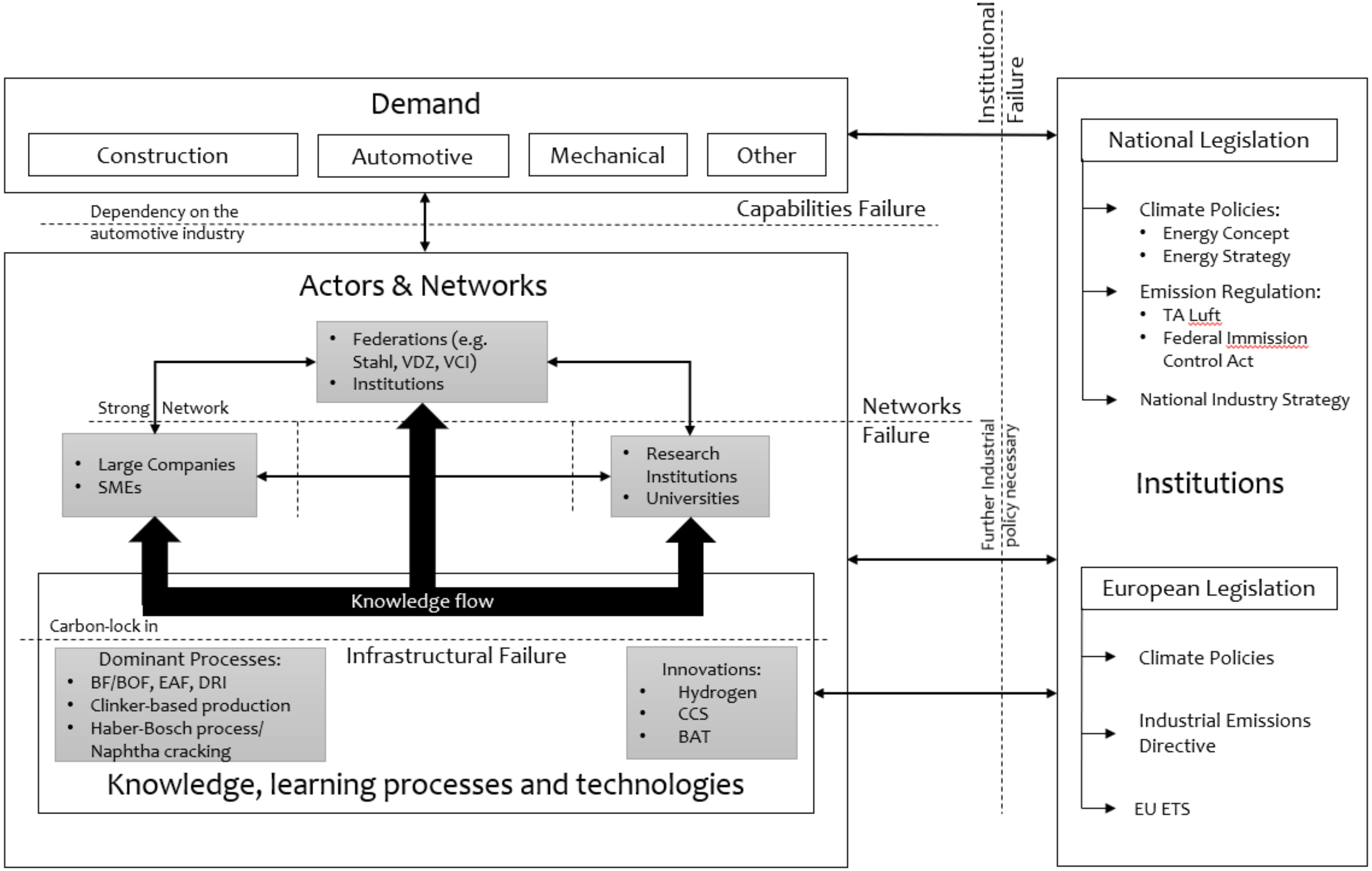

(a) Germany

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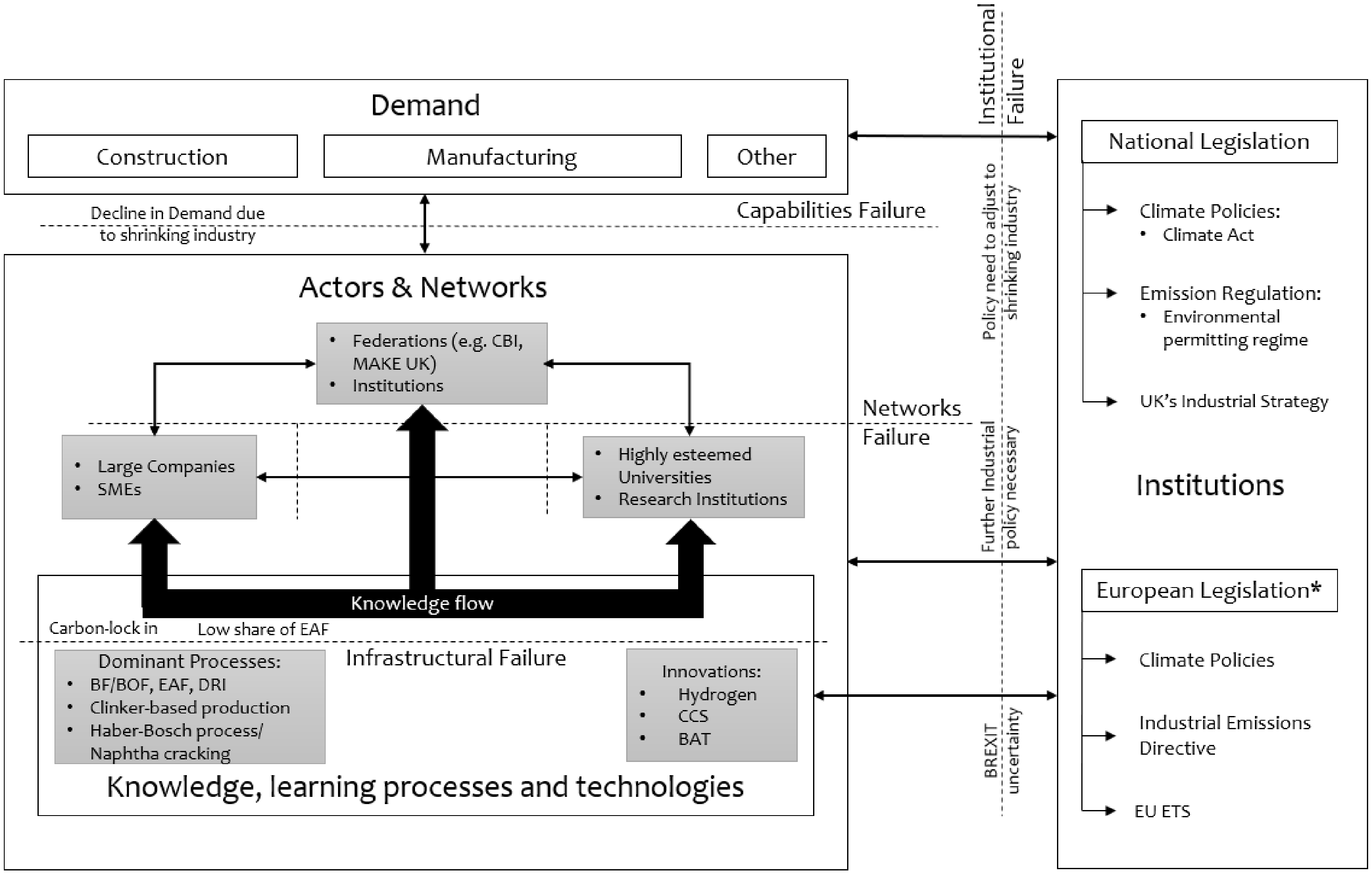

(b) UK

Figure 12 Industrial SIS for a) Germany and b) UK with the threats observed

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Table 15 Strengths and threats of the German and the UK SIS from a failure perspective

Failures	SIS block[3]	Germany		UK	
		Strengths	Threats	Strengths	Threats
Interactions	**Actors and Networks**	• Network of active associations and companies • A large number of SMEs especially for the chemical sector	• Strong Network interactions lead to lobbying practices and strategic decision that threaten competition	• Renowned Universities that perform research activities • A large number of SMEs especially for the chemical sector	
Institutional	**Institutions**	• Active environmental policy • Optimistic targets and political will to achieve them	• Industrial strategy needs to be elaborated • Policy needs to support investment in high cost innovation • Strict regulation causes carbon leakage	• Active environmental policy • Optimistic targets and political will to achieve them	• Industrial strategy needs to be elaborated • Policy needs to support investment in high cost innovation • Strict regulation cause carbon leakage • Policy support is necessary to balance the shrinking industry • Uncertainty after withdrawing from the EU

[3] The connection between failures and SIS blocks is not exclusively limited to the ones described on the table. However, for the examined sectors of industry these connections provide the necessary insights for our analysis.

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Capabilities	**Demand**	• Strong consumers (e.g. automotive industry for the iron and steel sector) • Adequate operational capabilities	• Possible downturn when the automotive industry faces problems • Problem supporting innovative processes due to high investment cost	• Adequate operational capabilities	• Problem supporting innovative processes due to high investment cost • The shrinking industry causes decline in demand
Infrastructural	**Knowledge Base-Innovation**	• Strong Infrastructures • High share of EAF compared to BF/BOF for steel production • Existing DRI plant	• Carbon lock-in to conservative dominant processes • Difficulty combining technologies like CCS, EAF	• Strong Infrastructures	• Carbon lock-in to conservative dominant processes • Difficulty combining technologies like CCS, EAF • Low share of EAF compared to BF/BOF for steel production

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2.6.1 Interactions

Interactions between agents and networks inside a system play a critical role in knowledge diffusion. These create a communication network between all system actors and not just between two firms of the same sub-sector. Typical examples include interactions between firms and research centers or between enterprises and the government or policy framework (Woolthuis et al., 2005). According to the SF framework, these interactions can be divided in weak and strong network interactions (Carlsson and Jacobsson, 1997). Both negatively affect interactive processes of learning, which are a vital part of innovation fostering in systems of innovation (Lundvall, 2016), either by weak exchanges between actors that hinder innovation or by tight connections that do not allow innovation to surface at all (Weber and Rohracher, 2012).

At a first glance, the network structure of both industrial innovation systems appears quite similar. The three sub-sectors examined, iron and steel, cement, and chemicals, consist of active firms from both countries; while research and education institutions, governmental entities and business confederations operate as umbrella networks. Nevertheless, the internal relations and balances between agents vary significantly between the two countries. For example, the German iron and steel industry features a vaster and more influential network of firms and associations, since some of the largest stakeholders are located and/or headquartered in Germany, with implications for the global iron and steel market, as discussed in Section 2.4. The UK is characterised by fewer stakeholders of this sector, which has constantly been shrinking in the country (Worldsteel, 2020). A similar phenomenon is observed in their cement industries. In contrast, their chemical sub-sector both host and affect critical stakeholders, with ties especially to the pharmaceutical industry (Europe BusinessChief, 2020).

Our discussion on SIS indicates that Germany is generally considered more influential regarding firm operation and relevant corporation associations. However, these interactions show characteristics of powerful networks, as was especially the case with price fixing between ThyssenKrupp and Salzgitter (Schuetze and Seythal, 2019), and the lobbying power of the associations in the recent past (Markussen and Svendsen, 2005). Such networks, forming a compact regime, have the capacity to block innovation if collective interests are threatened, leading to interaction failures. On the other hand, the UK is described by a more interactive research pillar: some of the world's most renowned universities in the engineering field are situated in the UK. These institutions are greatly involved in R&D, industrial and otherwise.

Another important factor of the network in every innovation system is the governmental entities interacting with the system, which show significant resemblance between the two countries. The main difference lies in the portfolio of the ministries closely related to industry. In the UK case, the most relevant and responsible governmental entity is BEIS (Department of Business, Energy and Industrial Strategy, 2020). In Germany, the jurisdictions regarding the industrial sector are settled by the Ministry for Economic Affairs and Energy. However, both entities interact similarly with the industrial sector in each country, mainly through policies that set environmental targets, or through strategies aiming to help companies carry out research in innovative technologies, as elaborated in Sections 2.4-2.5.

Industrial networks in the two innovation systems differ from each other but both are generally considered stable in the interactions developed. Both networks are well constructed and have a number of incumbents in every sub-network, with Germany focusing more on associations and the UK on universities and research institutions. However, strategic practices of actors can threaten competition, if no regulations are to take place; excluding such cases, system failures caused by interactions among network agents is not considered highly possible in any of the two countries.

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2.6.2 Institutions

According to Carlsson and Jacobsson (1997), institutional failures can be separated in two distinct categories: hard and soft. The first type is associated with the legal and policy framework of the examined sector, but also health regulations and labour laws indirectly affecting the system; while soft institutional failures are mostly related to a wider spectrum of cultural standards, norms and habits.

The UK experiences a long-lasting transition from manufacturing towards services, altering the societal structure in the form of shifting employment balances and thus leading to a shrinking industry (Allen, 1988). A sector's inability to keep up with the overall economic growth of a country leads to decreased investments within the sector (Tvaronavičius and Tvaronavičiene, 2008) and, as such, to decreased chances of developing technological innovation. Given the high correlation between investment in research and productivity (Haskel and Wallis, 2013), the transition towards services act as a key challenge for the UK industrial sector, since it is more susceptible to decreased investments, with the potential to lead to severe institutional failure, if not adequately addressed. Existing companies in a shrinking environment are more susceptible to locking into traditional and carbon-intensive operations so as to secure their profits (Buschmann and Oels, 2019). An observed global societal transition towards services as a substitution of industrial manufacturing (Bugeaud et al., 2013) indicates that adjustments are necessary even for the more stable German industry.

Policy-related routes have also been a crucial parameter for the success or failure of big firms and industries (Parker and Cox, 2020; García-Cabrera et al., 2019). Both Germany and the UK have demonstrated determination towards mitigation of climate change, through environmental legislation. The two have equally legislated their NECPs, formulating a national strategy related to the decarbonisation of their economies, while also setting emission targets for their industrial sector. As EU member-states, with EU legislation remaining active in the UK until the end of 2020 as well despite it having withdrawn from the bloc (Thomson Reuters Practical Law, 2020), they have also adopted environmental legislation, directives and regulatory mechanisms, such as the EU ETS, the IED and BAT (Drotloff, 2014; Rogge and Hoffmann, 2010; European Commission, 2020b). However, specific industry-related strategies for both countries lack novelty, since the UK strategy seems to focus more on financial rather than environmental issues (Pfeifer et al., 2018), while the German draft has received significant criticism (American Institute for Contemporary German Studies, 2019). The observed policy inconsistency is attributed to the leniency of emission targets on the industrial sector in order to avoid carbon leakage to other countries with more permissive emission legislations (Naegele and Zaklan, 2019). These could include countries without an ETS scheme established, or more importantly countries with heavy and competitive industries and an established nation-wide ETS, like China, which however feature significant shortcomings, like low market activity, single-mode settings, lack of national-level legislation, and limited data transparency (Weng and Xu, 2018). Harmonisation of industrial policy with stricter climate mitigation action requires high amounts of capital invested (Crompton and Lesourd, 2008). Increased costs as well as carbon leakage constitute two existing barriers for effective legislative initiatives, threatening to cause insufficient prioritisation of the legal system to implement policies focused on decarbonising energy-intensive industries. According to Bataile et al. (2018) the transition towards a "greener" industry is heavily dependent on a strict and committing emissions mitigation policy. The lack of willingness to propose coherent industrial policies may result to institutional failure of both innovation systems endangering the decarbonisation of their industrial sub-sectors.

Additional institutional challenges are present in the case of the UK, because of its withdrawal from the European bloc. Brexit may increase volatility on a policy level, resulting in either looser or stricter legislative landscape. The autonomy of the country to form its own legislation without restrictions from a supranational body, such as the European Commission, means that the UK will have to abide by its own laws, which may be more easily modified.

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Hence, the pathway that governmental authorities choose may significantly affect the decarbonisation of the industrial innovation system itself.

We conclude that, on an institutional level, both countries show determination from a policy perspective, although their efforts need to focus more on issues like carbon leakage due to strict regulations. The UK industrial system faces additional challenges due to the shrinking industry and the post-Brexit policy uncertainty.

2.6.3 Capabilities

A system failure can also emerge from the unwillingness or inability of firms to adjust to new technological and environmental standards. Industrial low-carbon transitions require the necessary financial and technological resources, flexibility and learning capacity, which is usually related to the development capability of a specific corporation (Woolthuis et al., 2005). Industry is characterised by the requirement of high capital costs for any type of investment regarding the modification of its equipment (Crompton and Lesourd, 2008). The long periods of investment cycles mean that a firm investing in the modification of a production procedure will have to expect significant delays before the return of the capital invested (Worrell and Biermans, 2005). Diffusion of technologies like hydrogen, struggling to be economically competitive (Dawood et al., 2020), are further affected by long investment cycles. This is considered a significant barrier for every industry and specifically for shrinking markets. Therefore, the UK industry is more susceptible to a capability system failure on its way to decarbonisation, and this is especially true for its shrinking iron and steel and cement sectors, as discussed in Section 2.5.

Another significant barrier to industrial decarbonisation lies in energy-intensive industries mainly providing supplies to other industries and businesses that are generally more reluctant to use low- or zero-carbon material due to the lower short-term returns (Janipour et al., 2020). This reluctance down the line, therefore, does not motivate any of the three industrial sub-sectors to decarbonise their practices and products. Lack of dedication to adopt “greener” technologies is strengthened by the fact that other major exporting countries, like China, provide cheaper commodities, since they are not engaging to energy efficiency investments and industrial environmental upgrades (Mao and He, 2018). Consequently, the UK and German industrial systems alike may hesitate to adapt to environmentally friendly technologies, in order to be able to compete with non-European exporters that possess a competitive edge. These barriers apply to both countries since other emerging economies, including China, account for most of the industrial production (World Steel Association, 2020b; USGS, 2020). In fact, China’s expansion poses a significant challenge for the UK economy, due to the lengthy period of its shift towards services, accompanied by a continuous downfall of the industrial sector, and coupled with Brexit volatilities and subsequent efforts from other European countries to increase their share in services (Latorre et al., 2020; Jafari and Britz, 2020). Even though some of the challenges are also shared by Germany, the country’s sector has shown resilience, demonstrating a more stable industry supported by its eminent automotive and construction sectors, especially with regard to the iron and steel sub-sector (Stahl, 2020b). This challenge for the UK industry is augmented by the willingness of Chinese investors to penetrate into the British market, by investing in existing industrial plants. An interesting example is a Chinese endeavour for saving the “British Steel” company, which is facing severe financial problems; although this endeavour has not yet materialised (Davies, 2020), there is growing uncertainty regarding the future of UK iron and steel enterprises.

We therefore conclude that the German industrial system appears more robust regarding capabilities bottlenecks, in comparison with the UK, due to the high influence of demand. Nonetheless, its dependency on specific midstream sectors (e.g. automotive) means that if these sectors face production decline, the upstream industry will also encounter sales cuts, making it more vulnerable to aforementioned barriers. High investment costs also pose a threat to both systems regarding their ability to financially support new technologies.

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2.6.4 Infrastructure

The last component of the SF framework is related to the analysed system's available infrastructure, which can be separated in two categories (Johnson et al., 1998). The first one focuses on external factors, such as energy and communication infrastructure. The UK and Germany are both considered some of the most economically and technologically developed countries worldwide. General infrastructure, such as communication and energy networks/grids, can support the functional operations of an installation. The second category refers to the technological and scientific infrastructure, such as knowledge and abilities, i.e. the potential for knowledge diffusion and patents, which can be characterised as internal parameters of an industrial system. Our comparison focuses on the knowledge base employed by each sub-sector in the two countries. The blast furnace dominates the iron and steel production, while the more efficient electric arc furnace is more widespread in Germany than in the UK, accounting for almost 30% of iron and steel production (Arens et al., 2017), whereas in the UK this share is around 17% (Millward-Hopkins et al., 2018). This means that the German iron and steel industry already features stronger decarbonisation technologies in comparison, resulting in a lower CO_2 intensity (cf. Section 2.2.1). The cement industry is characterised by a single technology, which is used in both countries. However, a distinction is made based on the fuel consumed by each system; for example, biomass and waste are used in 40% of UK's total energy consumed (WSP et al., 2015a), which is significantly lower than Germany's (60%), a difference that can in part be attributed to different technical and environmental requirements for different materials (Usón et al., 2013). Nevertheless, CO_2 intensity of the UK' cement sector is lower than in Germany due to a substantial share of natural gas in the clinker production (cf. Section 2.2.1).

Apart from the existing technologies, knowledge diffusion of new carbon-free technologies in the industrial sector also face possible challenges. The considered technologies include the use of low- or zero-carbon hydrogen in various procedures of the industry, and the capture and storage of carbon dioxide, with the new UK Budget 2020 promising to establish a fund for financing two CCS installations (Her Majesty's Treasury, 2020). However, since none of the countries has implemented such technologies yet, examining potential infrastructural failures on an innovation level fails to reach conclusive results on such a premature stage. The UK has been an important driver of hydrogen use and research (Stockford et al., 2015), while in Germany many energy-intensive industrial firms have shown interest in a hydrogen strategy (Schwarze et al., 2017; Vogl et al., 2018). Policies should also address possible infrastructural concerns regarding these technologies (Yang and Ogden, 2007), possibly justifying the slow diffusion. Specifically, incompatibility between electrification techniques, like EAF, with CCS, could act as a barrier for the expansion of their application (Janipour et al., 2020), and especially CCS which is in the early stages for both countries, as discussed in Sections 2.4 and 2.5. Less invasive technologies reducing production of CO_2 emissions (like BAT) by achieving energy efficiency can be further implemented in both countries (He and Wang, 2017). However, as examined in Section 2.4, these technologies experience limitations in achieving long-term targets.

From an infrastructural perspective, both systems have a strength to stably maintain their processes. However, the danger of carbon lock-in to conservative technologies exists for both Germany and the UK, especially considering difficulties in combining technologies like EAF and CCS.

2.7 Conclusions

This research aims to map the industrial sectors of Germany and the UK from a systemic approach, in order to understand how innovation is diffused through interactions between actors and identify barriers to entry for new and sustainable technologies. The analysis is focused on the energy-intensive sub-sectors of iron and steel, cement and chemicals, since they represent the majority of industrial CO_2 emissions in the two countries. By implementing

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the SIS framework, the role of actors, institutions, demand and knowledge is examined for both countries' sub-sectors, while by combining the structural elements of SIS with the SF framework, existing or potentially emerging risks for the diffusion of innovative technologies related to the decarbonisation of these sectors are identified.

The economic growth of both Germany and the UK are found to be strongly related to the success of the examined sectors. Especially for Germany, the iron and steel industry has been a main driver for the country's economy, providing the necessary materials for the vast domestic automotive industry and as such affecting a vast number of value-creation chains. These business-to-business networks developed between companies in each sub-sector and their respective consumers prove a strong influence of demand on the German industrial innovation system. Even though different interests exist inside the system, large corporations, coupled with powerful associations with high impact on the global industry, lead to stability of the German industry, although the strong networks formulated present occasional challenges. These networks have the capacity to delay environmental regulation affecting the transition pathway towards greener technologies. However, the observed balance of the German system is not equally reflected in the UK industry: an ongoing transition of the country from an industrial towards a service-based economy poses major threats for the system, progressively leading to the shrinking of industry, additionally facing the challenges and uncertainties associated with Brexit. Future policy decisions on the roadmap that will be followed independently or in collaboration with the EU, regarding industrial decarbonisation, need to address these institutional uncertainties.

This critical difference between the two systems allowed a comparative analysis of the two countries to provide valuable insights for existing challenges incommoding the creation and effective diffusion of innovation, but also for potential challenges found in the UK that the stable system of Germany is not yet experiencing. China's role as a significant barrier is frequently raised, since different domestic mechanisms and conditions keep prices low and threatens the examined industrial systems. This competitive advantage, also valid for other emerging economies, affects the manufacturers of the UK and German systems, increasing imports on the demand side, while also decreasing demand for domestic supply. Addressing carbon leakage is a challenge that needs to include action on a policy level, like the carbon border tax adjustment to boost competitiveness of specific sectors (Kuik and Hofkes, 2010). The phenomenon mostly affects the UK, since the automotive industry helps Germany's industry withstand the pressure and retain its shares, but further leakage can potentially act as a disruptive force against the German stability. Addressing the issue both on a national and a European level has led to policy and institutional inconsistencies, since strict emissions reduction targets needed to be relaxed through free allowances for the industrial sectors, in order to boost competitiveness. However, these policy inconsistencies may act as a bottleneck for innovative technologies allowing the regime to retain currently energy-intensive processes. In particular, there has not been much progress with respect to reducing CO_2 intensity in most energy-intensive sectors. We conclude that industrial policies need to have a clear strategy for the transition of the system towards sustainability, providing ways to finance promising green technologies, such as the use of blue or green hydrogen and CCS. Such technologies receive significant interest from the private sector, which raises concerns over high investment costs required for the implementation.

Our research can be further enhanced by combining the SIS approach with the MLP (Rip and Kemp, 1998; Geels, 2002), which has also been used to draw comparisons between the UK and Germany in the transport sector (Mazur et.,2015a), and system mapping frameworks (Nikas et al., 2017), which provide the opportunity to examine not only the interactions regarding the diffusion of innovation, but also to make use of tacit knowledge embedded in actors themselves to evaluate the broader context of the landscape and the regime as part of the transformation of the system towards sustainability. Another prospect is to expand the SIS analysis to include more industrial sub-sectors and as such unfold the entire national industries, providing the opportunity to examine cross-sectoral interconnections that would allow cultivation of innovative and collectively beneficial or conflicting technologies.

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Finally, as Systems of Innovation frameworks have been gaining attention both as climate policy support frameworks (Doukas and Nikas, 2020) and as part of integrative approaches (Doukas et al., 2018), they can be used coupled with integrated assessment models (van Sluisveld et al., 2020) and applied to help inform or design transformative policy pathways (e.g. Rogge et al., 2020, Geels et al., 2018a), as has recently been the case with other qualitative frameworks in relevant industrial case studies (Bachner et al., 2018) or otherwise (Nikas et al., 2018; Antosiewicz et al., 2019).

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3 Norway and Canada case study: green mobility

This study has been published in Koasidis, K., Karamaneas, A., Nikas, A., Neofytou, H., Hermansen, E. A., Vaillancourt, K., & Doukas, H. (2020). Many miles to Paris: A sectoral innovation system analysis of the transport sector in norway and canada in light of the Paris Agreement. *Sustainability*, *12*(14), 5832. https://doi.org/10.3390/su12145832

3.1 Introduction

The Paris Agreement set the target of limiting the rise of global temperature well below 2 °C. During the last decades, power generation is the biggest worldwide pollutant, followed by transportation (IEA, 2020). The latter plays a critical role in people's daily life, satisfying personal as well as commercial needs. National economies heavily depend on the development of this sector, but its environmental impact dictates drastic decarbonisation. Most transport means operate using fossil fuels and are responsible for 57% of global oil demand (Cazzola et al., 2016). The sector accounts for 23% of the world's final energy use and 14% of global anthropogenic GHG emissions (Bunsen et al., 2018). Therefore, the transformation of transport worldwide, in line with efforts towards reaching a global low-carbon economy, should be intensified.

Both passenger and freight transport are relevant for examining the diffusion of innovation in transportation, since they contribute almost equally to the sector's final consumption (Sims et al., 2014). Road, rail, water and aviation are the major motorised transport modals. Apart from energy efficiency improvements, transport decarbonisation entails penetration of low-carbon technologies, such as electrification, as well as through exploitation of less conventional fuels, such as biofuels and hydrogen. In particular, electric vehicles (EVs) are broken down into three categories: battery electric vehicles (BEV), depending exclusively on electric energy; plug-in hybrid electric vehicles (PHEV), which operate similarly to ordinary hybrid cars with the only difference being they can also be charged; and fuel cell electric vehicles (FCEV), which use hydrogen to produce electricity required to meet their energy demands—although considered as EVs, they mainly depend on hydrogen (Siskos et al., 2018).

Accretive technological improvements alone are not sufficient to cope with sustainability challenges (Evans et al., 2009). Sociotechnical systems require deep changes in order for these challenges to be addressed. Aiming to understand the systemic change, system thinking and design are important factors (Savaget et al., 2019). Studies on innovation systems enable understanding the dynamics of sociotechnical change through the connections between actors and networks, institutions, and knowledge and technologies (Freeman, 1991; Malerba, 2002).

The scope of this study is to map the transport sector of Norway and Canada from a low-carbon transition perspective, by examining the structure and functions of their innovation systems and assessing potential barriers that could hinder use and diffusion of sustainable technologies. The two countries were selected based on their profiles, which are similar in terms of GHG emissions, since in both countries the transportation sector has historically been a major emitter and held similar shares, accounting for almost 24% of each country's total emissions, while oil and gas extraction is also an important emitter (UNFCCC, 2017), as well as of the potential or penetration of renewables, yet different in terms of innovation diffusion: although they both feature high shares of transport emissions as well as high contribution of renewable energy sources (RES) in the national energy mix (IEA, 2019c), their EV shares in the transport mix differ significantly. At the same time, both countries are locked into their domestic oil reserves but in a different manner: although Norway holds significantly less oil reserves, a share (usually less than 3 per cent) of the surplus of its state-owned oil fund (the world's largest of its kind) is used to balance the national budget.

To support our analysis, we build on the Sectoral Innovation Systems (SIS) framework (Malerba, 2004), which

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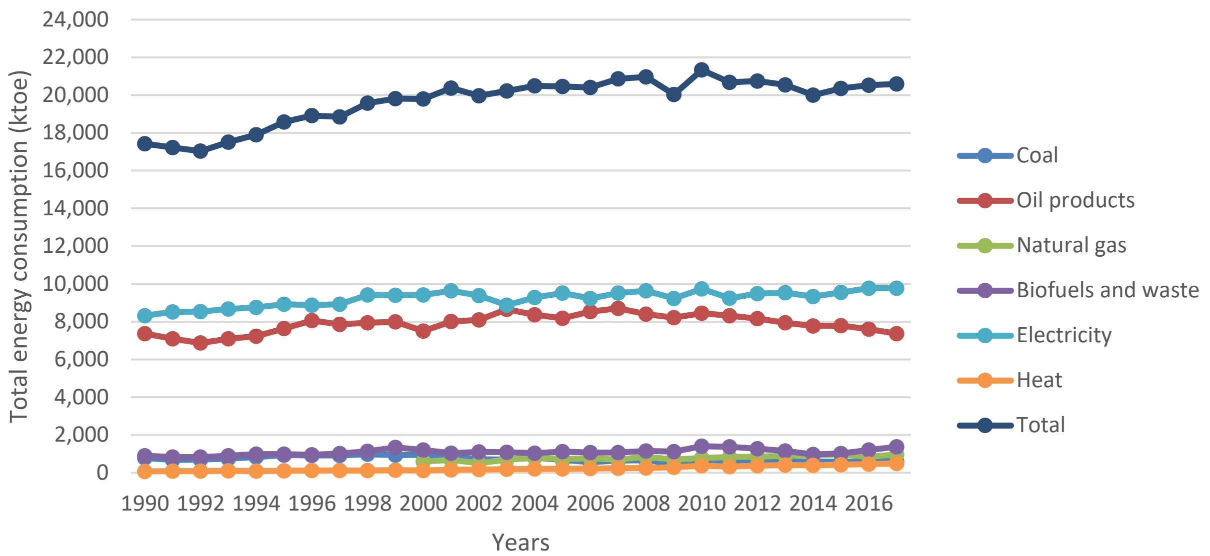
enables us to examine the multidimensional dynamics (Malerba, 2002) of the transport sector, aiming to identify the role of different actors in driving the transition towards carbon lock-out. This comparison is further elaborated by means of the System Failures (SF) framework (Woolthius et al., 2005), which investigates potential barriers to the diffusion of a specific technology; in this case low-carbon transportation methods, which are essential towards climate change mitigation.

3.2 Background

Norway is placed 61st in the list of global CO_2 emitters whereas Canada is the 11th biggest emitter accounting for almost 1.5% of the global emissions (Global Carbon Atlas, 2018). Currently the major energy sources in both countries are oil products and electricity while in Canada natural gas also holds a significant share (Figure 13). A distinct characteristic of Norway is that 95% of electricity produced comes from hydropower while the respective share in Canada is about 60% (Figure 14) (IEA, 2017). However, large inequalities in the distribution of Canada's resources create significant differences among the provinces (Fertel et al., 2013), as is the case with the abundant hydropower potential in the region of Quebec (Vaillancourt et al, 2019). This could be a factor for enabling the transition to EVs, especially in certain regions with an increased share of renewable energy production. On the other hand, Canada is among the top 5 oil producers and top 10 oil consumers, owning a great number of domestic oil reserves, accounting for 10% worldwide (EIA, 2020a). This might hinder the energy transition of Canada's transport sector since domestic reserves ensure reliability and security of supply. Norway owns a number of domestic oil reserves as well, but this equals to 20 times lower than Canada's, and two-thirds of its oil production is exported (EIA, 2020b; 2020c).



(a) Norway

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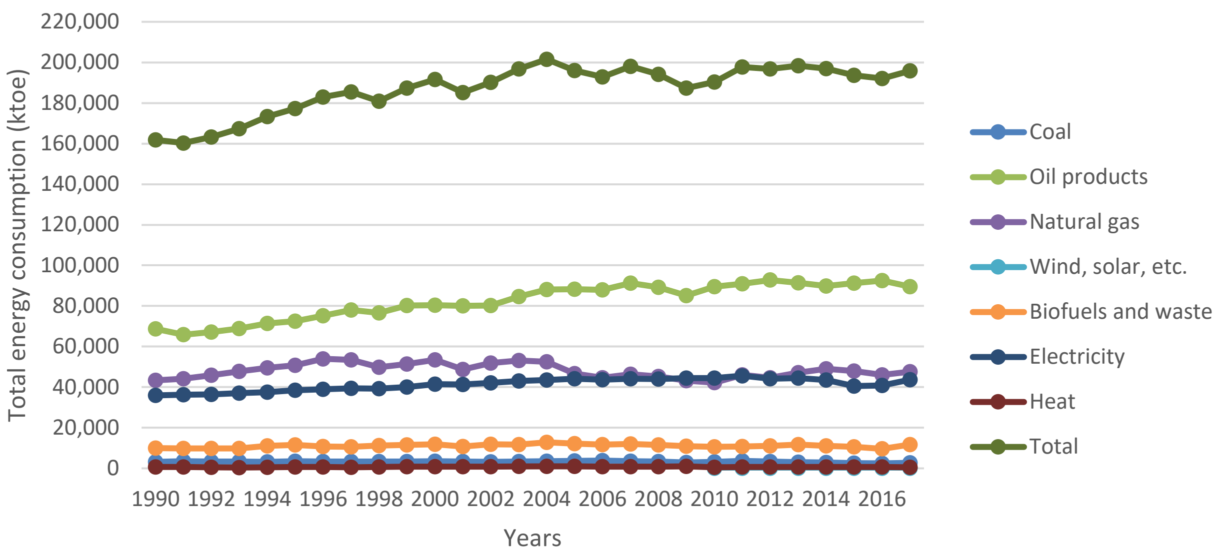

(b) Canada

Figure 13 Total energy consumption per energy source in a) Norway, and b) Canada

Source: IEA (2017), own elaboration

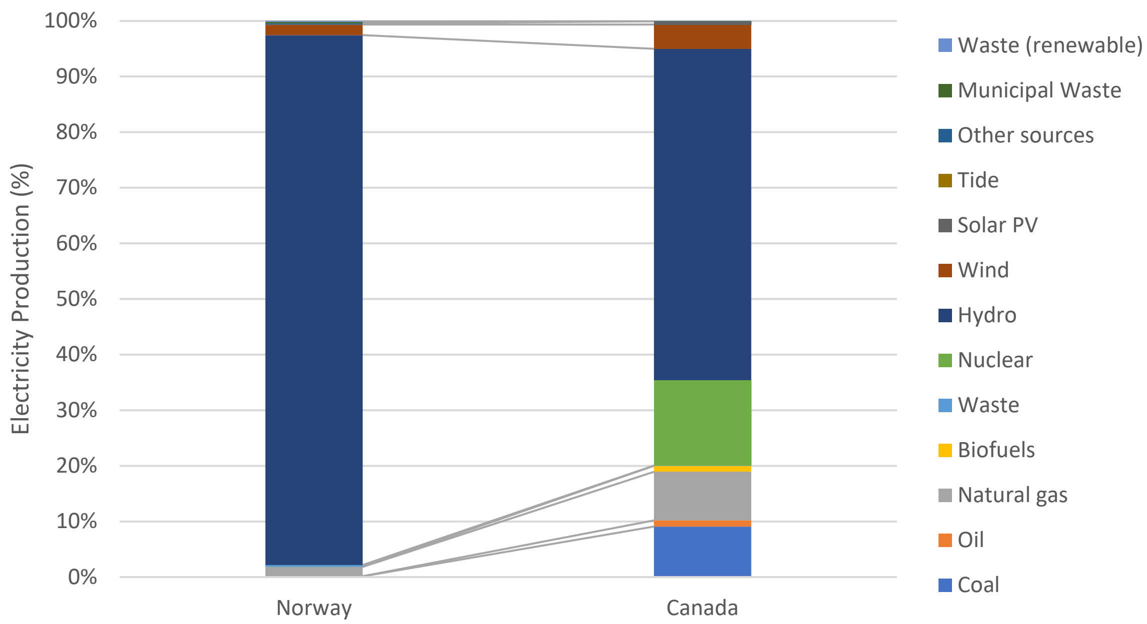

Figure 14 Comparative electricity production per energy source in Norway and Canada

Source: IEA (2017), own elaboration

The transport sector contributes to final energy consumption with 22% and 31% in Norway and Canada respectively, and is dominated by use of oil products, as shown in the Figure 15. It should also be mentioned that oil contribution in Norway's transport sector has dropped since 2011, with biofuels (mostly imported) marking an increase, particularly since 2015, while in Canada the share of oil remains almost stable.

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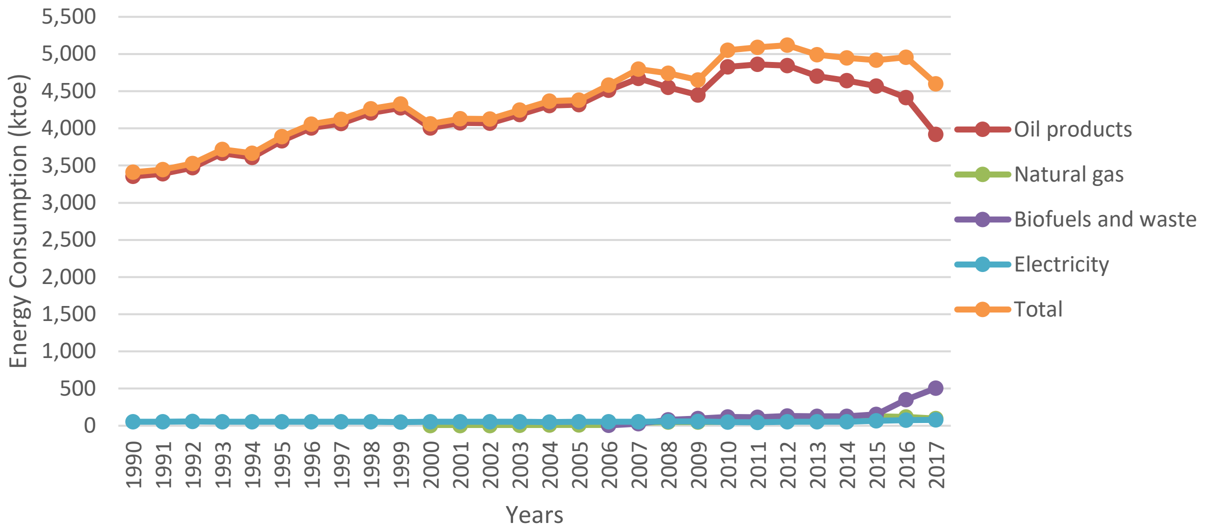
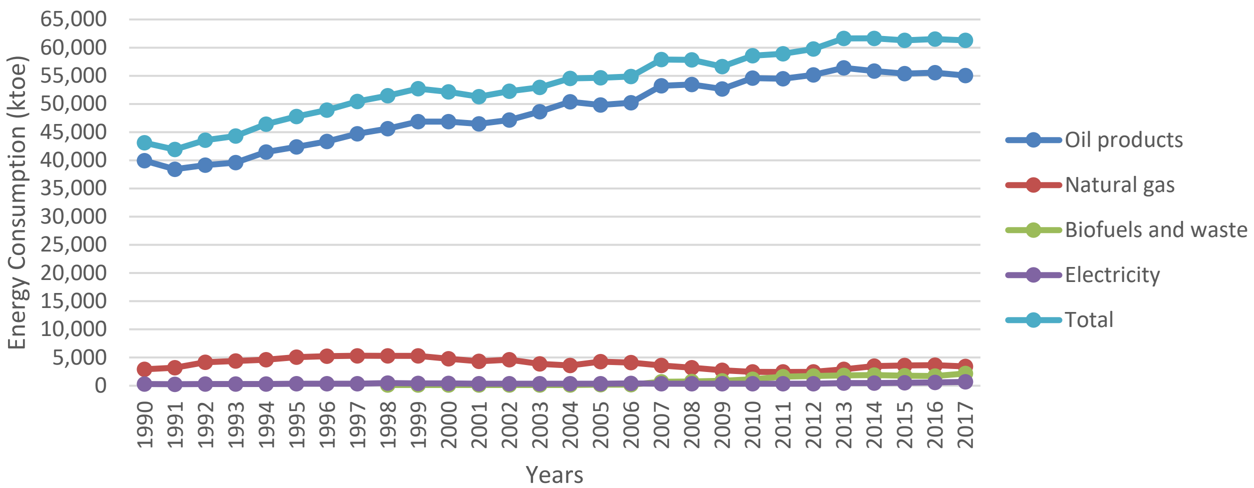


(a) Norway



(b) Canada

Figure 15 Transport energy consumption per energy source in a) Norway, and b) Canada

Source: IEA (2017), own elaboration

Regarding GHG emissions, the transport sector is one of the main contributors in both countries, accounting for almost 24%, while another major emitter is oil and gas extraction (dominating the Manufacture of Solid Fuels and Other Energy Industries category in both countries), even surpassing emissions from transport in Norway (Figure 16).

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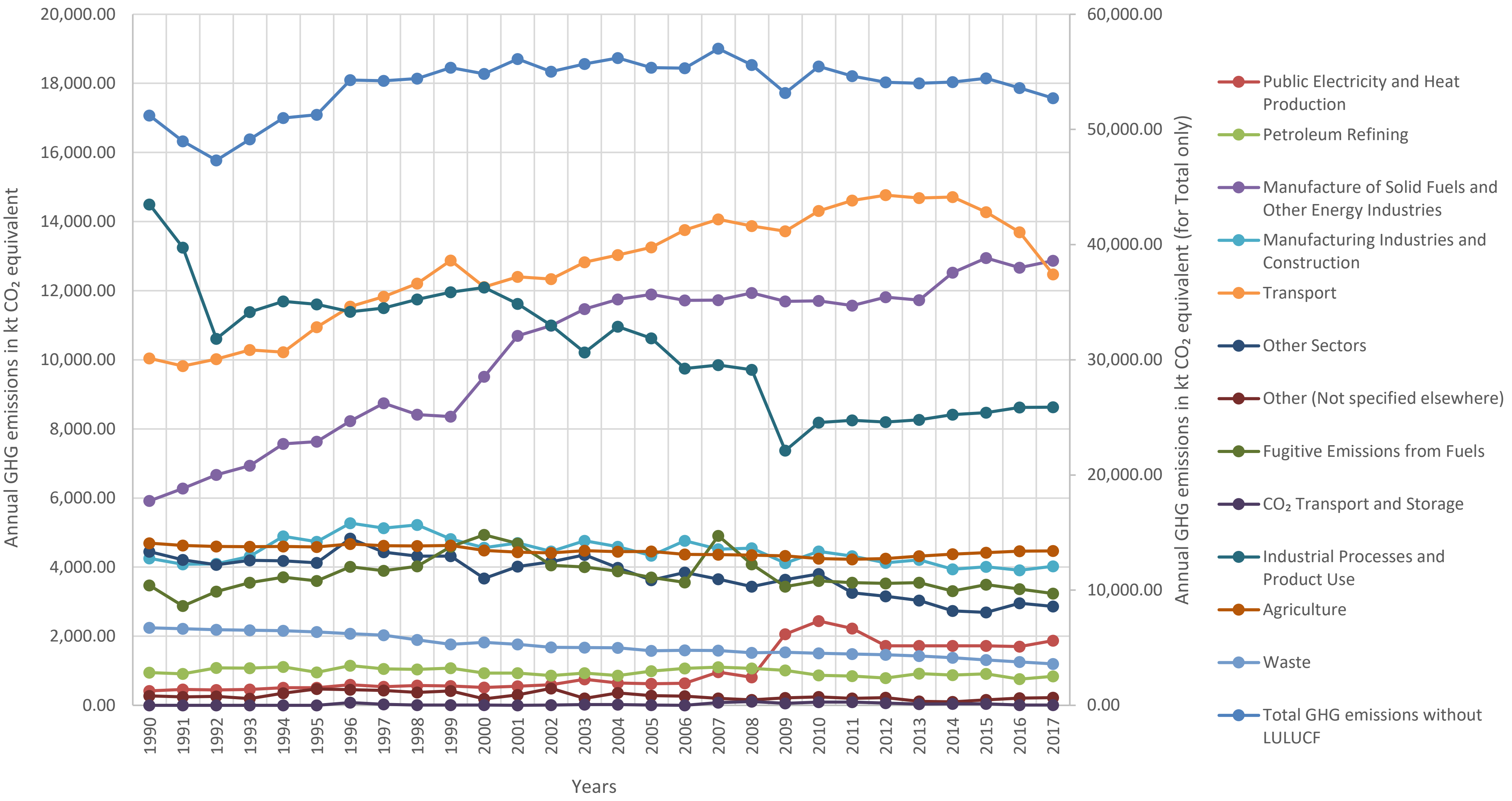

(a) Norway

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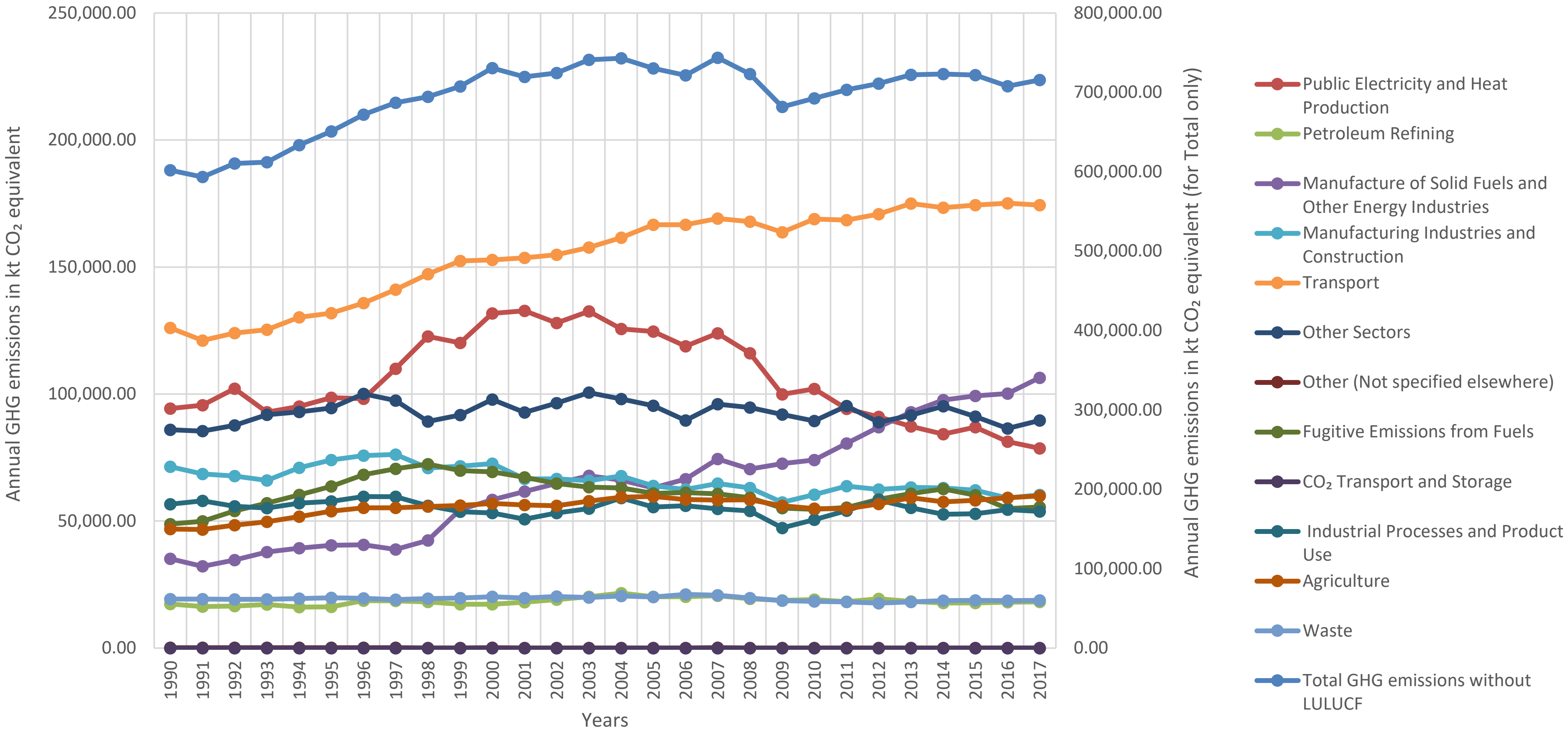

(b) Canada

Figure 16 GHG emissions per sector in a) Norway, and b) Canada

Source: UNFCCC (2017), own elaboration

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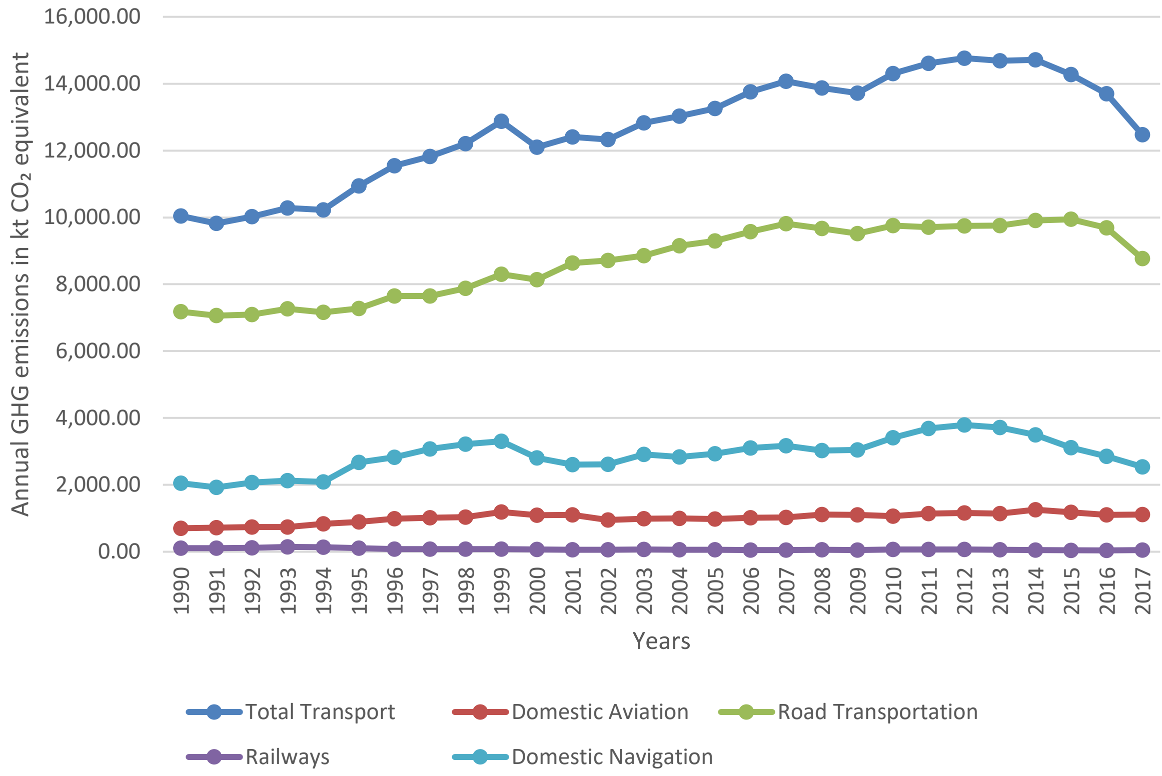
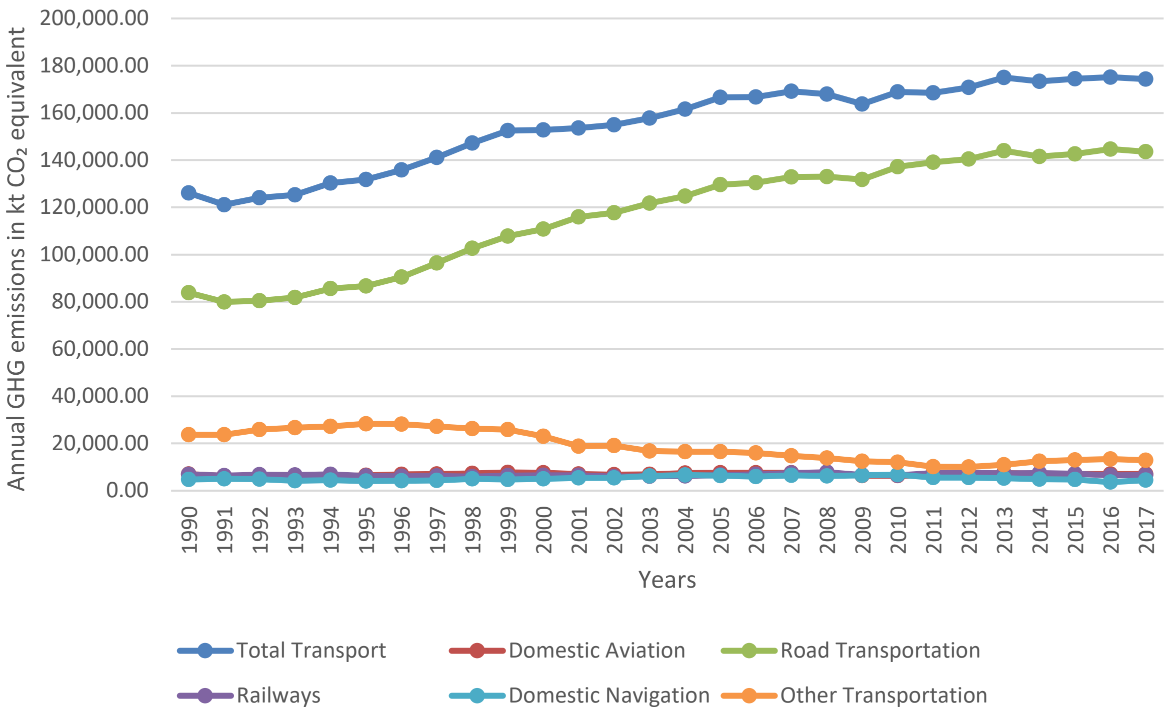


(a) Norway



(b) Canada

Figure 17 GHG emissions in Transport per sector in a) Norway, and b) Canada

Source: UNFCCC (2017), own elaboration

In its 2015 NDC, Norway set a target for 40% of CO_2-equivalent reduction until 2030, compared to 1990 levels – in cooperation with the EU. In the following 2019 climate action pledge, a 35-40% cut in the transport sector was specified, compared to 2005 levels (Norwegian Ministry of Climate and Environment, 2019); in 2020, it further

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strengthened its overall targets to 50-55% (UNFCCC, 2020). Regarding transport, emissions have been slowly decreasing since 2013 (Figure 16) – the dip in 2017 was mainly caused by an increase in biofuels. Still, in 2017 the sector was among the top GHG emitters, slightly trailing oil and gas extraction and, according to SSB data, transport emissions again increased from 2017 to 2018 (SSB, 2019h). Preliminary figures suggest that transport emissions dropped again in 2019: 7,7% in road transport (mainly driven by biofuels) and 6,5% in domestic sea and air transport (SSB, 2020a). Nevertheless, there is a need to take stricter measures for mitigating CO_2 emissions, while considering the country's ambition for all new passenger vehicles and light trucks being zero-emission by as early as 2025 onwards (Norwegian Ministry of Transport and Communications, 2016). Canada has also set targets, under the Paris Agreement, for achieving a 30% CO_2 emissions reduction, compared to 2005 levels. Contrary to Norway, Canada envisages that zero-emissions vehicle sales will have a 10% share, steadily reaching 100% by 2040 (Government of Canada, 2020a). Neither country has made significant progress in decarbonisation, with Canada's total and transport GHG emissions in fact reaching higher levels than 2005, while Norway managed to slightly reduce total and transport emissions by 5% and 6% respectively compared to 2005.

As far as carbon intensity is concerned, Norway has been showing a decrease in road transport since 2006, and in 2017 carbon intensity of road consumption was 61.3g CO_2/MJ; to put this into perspective, industry, which is another energy-intensive sector, had a carbon intensity of 24.9 g CO_2/MJ in the same year. Similarly, Canada's carbon intensity in road consumption has also been dropping since 2006, reaching 67.3g CO_2/MJ in 2017, whereas in industry it equals 35.1 g CO_2/MJ. However, both countries' road transport carbon intensity remains lower than the global level (68 gCO_2/MJ) (IEA, 2017).

3.3 Methodology

Systems of Innovation frameworks are widely used to analyse the importance of a system's actors, networks and processes towards the technological change occurred in a specific system (Hekkert et al., 2007). In particular, the SIS framework examines the interactions between actors and networks, as well as the impact of several factors on a sectoral level (Breschi and Malerba, 1997; Malerba 2002; Malerba, 2004; Malerba, 2005). This framework has been a useful tool for a plethora of research papers examining various sectors. Indicative examples include the studies of Rogge and Hoffmann (2010), Wesseling and Van der Vooren (2017) and Rho et al. (2015) that investigate case studies on power generation, the Dutch cement industry and the Chinese semiconductors industry respectively. In comparison, our research focuses on the decarbonisation of the transportation sector of Norway and Canada, and describes all sub-sectors of the transport sector (road, rail, sea and air) and is separated in four specific sections: 'actors and networks', 'institutions', 'demand', 'learning processes and technologies', as proposed by Malerba (2004). The examination of these four factors is deemed important since the technological progress of a sector is heavily affected by their co-evolution, which can play an important role in technological adaptation (Nelson, 1994; Metcalfe, 1998). For instance, knowledge and technological processes provide important information on the ability of new environment-friendly technologies to penetrate the studied system, by examining the existent habits of the system actors. The SIS framework has been a dependable tool for much research in the transportation sector. For example, Thiel at al. (2016) investigated the decarbonisation of transport focusing on policy investigation rather than technological innovation; Chan and Daim (2012) focused on the policy regarding the Chinese transport sector; while Schade (2016) studied the EU transport sector from various perspectives, of which decarbonisation was only one. Nonetheless, our approach differs from other research capturing broadly various systemic aspects of the transportation sector, with a focus on innovation progress and capacity as well as potential sectoral failures.

In this respect, we combine the SIS analysis with the SF approach (Woolthuis et al., 2005) based on the approach presented in Figure 18, in order to assess and compare the potential challenges that each transport system

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encounters on its way to decarbonisation through diffusion of innovative technologies. The SF framework examines potential barriers that may lead to a system's failure and separates them in four types: institutional, infrastructural, capabilities and interactions. This approach is considered essential for a better understanding of the transition processes. The SIS framework alone may be able to include a broad picture of the innovation system and its structure, but it does not always suffice for the identification of specific barriers related to the diffusion of new technologies. Complementing it with the SF method can greatly contribute to the understanding of the examined systems.

In comparison with other research, in which the SF framework is mainly used for the examination of industrial systems (e.g. Janipour et al., 2020; Bataille et al., 2018), our research conducts a comparative analysis of the transportation sector of the two countries. The main research questions posed during this comparison regard the structure of the transportation sector of the examined countries, their differences as well as their weaknesses towards their decarbonisation with the diffusion of innovative technologies.

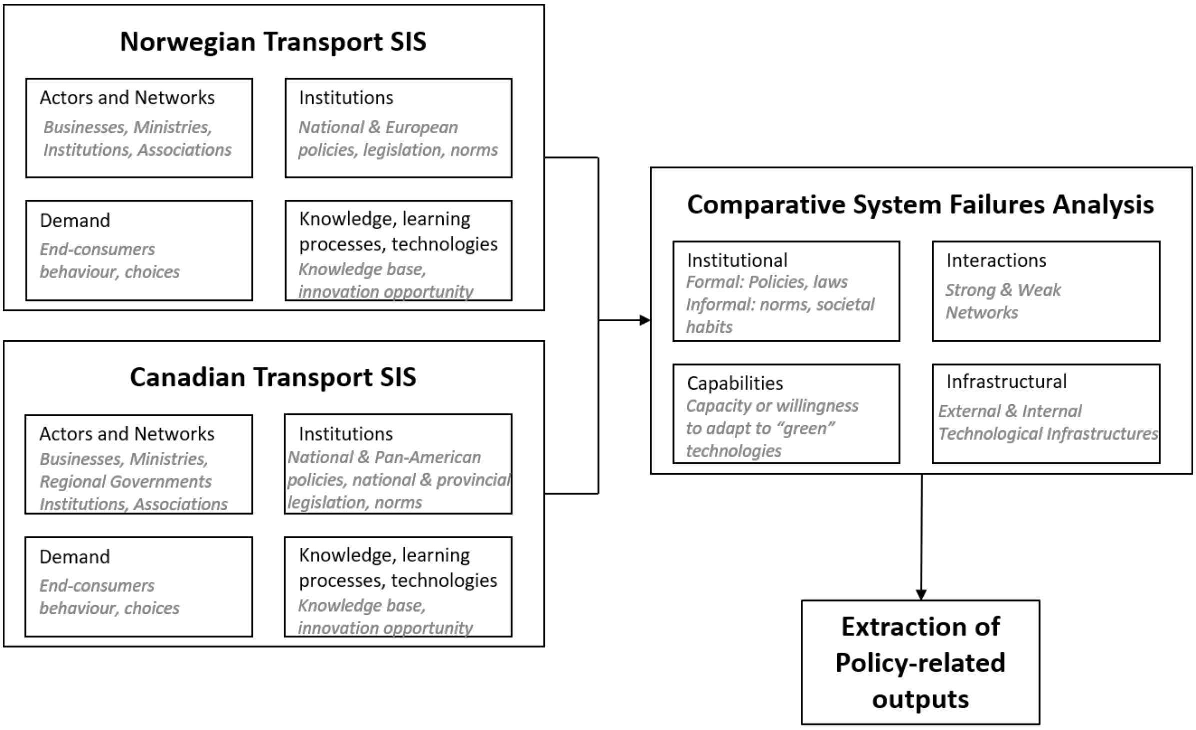

Figure 18 Methodological Approach

3.4 The Norwegian transport SIS

3.4.1 Actors and Networks

The Norwegian transport sector constitutes a network of actors that cover a broad range of subsectors including roads, rail, water transport like ferries and civil aviation, operating under the governance of the Norwegian Ministry of Transport and Communications (Government of Norway, 2020a). However, many of the policy instruments regulating transportation, such as taxes and regulations, are administered by other sector-overarching ministries, like the Ministry of Finance and the Ministry of Climate and Environment. Many administrative agencies operate under the Transport and Communications ministry. The Norwegian Public Roads Administration (NPRA) is responsible for the road transport system of the country, trying to increase security while implementing smart solutions. Management of the rail sector, after the Railway Reform in 2015, is shared between the publicly owned

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company Bane NOR responsible for the railway network and traffic management and the Norwegian Railway Directorate that manages and coordinates the sector from a broader perspective, exploring potential developments. Similarly, the Norwegian Civil Aviation Authority (CAA) supervises all activities related to commercial air transport (Brathen et al., 2000), while Norwegian National Coastal Administration manages the administration of ports and seaways. The Norwegian Ministry of Trade, Industry and Fisheries is also active in the water transport sector since the Norwegian Maritime Authority (NMA), which is subordinate to the ministry, is responsible for the ships under the Norwegian flag and those on Norwegian waters ensuring legal protection and implementation of climate action policies.

As was the case with Bane NOR, the Ministry of Transport and Communications does not only rely on public agencies, but also operates a large number of government-owned companies. The Vy Group, formerly the Norwegian State Railways (NSB), constitutes one of the largest companies in the Nordic Countries, operating mostly in passenger trains and bus services in Norway and Sweden, while under the subsidiary company CargoNet, offers environmentally friendly rail freight solutions. The operation of train lines has recently been subject to tendering, allowing competition. For instance, Go-Ahead Norway, a Norwegian subsidiary of the British company Go-Ahead, recently gained some important stretches from Vy. Targeting also for the mobility and tourist sector, the company strives for innovation having a fleet of 250 electric cars. The financial strength of the company, along with other public companies in bus transport, like Boreal Norge AS and Tide ASA, limit private companies to more regional markets. However, the private company Autolink AS, focusing on the distribution of automobiles, manages to perform transportation of cars through subsidiaries Cargolink AS and Motorships AS, for railway and shipping respectively. Avinor AS is another company owned by the Ministry of Transport and Communications, owning and operating the majority of state-owned airports. The company is a key actor considering sustainable transition, currently evaluating the electrification of civil aviation identifying potential conflicts arising in collaboration with the Zero Emission Resource Organisation (ZERO), an environmental organisation working on an emission-free transport sector, among other topics. Another association aiming for sustainability on transport is the Norwegian Electric Vehicle Association (Norsk Elbilforening), focusing on the promotion of electric vehicles as a means of environmentally-friendly alternative for personal transport. As the largest consumer interest organisation in the Nordics, the Norwegian Automobile Federation acts as a stakeholder with significant influence, engaging in a broad range of transportation issues, including EV policies. The Ministry also owns a number of constructing companies like Nye Veier AS (New Roads), which constructs, operates and maintains some major highways, as well as BaneService, operating mostly as a sub-contractor of Bane NOR. The combination of strong government-owned companies and private enterprises proves the increased role of the government in the economy of Norway (Vasudeva, 2013).

The petroleum industry is Norway's largest industry (Government of Norway, 2020b). Large companies like Equinor ASA, one of the strongest operators in Norway regarding oil and gas (Kharlamov et al., 2013), and Norsk Hydro, which mostly focuses on aluminium, may be considered outside the boundaries of the Norwegian transport SIS. However, as major energy industry agents acting at the borders of the system, they have the strength to formulate transition pathways affecting the decarbonisation of transportation (Saboori et al., 2014).

On the research front, a major actor in the transport sector is the Institute of Transport Economics (TØI), an institution focusing on performing applied and academic research for all subsectors of transport, advise authorities and disseminate key outputs. The institution collaborates with the University of Oslo on research projects and scientific cultivation. TØI is also part of the Nordic Road and Transport Research which is a collaboration among the research institutions of the Nordic countries, aiming to effectively disseminate results to decision makers, assisting knowledge transfer among the countries. Another major research institution in Norway is CICERO Center for International Climate Research, performing interdisciplinary research on climate change from a multi-sectoral

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approach, including transport (Fuglestvedt, 2015).

3.4.2 Institutions

Norway is frequently considered as a pioneer in climate targets, being one of the first nations to pledge to become carbon-neutral by 2050, back in 2008 (Gössling, 2009; Rosenthal, 2008). However, despite the promising targets, carbon neutrality is not officially legislated, creating confusion regarding the substance of the original targets and the direction of Norwegian policy (Hermansen et al., 2019). In fact, the Norwegian Climate Change Act, passed in 2017, sets general targets for Norway to become a low-carbon society by 2050, but does not specify that all cuts in GHGs shall occur in Norway (Lovdata, 2017). Norway largely follows the European Union and participates in the EU Emissions Trading Scheme (ETS) and Effort Sharing Regulation (ESR) despite not being a member-state (Sæverud and Wettestad, 2006; Hermansen et al., 2019).

In 2016, the National Transport Plan 2018-2029 (Norwegian Ministry of Transport and Communications, 2016) was revised in order to transform the transport sector to reduce emissions and costs as well as to increase safety and use of new technologies. A coherent strategy was necessary for Norway; as acknowledged in the plan, the transport sector accounting for a quarter of total GHGs is mainly driven by the low population density. To finance modernisation of transport, around €100 billion are to be used in the twelve-year period aiming to achieve significant emission reduction of buses, coaches and trucks with decrease rates varying from 50 to 100% until 2030, while also increasing the percentage rate of biofuels in aviation to 30% by 2030 (Grantham Research Institute, 2020). According to the plan, all new passenger vehicles registered in 2025 are expected to be zero-emission.

Norway is considered a leading electric vehicle (EV) country, with the world's highest share of EVs per capita. As early as 2014, more than 18% of new cars sold were electric (Ryghaug and Toftaker, 2016), peaking at 60% during March 2019 (Nikel, 2019). Since then, this percentage has decreased slightly, with sales of new cars in 2019 ending at 42% EVs and 14% plug-in hybrids (Henley and Ulven, 2020). Nevertheless, this is a result of long-term effort, since the state incentivised EVs from as early as 1990: EVs were exempted from import and value added tax, an exemption that was made permanent in 1996; in 1997, they were exempted from road tolls, while in 2000 EVs were excluded from VAT as well (Aasness and Odeck, 2015). These incentives managed to distribute electrification costs between end-users and the state, making it economically beneficial for the entire economy (Figenbaum and Kolbenstvedt, 2013). However, the incentive policy has faced some criticism regarding the core idea of intervention towards a single technology and certain privileges, like EVs capacity to use bus lanes causing traffic issues (Holtsmark, 2012). Such criticism, combined with the increased diffusion of EVs, including of premium brands and models, led to the phase-out of the incentives in the form of the 50% rule, which started in 2017, aiming to limit the incentives on ferry fares, public parking and toll roads to 50% of the price of fossil fuel vehicles (Norsk Elbilforening, 2020b).

To explain the strong EV policies in Norway, there is a need to take into account the broader climate mitigation backdrop of the country. There is little gain in decarbonising the power sector, since Norwegian electricity is already 95% renewable. Climate action in Norway has always been internationally oriented, meaning that Norway is occupied with fulfilling its obligations to the UNFCCC scheme and the EU climate change mitigation framework. As seen in Figure 16, the petroleum and industry sectors constitute the top GHG emitting sectors in the country. These sectors are covered by the EU ETS in addition to a general CO_2 tax (introduced in 1991), and as such already regulated in terms of GHG emissions. Since 1990, industrial emissions have been heavily reduced as a result of huge publicly financed R&D programs. Conversely, emissions from petroleum extraction have in the same period (1990-2018) increased by over 70% but cutting emissions from this sector is politically costly because of the central position of the petroleum sector in the national economy. Hence, political attention is turned to another emission-

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intensive sector—transport—where only aviation is covered by the ETS. According to the EU's Effort Sharing Regulation (ESR), Norway has to cut non-ETS emissions by 40% by 2030 compared to 2005 levels, and flexible mechanisms in the ESR framework are according to the Cabinet only to be used if "strictly necessary". In other words, ESR emissions should be cut domestically. Since Norway has very small emissions from buildings and waste, the agricultural sector already has an intentional agreement with the authorities to reduce emissions, and railways are largely run on renewable electricity; what is left is essentially road and sea transport. Particularly road transport is already heavily taxed; therefore, it is politically less costly to indirectly subsidise EVs through lower taxes, than imposing more taxes and fees on road transport. For the same reasons, it is politically less costly to demand fuel retailers to blend in a certain share of biofuels into fossil fuels at the pump. The cost for taxpayers for the ambitious EV policies is, however, less visible in the public debate. In terms of sea transport, central actors see a considerable potential for economic growth in green shipping, and significant public R&D funds are therefore directed towards the maritime sector. However, the size of those funds is small compared to the R&D funds going into the petroleum sector.

3.4.3 Demand

Norway has an estimated population of around 5.3 million people as of 2019 (SSB, 2019c) and is characterised by low density due to the large area covered, which subsequently leads to increased long-distance transportation (Sovacool et al., 2018). However, the area of Greater Oslo has more than a million inhabitants creating a complex system with both urban and rural elements, with half of public transport activities taking place there (TØI, 2020). This sparse population pattern, coupled with the long coastline and the fact that many people and businesses are located near the sea requires a variety of transport methods to be used on the demand side, which is also evident from the distribution of emissions as seen in Figure 17, where despite the dominance of road, other means like water and air transport contribute non-negligible shares.

As of 2018, registered private vehicles were 2.7 million, out of which 7% were electric (0.2 million cars) (SSB, 2019e). As of 2019, there are 2.4 million households in Norway (SSB, 2019b) meaning that, on average, each household owns one vehicle. In 2018, passenger cars covered almost 58 billion km, which is around 78% of the 74 billion km travelled by all road vehicles, including buses and lorries (SSB, 2019f).

Domestically, passenger transport in 2018 accounted for 84,445 million passenger-km, while transport of goods was 53,081 million tonnes-km, out of 26,706 include mainland transport, while the rest comprises transport in the Norwegian continental shelf (SSB, 2019a). Figure 19 presents the share of each sector both in passenger and goods transport. Even though an increased percentage of maritime transport is observed for freight, the majority of goods require short-distance distribution (Rødseth et al., 2018), further establishing the dominance of road transport.

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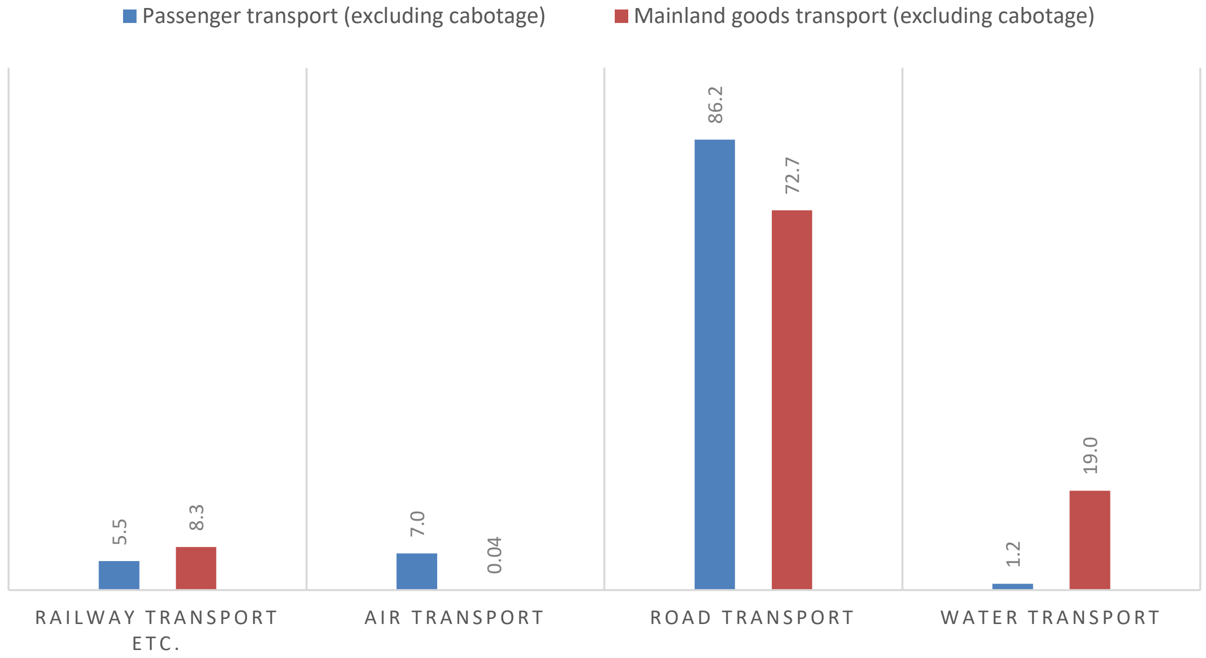

Figure 19 Shares of passenger and goods transport domestically in 2018

Source: (SSB, 2019a), own elaboration

The ability of railway transport to convert passenger transport to revenues accounting on around €500 million provides the subsector with capacity to effectively finance innovation towards sustainability as illustrated in Figure 20.

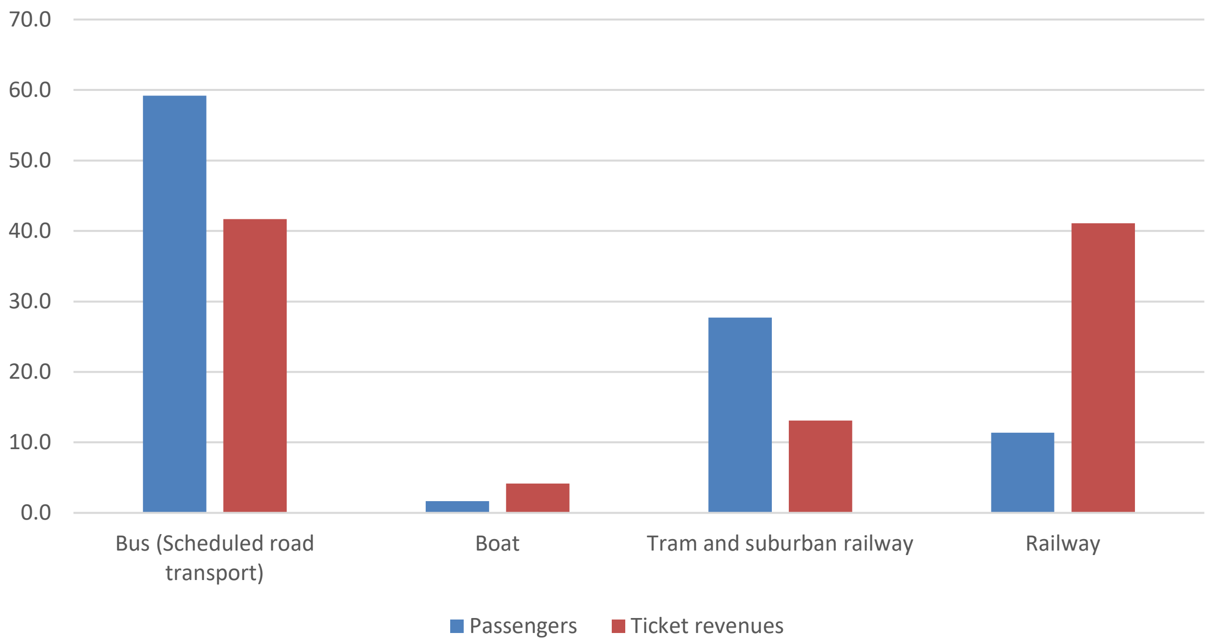

Figure 20 Shares of public transport passengers and ticket revenues in 2018

Source: (SSB, 2019d), own elaboration

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3.4.4 Knowledge, learning processes and technologies

The existing technological base of Norwegian transport heavily relies on traditional fossil fuels across all individual subsectors. However, increased production from renewable energy renders transport electrification an efficient pathway for the sustainability of the SIS. Initiatives throughout the broad spectrum of transport are in place, even though they are still premature, indicating actors' positive attitude towards the process (Sovacool et al., 2018).

Norway is one of the leading countries regarding the diffusion of EVs (Ryghaug and Toftaker, 2016), having already initiated transition towards sustainability in mobility. The country's electricity mix relies mostly on hydropower, with a share of at least 95% (Figure 14) that could even reach 99% depending on the yearly conditions (Egging and Tomasgard, 2018). Clean electricity production cultivates ideal conditions for climate action by means of electrification, as regions in which electricity powering EVs is sourced from GHG-intensive sources, like coal or oil, reduce or negate electrification benefits (Singh and Strømman, 2013). Norwegian households also rely on home charging, since 75% have their own dedicated parking (Hardman et al., 2018) counterbalancing the negative infrastructural effect caused by the small ratio of fast chargers compared to BEVs in stock (Gnann et al., 2018). For building this infrastructure, a public support scheme has taken place as early as 2009, while the fast-charging infrastructure of Norway was supported mainly by local utility companies, who initiated the first round of support for the operation of fast-charging stations (Lorentzen et al., 2017). Despite favourable conditions, EV diffusion is still in early stages, as shown in Figure 21, presenting the fuel mix used in private cars in 2017.

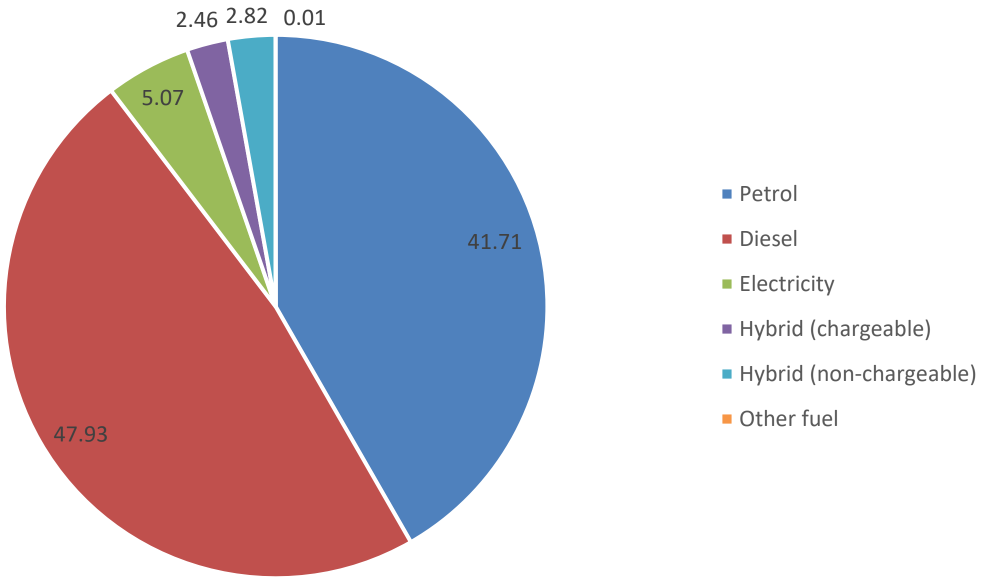

Figure 21 Shares of fuel used on private cars in 2017

Source: (SSB, 2019e), own elaboration

Fossil fuels heavily dominated private cars in 2017, with diesel-powered vehicles constituting almost half of the fleet. Energy content per litre is higher for diesel than petrol (Gallachóir, 2009), limiting the margin for efficiency provided by EVs and showcasing that increasing fuel efficiency of vehicles will require wider changes in the transport industry (Aamaas and Peters, 2017). However, the share of electric among total registered cars, is progressively increasing, reaching almost 7% in 2018 and 9% in 2019 (Figure 22). The distance covered by EVs, though, during the same period, was 5.3% of the total, surpassing 7% a year later in 2019 where EVs covered 3,400 million km out of a total of 45,562 million km (SSB, 2020b). Use of biofuels has also increased in recent years

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(Figure 15), but the production cost has led to high levels of imports (Hagos et al., 2017). Controversy surrounding biofuels (Marsh, 2008), especially regarding the unsustainability of palm oil as a source (Bjorkhaug et al., 2018), coupled with policy inconsistencies related to incentives, limits the diffusion of biofuel innovation in the Norwegian system (Fevolden and Klitkou, 2017). Despite the ambitious targets set for electrification, biofuels constitute an important additional measure as part of Norway's decarbonisation strategy for the transport sector.

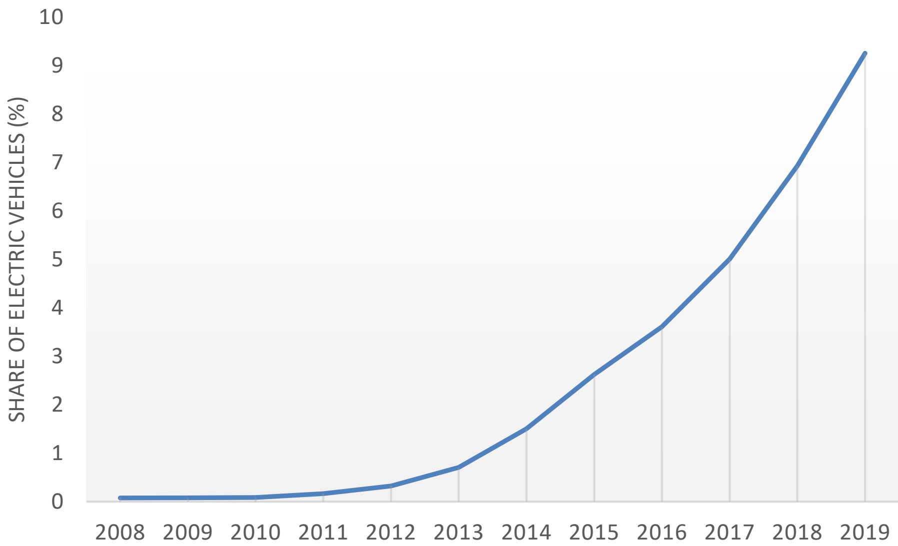

Figure 22 Share of EVs in Norway

Source: (SSB, 2019g), own elaboration

Regarding water transport, effort is also focused on limiting the use of fossil fuels in ferries, passenger boats, but also in other means of transport, like cargo trucks, by introducing alternative fuels (Renkel and Lümmen, 2018). Despite EV diffusion being the main innovation in the Norwegian transport system, the maritime sector has a significant share in the transport of goods as seen in Figure 19, which is also evident from the share of emissions in Transport with road dominating, but significant amounts are also produced from sea, as seen in Figure 17. While Norway has no car industry, its maritime sector is technologically cutting-edge from an international perspective, exemplified by the production of the first fully electric ferry in 2015 by the Norwegian company Norled and the country's leadership in the use of electric ships the following period (Chin et al., 2019). In Norway's 2015 NDC, along with ambitions to reduce emissions in the transport sector, environmentally-friendly shipping was mentioned as part of the priority areas of the county's national policies, indicating significant political attention towards the potential for green growth in the maritime industry. In the Government's action plan for green shipping (Norwegian Government, 2019), multiple funding agencies were described that could provide financial support, like Enova, whose role as an important funding agency will be maintained the following periods, Innovation Norway with green shipping being a major recipient of almost €7 million and the MAROFF programme from the Research Council of Norway, with the Ministry of Trade providing almost €16 million for maritime research and innovation in 2017. The collaboration between the authorities and the business sector is also important with public-private partnerships established, like the Green Shipping Programme, receiving more than half a million euros from the national budget in 2019. Following that, in 2016 the National Transport Plan 2018-2029 set the ambition that by 2030, 40% of all ships in short-distance sea shipping will use biofuels or be low- and zero-emission vessels and ensure that all new national highway ferries use low- or zero-emission solutions, while also contributing to county municipal ferries and fast ferries using low- and zero-emission solutions (Norwegian Ministry of Transport and Communications, 2016). Green shipping is also part of the Norwegian stimulus packages

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to boost the economy in the wake of the Covid-19 breakout.

On a similar approach in the aviation sector, Avinor acquired a small electric airplane to trigger research on electrifying air transport (Avinor, 2020), although progress is limited compared to marine transport.

The Norwegian railway network consists of lines, 62% were electrified, as of 2007 (SSB, 2008), while as of 2019 more than 1,000 km of non-electrified lines existed (Zenith et al., 2019), mostly covered by fossil fuels. Electrifying the remaining parts of the network or introducing more efficient fuels is a major challenge of the transport SIS in Norway, because of costs and a sparse population pattern.

The key outputs from the Norwegian transport SIS are presented in Table 16.

Table 16 Key outputs of the Norwegian transport using the SIS blocks

SIS blocks	Key results
Actors and Networks	• High participation of the public sector either through state-owned companies or private-public collaborations • Strong actors from the petroleum industry
Institutions	• Early policy through incentives for EVs, which has been criticised in recent years.
Demand	• High share of road transport • Water transport shows a significant percentage in the transport of goods
Knowledge, learning processes and technologies	• Current regime dominated by diesel and petrol vehicles • EVs remain the major innovation in the system with their share increasing • Electrification is the main measure of the decarbonisation strategy, but the Norwegian government is interested in biofuels as an additional measure • Local utilities responsible for developing the fast-charging infrastructure

3.5 The Canadian transport SIS

3.5.1 Actors and Networks

The Canadian transportation sector is characterised by a variety of activities depending on the means used. Each transportation method is related with different associations, networks and firms. Regarding automobiles, Canada is considered one of the biggest car producers worldwide, manufacturing more than 2 million vehicles per year (OICA, 2018). Despite Canada being a major car producer, there is no automobile manufacturer headquartered in the country: all stakeholders are firms established in other countries, especially in USA and Japan (e.g. Toyota and GM) (Government of Canada, 2020b). Canada also hosts one of the most important bus manufacturers worldwide and the largest in North America, the NFI Group, as well as, one of the major train and planes manufacturers, Bombardier Inc. Furthermore, because of its abundance of fossil fuel reserves, Canada is also strongly involved in oil and natural gas production, especially in the Western provinces (Radović et al., 2018). There are Canadian as well as international fossil fuel companies operating in Canada. Regarding the former, Suncor Energy and Canadian Natural Resources are considered among the biggest in the country (Forbes, 2020). International fossil fuel corporations are also quite active in Canada, like Chevron and Exxon Mobil. This activity of fossil fuel companies is an important factor in the system, since they are usually involved in political campaigns promoting their actions (Exxon Mobil, 2017), which can be considered as a barrier against rapid decarbonisation actions, considering that the energy industry is a large contributor to the Canadian economy (Vaillancourt et al., 2015).

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Apart from vehicle manufacturers and fossil fuel producers, passenger transport operating and logistics companies also play an important role in the setup of the Canadian transportation sector and its low-carbon technological transition. Each town and city in Canada has its own urban bus transportation network, while the three biggest cities (Toronto, Montreal and Vancouver) also possess a metro system. Furthermore, some smaller cities (like Calgary and Edmonton) have a light rail system for urban transportation (Calgary Transit, 2020). This plurality of independent networks and associations can lead to a greater need of cooperation and coordination, which is not easily achievable, resulting in delayed actions towards a transition to a "greener" system.

Apart from urban transportation, Canada is characterised by a variety of bus and train companies operating long-distance routes, being the second largest country in the world. Regarding freight transport, Canada hosts 70 public and private rail companies and approximately 208,000 trucking businesses (Transport Canada, 2019). Regarding sea and air transportation there are fewer firms operating in Canada and the majority of them are headquartered in other countries, especially for international transportation (Transport Canada, 2019). The only exceptions are Air Canada (passenger and freight), WestJet (passenger) and Air Transat (passenger) airlines, which accommodate many international destinations (Transport Canada, 2019).

As discussed above, transportation is a complex sector as it consists of many sub-sectors, such as road, rail, sea and air transport, all of which can also be separated into passenger and freight. It is, therefore, supported by many associations affecting the sector's landscape and diffusion of new technologies. At the local level, the CUTA (Canadian Urban Transit Association) plays an important role on knowledge diffusion, urban authorities' advocacy and communication among various local transit authorities. It consists of hundreds of members, such as universities, federal and provincial ministries, businesses and urban transit authorities. Some significant members of this association are the Transportation Research Institute of the University of Toronto, the Transportation Association of Canada (TAC) and corporations like the NFI Group. TAC, in particular, is a similar umbrella organisation but with a broader spectrum of actions, focusing on road transportation and infrastructure at national and local level, while its pillars of action include environmental protection and mitigation of climate change: it has established its own Environment and Climate Change Council, which proposes technical solutions for both mitigation and adaptation (TAC). Similar umbrella organisations for other means of transport are the Railway Association of Canada (RAC), the Shipping Federation of Canada and the Air Transportation Association of Canada (ATAC). There are also associations representing freight transportation stakeholders. The Private Motor Truck Council of Canada is the main Canadian association promoting interests of the private truck companies and disseminating knowledge on various issues related to road transport. There are also associations representing companies purchasing freight transport services and contributing to the interaction between freight transportation companies and their customer base; the Freight Management Association of Canada (FMA) is considered an important federation among these, with its members' annual contribution to the Canadian economy accounting for $100 billion dollars and the transportation services they use for $4 billion dollars

Apart from numerous associations, there are also federal and public actors involved in the transportation sector, especially in the diffusion of new "green" technologies. An important actor knowledge "production" and diffusion is the Transportation Research Institute of the University of Toronto, which engages in relevant research areas, such as alternative fuels, traffic congestion etc. (University of Toronto Transportation Research Institute, 2020). Another university carrying out research in transport and particularly EVs is the University of Concordia in Quebec, authoring a high number of electric mobility-related publications, while the Hydro-Quebec Research Institute, owned by the public utility Hydro-Quebec, excels at research focused on electric technologies, such as batteries (Haley, 2015).

Federal government institutions are also related to a sustainable, low-carbon transition of the country's

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transportation sector. Transport Canada is the ministry related to regulations regarding the sector, by promoting policies towards its safe, efficient and environment-friendly operation. Environment and Climate Change Canada, the ministry related to climate change and action, also plays an important role, being responsible for aspects of global environmental change and air pollution that are intertwined with the transport sector (Government of Canada, 2020b). Finally, in 2015, the Canadian Council of Ministers of the Environment (CCME), consisting of every minister of environment and climate change of each Canadian province as well as of the federal minister, established a Climate Change Committee (CCC), aiming to implement the Pan-Canadian Framework for Clean Growth and Climate Change (PCF), which sets various targets for the entire economy (Pan-Canadian Framework on Clean Growth and Climate Change – Canadian Intergovernmental Conference Secretariat, 2020).

3.5.2 Institutions

Among the economic sectors targeted by the PCF, special attention is given to electricity, industry, agriculture and transportation. Regarding the latter, environmental policy is broken down into four pillars: setting stricter standards and increasing energy efficiency; raising the percentage of zero-emission vehicles; investing in public transit and infrastructure; and using cleaner fuels. An example of the implementation of this framework is the electrification of transportation in Quebec, which intends to have 100,000 electric vehicles until 2020 (Pan-Canadian Framework on Clean Growth and Climate Change – Canadian Intergovernmental Conference Secretariat, 2020), with the allocation of at least $6.2 billion towards climate change mitigation with emphasis on electrification, as illustrated in the latest budget of the province (Government of Quebec, 2020). Electrification of transportation in Quebec, a province featuring an electricity system that is heavily dependent on hydro, is considered a significant measure towards abatement of GHG emissions (Haley, 2015).

Another important measure taken by the Canadian government is the legislation of the Greenhouse Gas Pollution Pricing Act (GHGPPA) in late 2018. The Act established charge rates for fuel use in various sectors, including the transportation sector, which are dependent on the emissions produced from each fuel's combustion and are different on each province. The GHGPPA is in force in half provinces and two territories: Ontario, New Brunswick, Manitoba, Saskatchewan and Alberta; and Yukon and Nunavut (Justice Laws Website, 2020). The legislation concerns fuel distributors, fuel producers and specific road, rail, marine and air carriers, who have to register to a platform of the Canada Revenue Agency (CRA), in order to claim their use of fuel, which is charged according to its associated emissions (Canada Revenue Agency, 2020). Results on increased costs for transport stakeholders, including people that are not involved professionally on this sector, since the price of fuels on gas stations has already been increased (Abedi, 2019).

Another important factor of environmental law is Canada's sub-national division: the country is separated in three territories and ten provinces with their own legislation, which may be less or more proactive than federal legislation (Fertel et al., 2013). For example, the Quebec and Alberta provinces have legislated their own carbon pricing regulations, in 2007 and 2015 respectively, acting faster than the federal government (Erutku, 2019; Brown et al., 2018). On the other hand, the province of Ontario, although having established its own carbon pricing scheme since 2017 (Erutku, 2019), showed great resistance to the proposed GHGPPA of the federal government after the provincial election of the conservative party. The provincial government of Ontario, in fact, initiated legal processes disputing the constitutionality of said Act, but the Court of Appeal of Ontario adjudged that the GHGPPA is not violating Canadian constitution. There was a similar case in the Court of Appeal of the province of Saskatchewan resulting in a similar verdict (Climate Change Litigation, 2020). Despite their result, these appeals indicate that provincial legislation and policy may not always act beneficially for climate action, leading oftentimes to conflicts with federal policy; while in other cases, sub-national environmental and climate policy may act faster than the federal government, with implications for the transport sector.

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These carbon pricing schemes constitute an effort of some Canadian provinces to participate in an emission trading scheme organised by the West Climate Initiative (WCI) and comprising the state of California (USA) and the provinces of Quebec, Nova Scotia and British Columbia. Membership of this scheme varies in time: Ontario, for example, became a member of this initiative since almost its beginning but withdrew membership in late 2018 upon election of its new provincial government, which proposed the Cap and Trade Cancellation Act (Legislative Assembly of Ontario, 2020).

Transportation 2030 is a policy of Transport Canada, aiming to transform Canada's transport sector into a more efficient, safer and greener sector by 2030. The policy's budget for 2017 was higher than a half of billion dollars and consisted of numerous measures: it included $120 million for electric vehicles and alternative fuel investments, $56.9 million for GHG regulation development and $229 million for supporting the Clean Energy and Clean Transportation Innovation Programming (Transport Canada, 2020b). One of such initiatives is the establishment of a research fund supporting rail, marine and air transportation so that they achieve a transition towards a more environment-friendly operation. This research fund cooperates with various public and private organisations operating in academia, government, transport and other relevant sectors related (Transport Canada, 2020a).

3.5.3 Demand

Canada is the second largest country worldwide and two of its three largest metropolitan areas, Toronto and Montreal, are located on the east side of the country, while Vancouver is situated on the west coast of the country (Krueger et al., 2020), being at a distance of approximately 4,400 kilometres by road and 3,400 kilometres by airplane from Toronto. Therefore, Canada is characterised by extensive transportation needs. Specifically, transportation accounts for 5% of its GDP and Canada has one of the largest transportation sectoral GDP per capita (Trading Economics, 2020e).

The country has a very wide road network expanding more than 1,300,000 kilometres in length, of which 443,000 are paved (Statistics Canada, 2019d). It is noteworthy that transportation activity related to road transport is increasing in every sub-sector, leading to emissions from road not only dominating in transport, but also steadily increasing, as seen in Figure 17. In the period 2000-2013 the passenger kilometres traveled by cars increased by 13% (OECD, 2017b), while gasoline sales have increased by 10% in the last ten years (Statistics Canada, 2019a), although car engine efficiency is constantly enhanced (Weiss et al., 2020). The increase of passenger transportation is also visible on the bus industry, the revenue of which had increased from 8.6 billion dollars in 2005 to 20.3 in 2017 (Statistics Canada, 2020e). A similar effect is also observed in freight transport, where the activity of trucks had doubled between 2000, with 84.7 billion-tonne kilometres of domestic activity, and 2014, with 166.6 billion-tonne kilometres, with an augmenting tendency. Moreover, the tonnage of cargo transported in the same period had almost tripled (Statistics Canada, 2019c).

The vastness of the Canadian land has also resulted in an impressive rail network, the length of which is more than 60,000 kilometres (Statistics Canada, 2019d). In comparison with the road sub-sector, rail transportation activity is considered slightly less increased: total passenger car-kilometres have shown an increase from 58 billion in 1990 to 71 billion in 2017, fluctuating significantly during this period (Statistics Canada, 2020h). Furthermore, domestic freight activity increased from 207 billion-ton kilometres in 2000 to 282.2 in 2015 (Statistics Canada, 2019a). On the other hand, total freight activity (including international trade) of the train sector has shown a similar augmentation rate from 534 billion-tonne kilometres to 761 billion-tonne kilometres. This increase is also reflected in the revenue of rail companies which almost doubled in this period, reaching $13.52 billion dollars in 2014 (Statistics Canada, 2020h). Although, rail activity is increased, total fuel consumption (diesel oil) remained almost stable during this time span (Statistics Canada, 2020g).

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Another important means of transportation but less extended in Canada is water transport, separated in three categories: inland waterways, referring to rivers; the Great Lakes, referring to boats traversing these lakes; and sea transport. The length of inland waterways and the marine network of the Great Lakes is 2,825 and 2,662 kilometres respectively (Statistics Canada, 2019d). Furthermore, the country has 557 port facilities (Transport Canada, 2019). Regarding inland waterways and the Great Lakes, domestic activity fluctuated during the period 2000-2011 but did not show a clear upward or downward tendency, with an annual average of 4.7 and 23.83 billion-ton kilometres respectively. On the other hand, domestic coastal shipping greatly increased during the same period (Statistics Canada, 2019c). It is important to mention that most sea trade is related to international trade; in 2011, tonnage traded internationally accounted for 73% of the total sea freight activity (Statistics Canada, 2019f). Another important sector of marine transportation is containerships. The main ports in Canada are Vancouver, Montreal and Halifax. From 2005 to 2011, their total activity was increased by almost 400,000 TEUs. In 2011, the number of TEUs handled in these three ports were 2,500,000, 1,220,000 and 370,000 respectively, with the port of Halifax having a downward tendency. Another fact that demonstrates the increased number of containers handled in Canadian ports is the rapid growth of the Prince Rupert port in British Columbia, which started operating in late 2007 and in 2011 already surpassed the port of Halifax, handling 400,00 TEUs (Statistics Canada, 2019e). Last but not least, marine transportation also serves traveling passengers. In 2018, major ferry routes in Canada carried 53 million passengers and 21 million cars (Transport Canada, 2019).

The last method of transportation is aviation. Canada has approximately 1,200 airports (Statistics Canada, 2019d), serving passenger and/or freight flights. The four busiest airports of Canada are located in Toronto, Vancouver, Montreal and Calgary, with Montreal having two airports carrying freight flights (Statistics Canada 2020a; Statistics Canada, 2020b). In the period of 2008-2018 passenger activity significantly increased from 109 million to 159 million passengers. In fact, domestic passengers increased by 23 million, transborder passengers between Canada and the USA by 10 million and the rest of the increase is related to other international activity (Statistics Canada, 2020c). This rapid increase is also reflected on the total activity measured in passenger kilometres, which was increased by almost 20% in just two years (2015-2017) (Statistics Canada, 2020d). A similar upward tendency is also observed on air freight transport. In 2008, a total of 972 million tonnes of cargo were handled, whereas in 2018, this figure reached 1.434 billion tonnes. Domestic cargo increased by 200 million tonnes, international cargo excluding transborder trade by 275 million and transborder freight slightly decreased (Statistics Canada, 2020a). This is reflected on the total tonne-kilometres handled, which increased by 38% during the period 2015-2017 (Statistics Canada, 2020d). As expected, the increase of air transportation activity is reflected on aviation's fuel consumption, which in 2017 had increased by 14% compared to 2012. Specifically, in 2012 the total fuel consumed was 6.6 billion litres and in 2017 it reached 7.55 billion liters (Statistics Canada, 2020c).

Demand demonstrates that Canada has a fast-growing transportation sector, the GDP of which has increased from $58 billion dollars in 2000 to $90 billion dollars in 2019 (Trading Economics, 2020d). This constant growth of transportation has a two-fold impact on its transition to a sustainable sector. A growing sector is capable of investing towards new, low-carbon or carbon-neutral technologies, with a lower degree of dependency on state subsidies (Bigerna et al., 2019), since incumbent firms are growing and are able to invest more. On the other hand, a growing sector demonstrates high energy demand, thus stricter policies must be implemented in order to avoid a carbon lock-in (Castro Verdezoto et al., 2019).

3.5.4 Knowledge, learning processes and technologies

As mentioned before, the transportation sector consists of a plethora of sub-sectors. Some of these are characterised by a variety of fuels used and others are dependent on one single fuel. Road transportation is separated into passenger and freight. Regarding passenger transportation there are various types of vehicles used.

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The most common type is vehicles combusting gasoline, accounting for almost 94% of new registered passenger cars in the between 2014 and 2018. Furthermore, almost 4% of cars registered in the same period use diesel as their energy source. The remaining 2% of cars consisted of hybrid, plug-in hybrid and battery electric vehicles. Nonetheless, it is noteworthy that sales of electric cars have met a significant increase recently. In 2018, the newly registered electric cars reached 3.5% of total cars, including hybrid and plug-in hybrid cars(Statistics Canada, 2020f). Apart from the fuel used on each car, another important factor is fuel efficiency of cars depending on equipment and size. Canada is considered the world's least fuel-efficient country regarding passenger vehicles, since it has the largest and second heaviest cars worldwide. The average emissions of a Canadian light-duty vehicle per kilometre are higher than 200 grams of CO_2 (Shaffer, 2019), showcasing the high potential for improvement, as is the case with the trend in neighbouring countries like the USA (Joost, 2012). On the other hand, road heavy freight transportation is characterised by exclusive consumption of diesel oil for trucks handling cargo (Canadian Energy Research Institute, 2013). Lastly, regarding road transport, biofuels are mixed with diesel and gasoline in order to reduce their carbon emissions (Mondou et al., 2018). The mix rate of biodiesel and ethanol in diesel and gasoline respectively varies per province, in accordance with federal regulation. The maximum rate for ethanol is 8.5% and is presented in the province of Manitoba, whereas the maximum rate for biodiesel is 4% occurring in the provinces of Ontario and British Columbia. However, there are provinces, such as Quebec, not mandating a specific rate percentage (Global Agricultural Information Network, 2019).

Regarding train transport, the main driver of fuel consumption is freight, which is using solely diesel as its energy source. The same phenomenon is observed in intercity passenger trains. The only other energy source used by rail transportation is electricity, mainly used for urban transit. Indicatively, in 2013, 93 PJ of diesel were used for intercity passenger and cargo transportation, whereas only 3 PJ of electricity were consumed for urban transit, during the same year (Statistics Canada, 2019b). Air transportation is characterised by a similar distribution of fuels, with two different fuel types being mainly used; jet fuel and aviation gasoline. Jet fuel is dominating this sub-sector with a usage percentage over 99%. Lastly, marine transportation is also dependent on two types of fuels, but these two fuels are more homogenously distributed: residual fuel oil accounts for 65% of energy consumption, whereas distillate (diesel) fuel oil for the remaining 35% (Statistics Canada, 2019b). Contrary to road and rail transportation, aviation and marine transport do not use biofuels in their fuel mix, as is the case worldwide (IEA, 2019d).

There are many technologies that can be used in order to reduce GHG emissions in the transportation sector towards climate change mitigation. Some of them can be applied to specific sub-sectors whereas, others can be widely used. A technology widely applicable is the increase of electric vehicles usage for road and rail transportation, as well as the introduction of electric mobility to air and marine transportation. Regarding passenger vehicles, some Canadian provinces (Ontario, Quebec and British Columbia) have provided subsidies to citizens in order to promote the purchase of electric vehicles. Towards this direction, the federal government in 2019 also legislated the provision of subsidies (up to $5,000) to people buying electric vehicles (Thorne and Hughes, 2019).

Another area in which electric vehicles are not widely used in Canada is train transportation, which is dominated by diesel combustion, since electrification of train services leads to financial uncertainty, especially for long distances between different regions (Marin et al., 2010). Furthermore, electric mobility is considered a future solution for the reduction of GHG emissions in road freight transportation by means of electric trucks (Liimatainen et al., 2019), as well as marine and air transportation with electric boats and planes (Reabroy et al., 2015; Han et al., 2019). These technologies have mainly been examined on a research level and have no major applications. On the other hand, increased penetration of electric cars and trains, which is already taking place in other countries, would result in significant GHG emissions reductions because of Canada's hydro-dominated power generation

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mix (Dolter and Rivers, 2018), especially in provinces like Quebec with a high share of production from renewable sources. Therefore, the only sector that has experienced a mild transition towards a reduced dependence on fossil fuels in Canada is road transportation, because of the slow penetration of electric cars. The rest of the sectors have not demonstrated any noteworthy tendency towards the exploitation of Canada's clean electricity.

Another impacting action is the increase of biofuels use in diesel and gasoline blends, by promoting advanced biofuels (Mondou et al., 2018). Specifically, Canada has the largest biomass reserves per capita, since they account for 7% of global potential biomass production (Generation Energy Council, 2018). Another fuel that can be used for transportation needs is green hydrogen, through electrolysis using RES. Furthermore, the country is characterised by an important research activity in hydrogen exploitation, regarding its production, storage and usage on the transportation sector (Lemieux et al., 2019; Ghandehariun and Kumar, 2016; Hasseli et al., 2008; Marin et al., 2010). Canada has a lot of hydrogen stakeholders ranging from hydrogen production companies to car manufacturers, who are interested in hydrogen fuel cell technology.

The key outputs from the Canadian transport SIS are presented in Table 17.

Table 17 Key outputs of the Canadian transport using the SIS blocks

SIS blocks	Key results
Actors and Networks	• Mostly private firms operate in the sector • Fossil fuel powerhouses have significant influence • Increased localised elements. Western provinces are strongly involved in oil and natural gas production
Institutions	• Policy depends both on the federal and the regional governments • Some provinces resist federal legislation (e.g. GHGPPA) • No universal carbon pricing scheme. Some provinces participate in a scheme with the state of California (US)
Demand	• The vast area of Canada creates increased transportation needs for multiple means
Knowledge, learning processes and technologies	• The current regime is dominated by inefficient gasoline vehicles • EV share slowly increases • EV diffusion more influential in regions with high share of hydro-power generation (e.g. Quebec)

3.6 Comparative Analysis

The transportation sector in both Norway and Canada is characterised by dominance of fossil fuel combustion across all sub-sectors. This means that this sector is facing a contingent carbon lock-in related to fossil fuels and especially oil products such as gasoline and diesel. This phenomenon is caused by multiple factors including the high capital costs (Bahn et al., 2013), leading the majority of transportation stakeholders (from car manufacturers to car users) to stick to the use of conventional fuels. As Klitkou et al. (2015) note, the existing fossil fuel economy of scale in the transport sector implies a technological lock-in; the risk in both countries is high, acting as a significant barrier to a low-carbon transition. In this section, we compare the transportation system of two countries (Norway and Canada), in order to detect and analyse these barriers. The ability of their systems to overcome said barriers is studied through the SF framework (Woolthius et al., 2005), by examining specific features of each innovation system.

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3.6.1 Institutions

Institutions can be separated in formal and informal. Formal institutions are related with the broader legal and regulatory system, with a focus on specific regulations. On the other hand, informal institutions concern social values, norm and habits (Johnson and Gregersen, 1995). The failures associated with these types of institutions are characterised as hard and soft institutional failures respectively (Carlsson and Jacobsson 1997).

At a first glance, Canada seems more susceptible to institutional failures. Delving further into the formal institutional framework, both countries have taken legislative action towards the mitigation of climate change, including inter alia regulations regarding the transportation sector and its emissions. For example, Norway was one of the world's first countries to introduce a CO_2 tax (1991) and, despite not being a member state of the EU, participates in the EU ETS and ESR (Sæverud and Wettestad, 2006; Hermansen et al., 2019).Canada has legislated its own carbon pricing system (Justice Laws Website, 2020), which is not yet implemented in every province but only in seven of Canada's provinces. Since the Canadian carbon pricing scheme is formulated and regulated solely from the Canadian federal government, a change of governmental views on environmental issues may easily affect it. As for Norway, even though the EU ETS is applied at the national level, in the transport sector it only covers aviation, whereas the Norwegian CO_2 tax, set by the Norwegian Government and Parliament, affects aviation, road and sea transport (except domestic fisheries, which have a progressive refund scheme based on energy efficiency). Hence, Norway is also prone to a similar change in political will. That said, the Cabinet has signaled a stepwise increase in the CO_2 tax. Also, a number of other taxes and fees regulate transport in Norway, such as the road use tax, vehicle purchasing taxes and toll roads. Regarding targeted legislation, electrification strategies are another critical institutional factor. Since the 1990s, Norway has been a pioneer regarding regulations towards EV penetration (Aasness and Odeck, 2015), which has led to a significant share of EVs in the Norwegian market for new cars in 2019, with a sales percentage of around 42% (Henley and Ulven, 2020). In comparison, Canada's EV legislation has been quite slow-paced, as also reflected on low sales, since newly registered electric cars were just 3.5% of overall car sales in the country (Statistics Canada, 2020f).

Compared to Norway, Canada demonstrates wider adherence to fossil fuel combustion on passenger and freight transportation. A characteristic example is the Canadian railway system, which is mainly powered by diesel (Statistics Canada, 2019b), whereas the Norwegian railway network is heavily dependent on electricity (SSB, 2008). From an institutional perspective, this insistence is partially associated with the Canadian federal government's hesitation to legislate for the use of alternative fuels while domestic oil and natural gas reserves remain abundant (Mondou et al., 2018), as well as increased costs and other technological challenges. A potential institutional failure due to contingent unwillingness to invest on infrastructure supporting green technologies is not as relevant for either country: both countries have already proposed significant investment plans towards the modernisation and environmental friendliness of their transportation systems (Norwegian Ministry of Transport and Communications, 2016; Transport Canada, 2020b).

Apart from these challenges, Canada is also prone to another potential institutional failure: the country is divided in provinces that have their own government and legislation. Local governments may not always comply with the federal government's legislation, thereby slowing down the transition of the transportation sector. A typical example of this malfunction is the case of the government of Ontario being against the nationwide legislation of the carbon pricing scheme, leading to a delay of its implementation. Such examples demonstrate that the independence of Canada's provincial governments may result to a slower transition or even a carbon lock-in.

3.6.2 Interactions

Knowledge diffusion is greatly affected by the interaction between the various agents and networks existing in an

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innovation system, since these interactions create a communication network between stakeholders. A typical example is the interaction between government policy and enterprises operating on the examined system (Woolthuis et al., 2005). Interaction system failures are either caused by powerful dependencies that can heavily subdue innovative technologies, or by weak connection impeding innovation (Weber and Rohracher, 2012). According to Carlsson and Jacobsson (1997), these interactions leading to system failures are called strong and weak network interactions.

At a first glance, both countries' system consists of a vast variety of networks and actors, including transportation corporations, regulating authorities, governmental bodies and coordinating associations operating as umbrella networks. Nevertheless, a closer look provides a different perspective. Norway is characterised by the abundance of government-owned corporations, involved in almost every sub-sector of the transportation system (Bane NOR, 2017). On the other hand, Canada's transportation sector is dominated by private-owned entities, operating in every part of its innovation system (Transport Canada, 2019). Existence of a wide governmental control can lead to better orchestration (Shaw et al., 2019) and coordination (Lei & Nugent, 2018) of transition policies, which is important for avoiding technological lock-in. Nonetheless, the plurality of private stakeholders can also have a positive impact towards a transition, since they strive for competitiveness and larger market shares (Mah, 2020) but also because the performance of private firms is usually dependent on their corporate social responsibility regarding environmental strategies (Hadj, 2020). It is also noteworthy that, in Canada, there are more stakeholders in each subsector, partly due to it being one of the largest and non-homogenous countries in the world with major regional economic and systemic differences. Furthermore, in comparison with Norway, Canada plays an important role in the global transportation value chain, with many vehicle manufacturers operating in the country. These companies are not necessarily Canadian; many of them (especially regarding the automobile sub-sector) are headquartered in other countries. With the automotive industry acting at the global scale, the transition of the largely domestically supplied Canadian transport sector will to a certain extent depend on international market trends rather than national initiatives. The same lesson also applies to Norway, although Norway—in contrast—has no car industry, other than supplying parts to car manufacturers abroad.

Another similarity of the countries examined is the fact that both are fossil fuel producers with significant fossil fuel industry, in which local and international firms operate. Apart from a strong presence of Norwegian firms, the country is also characterised by the operation of various European corporations such as Shell and BP. The oil production landscape in Canada is similar, with the only difference being that Canadian enterprises have a smaller presence and the main stakeholders headquartered outside of Canada are mainly American firms, such as Chevron and Exxon Mobil. Although oil companies are not a component of the system analysed, their interactions with and within it are crucial since the main energy source in the transportation sector are oil products such as gasoline and diesel, especially in the case of Canada and the oil-rich Western provinces. Their operation is deemed significant, since oil companies in both countries usually create strong lobbies in order to maintain their high revenues (Grasso, 2020), which can lead to carbon lock-ins and significant interaction failures.

3.6.3 Capabilities

Another factor that may lead to a system failure is the inability of the system and especially the unwillingness or inability of firms in the system examined to adapt to new technological standards, in contrast for example with the local utilities in Norway, who took initiatives to develop fast-charging infrastructure, as examined in Section 3.4. The transition to low-carbon transportation depends on the development of firms operating on this sector, since features such as financial resources, learning capacity and flexibility are required (Woolthius et al., 2005). Furthermore, the transition of the transportation sector in particular requires the willingness of people to contribute to climate action, since a large share of energy is used for passenger transportation. This entails

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significant behavioural changes. For instance, despite the provision of subsidies, many people avoid buying an electric vehicle, since electric vehicles remain costlier than conventional ones (Sheldon & Dua, 2019) and price is a significant aspect for citizens regarding fuel choice (Andersson et al., 2020). Taking into consideration that gasoline price in Canada is almost 50% lower than its price in Norway (Global Petrol Prices, 2020), Canadians are more hesitant regarding the purchase of an EV, since they still have access to relatively cheap fuel. Similarly, Norway's electricity prices are considerably lower than the EU average, making EVs even more economically attractive for Norwegians, since they can be cheaper to use, in addition to being cheaper to obtain due to the heavy subsidies. This preference towards cheaper fossil fuels is also reflected on Canada's automobile manufacturing industry. Although Canada is one of the major automobile manufacturers worldwide (OICA, 2018), it accounts for only 0.4% of global electric car production (Martine, 2020). A similar problem is also affecting the hydrogen vehicle market, since they have traditionally been more expensive than regular cars (Bento, 2010).

Excluding car transportation, the other sub-sectors of the system analysed are mainly driven from companies operating on each sub-sector. Regarding passenger transportation via rail, water or air, choices for passengers are limited, although there is a recent tendency towards electrification of ferries in Norway as discussed in Section 3.4. The vast majority of passenger planes worldwide combust kerosene, with passengers not being yet able to choose a considerably "greener" air transportation option. Nevertheless, they are able to choose transportation firms that demonstrate a more environment-friendly policy, if the costs remain at a similar level. On the other hand, companies operating on the industrial sector can demand from cargo transportation firms to carry their products in "greener" ways: according to Touratier-Muller et al. (2019), manufacturers are usually the ones forcing logistics companies to take environmental measures for the transportation of their products.

3.6.4 Infrastructure

According to Woolthius et al. (2005), the unavailability of infrastructure is considered the last component of the system failure framework. Infrastructural failure is related to two different types of infrastructure (Johnson et al., 1998). The first category examines external factors related to communications and energy infrastructure. Norway and Canada are both two very developed countries with high GDP per capita and their communication networks are capable of supporting the operational requirements of the transportation sector. Their energy infrastructure is also modernised and capable of meeting the requirements of the sector; however, availability of and access to fast chargers is still a potential bottleneck in both systems. Nevertheless, although it is considered an external infrastructural component, the energy grid has a greater importance regarding the transportation system and especially the further diffusion of electric mobility. The transition towards a higher percentage of electric mobility contributes to the mitigation of climate change only if the electricity mix is characterised by high RES penetration. Norway's and Canada's electricity production is mainly based on hydropower; hence, the electrification of their transportation systems is significant towards the reduction of GHG emissions. The second type of infrastructural challenges is focusing on internal factors, including scientific and technological infrastructure which can contribute to the diffusion of the examined technologies to the system. The main differences on the technologies used in Norway and Canada are related to road and rail transportation. Regarding road transportation, Norway is characterised by a very high (in comparison with other countries) percentage of battery electric cars, being about 10% (Norsk Elbilforening, 2020a). On the other hand, battery electric cars in Canada account only for 0.72% (Statistics Canada, 2020f). This contrast is also demonstrated on rail transportation. In Norway 62% of rail tracks are electrified (SSB, 2008), whereas, in Canada electric tracks are only used on urban transportation such as metro train systems (Statistics Canada, 2019b), partly due to large distances nationwide and to respective capacities in the neighbouring United States. Concerning the other sub-sectors of the system, both countries exploit the same technologies. However, it is noteworthy that Norway has been experimenting on using electricity on other sub-

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sectors too, with some pilot projects related to marine and air transportation (Gagatsi et al., 2016; Avinor, 2020), showcasing the country's significant efforts to electrify not only road but also sea transport and short-distance domestic aviation.

Apart from the status quo of the existent technologies, infrastructural failure is also related to the potential of further diffusion of these technologies and the penetration of new ones. Regarding electric mobility, Norway has two important advantages over Canada. As discussed above, electric mobility has already achieved an important penetration regarding road and rail transportation in comparison with Canada. The second advantage is the fact that Norway is almost 30 times smaller than Canada and it is also more densely populated. Therefore, the expansion of electrification is considered easier in Norway, especially regarding fast-charging stations and other equipment necessary for electric vehicles (Klitkou et al., 2015). This advantage is also critical, regarding marine, air and especially rail transportation. Because of its vast land area, Canada has hundreds of airports, seaports and an expansive railway network. Therefore, the purchase and installation of the required equipment for the transition to electric mobility is deemed far more expensive than in Norway. Electricity though is not the only alternative for fossil fuels. The mix of biofuels and the combustion of hydrogen and ammonia are three other solution towards climate mitigation. Regarding the first two alternatives Canada has demonstrated greater progress than Norway. Canada has a hydrogen association contributing to the diffusion of hydrogen-related knowledge to many stakeholders, including actors of the transportation network. Furthermore, it is characterised by great reserves of biofuels and is an important producer of biodiesel and ethanol (Generation Energy Council, 2018); capacity in required reserves and a developed biofuels industry mean that further penetration of biofuels can be achieved relatively easily in the country. In Norway, production of biofuels has so far been scarce, despite good access to potential raw materials, but there are plans to ramp up production significantly. Although the use of biofuels and hydrogen can contribute to mitigation of climate change, they are also associated with important bottlenecks. Especially, further use of biomass has created several concerns regarding food security (Pries et al., 2016), as useful crops can be used for production of biofuels instead of food supplies, while accounting biogenic carbon also remains controversial (DeCicco, 2012). On the other hand, the diffusion of hydrogen combustion is not favoured in either country since both are characterised by high hydropower penetration, instead of other renewables associated with green hydrogen, thereby significantly contributing to the penetration of electric mobility (Klitkou et al., 2015).

The key outputs of the system failures comparative analysis are presented in Table 18.

Table 18 Key outputs from the comparative analysis based on the SF blocks

<table>
<tr><th>SF blocks</th><th>Norway</th><th>Canada</th></tr>
<tr><td>Institutions</td><td>Strong incentive policy has led to high share of EVs, however GHG emissions remain high</td><td>Policy inconsistencies due to provinces not always complying with federal legislation
Hesitation to legislate against fossil fuels
Slow-paced EV legislation</td></tr>
<tr><td rowspan="2">Interactions</td><td colspan="2">In both countries, fossil fuel companies create strong ties through lobbying processes, leading to carbon lock-in</td></tr>
<tr><td></td><td>The phenomenon is more intense in the oil-rich Western provinces</td></tr>
<tr><td>Capabilities</td><td>Cheap electricity price provides an opportunity for the use of EVs, independent from other types of incentives</td><td>Price hesitations for EVs compared to gasoline</td></tr>
</table>

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Infrastructures	• Despite pledges, biofuel production has been scarce • Spillover to green shipping indicate that innovation other than EVs can evade the examined failures • The fast-charging network is dependent on initiatives from local utilities	• Electrification of rail very expensive due to the length of the network

3.7 Results and Discussion

The abundance of fossil fuels and the economic prosperity of both countries have led to a continuously increasing activity of the transportation sector, accounting for approximately one quarter of GHG emissions in both countries. Institutionally speaking, both countries have taken action towards legislating various reforms in order to support the transition towards a "greener" transportation sector, including not only road, but also marine and air transportation. In the case of Norway there has been significant activity in the maritime sector, which is gearing up its domestic innovation capacities with emphasis on cutting-edge technologies in environmentally friendly shipping. While road EV diffusion is still the main innovation on the SIS of Norway, there are indications of a spill-over from electrification in road transport to sea transport, where Norwegian high-tech companies engage in R&D activities with the support of public investments. The lack of such activities in the case of Canada is evident in the legislative rigidities among the federal and provincial governments, as was the case with the dispute over the GHGPPA act and the support given to the domestic oil industry, who strongly opposed it. The interactions between the networks and actors of both innovation systems are generally stable, and in Norway actors are becoming increasingly integrated through joint initiatives, but the level of emissions from transport are so far not reduced drastically, despite efforts in both countries, indicating the lack of sincere effort from the system actors in addressing these challenges. Both countries are characterised by an abundance of incumbents in every sub-network, but in the Norwegian maritime sector there seems to be great potential. Most incumbents are private-owned in Canada, while the picture is more mixed in Norway, both publicly- privately owned companies, as well as public R&D schemes targeted towards both the public and private sector, with various implications—both positive and negative—for innovation coordination and struggle for competitiveness. Another contingent barrier is the significant activity of oil companies in both countries, which may result in lock-ins, with oil industry accounting for an important portion of both countries' exports. Excluding this challenge, the innovation systems of Canada and Norway are not considered highly susceptible to a system failure caused by the network agents' interactions.

Both countries' systems face challenges related to demand, some of which are also related to actors not directly involved in the system, such as the oil industry; hence they are not so easily affected by changes within systems. Regarding factors that are more closely related to system demand, Norway demonstrates a more robust transportation sector since there is larger demand for EVs and a generally more conducive landscape supporting the transition. This higher demand for EVs in Norway mainly results from the country's legislation which has promoted the purchase of EVs with multiple financial stimuli, such as subsidies, lower toll rates etc. The external infrastructural factors do not pose any significant challenges for neither country, since both Canada and Norway dispose developed communication and energy networks. Regarding internal factors, there are concerns that the fast-charger infrastructure is not developed rapidly enough, which could be a diffusion barrier in case demands rises beyond the capabilities of the existing infrastructure. Norway is facing fewer challenges on the sector of electric mobility, given the already existing network, even though it needs to be extended, but it is less capable of

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a hydrogen or biofuel diffusion, although significant initiatives exist, especially in biofuels. In comparison, Canada has greater expertise and technical capacity, evident in the difficulties of Norway to increase the domestically produced share of biofuels despite the ambitious targets set. As a result, both countries may experience an infrastructural system failure towards the penetration of electric vehicles and the transition of its transportation sector either in the form of difficulties surrounding the charging infrastructure, or the limitations in the transition to alternative fuels.

In summary, Canada faces more risks in comparison with Norway, which may lead to a rockier road to decarbonisation. This obstacle stems mainly from Canada's demand and institutions dynamics and, subsequently, from infrastructural requirements. Policy stringency is much more needed in Canada, therefore, towards counterbalancing these challenges and encountering the existent and potentially emerging bottlenecks, in order to overcome conventional technology lock-ins in the transportation sector. For this process, lessons learnt from Norway's progress can provide valuable policy insights into seizing opportunities and avoiding contingent threats. The sustainable transportation strategy of Norway has been historically focused on incentive policies to boost the share of EVs. This led to an exponential increase in their shares, while also boosting public awareness. However, the limited progress achieved in mitigating transport GHG emissions hint that, even though such policies are useful, the evaluation of their impact is exaggerated leading to a falsely cultivated image of transitional leadership, which even allows actors to ignore the lack of mitigation progress. Societal resistance towards these policies led to a reduction of such incentives in 2017 by 50%, without affecting the exponential growth trend, showcasing that as part of an effective decarbonisation strategy these measures need to play a supplementary role. In fact, cheap electricity prices from hydro-based power generation can provide a sufficient incentive for EVs due to the limited cost of use, an observation that can be useful for Canadian provinces like Quebec with significant hydro-power potential. On the other hand, spillover towards sustainable shipping, as well as smaller initiatives, such as the growing interest in electric aviation, indicate that actors can be properly engaged in the process, and actually plea for coherent strategies that place emphasis on financing innovative technologies and infrastructure. Both Canada and Norway need to address these requests from their respective systems, adapting their strategies in harmonisation with actor initiatives, as is the case of the electric ferry and the development of a fast-charging network from local utilities in Norway. Channelling investments towards technological research and private-public sector collaboration can potentially limit the strength of regime actors, like oil industry, as evident from the relative lack of extensive legislative rigidities in Norway that threaten the transition.

3.8 Conclusions

The scope of this study is the analysis of the transportation sector of Norway and Canada from a systemic approach. This method contributes to the examination of the diffusion of innovative and sustainable technologies through interaction between actors and networks. It also helps determine the barriers to their penetration into the studied systems. Our analysis does not have a single focus (e.g. electric vehicles) but investigates a broader spectrum of the transportation sector, including road, rail, marine and air transportation. The importance of actors, institutions, demand and knowledge is studied by means of the SIS framework, further coupled with the SF framework, through the identification of potentially emerging or existing challenges towards the adoption of climate-friendly, innovative technologies and practices.

The results indicate that Norway's EV incentive policy is less effective than expected, despite being considered pioneering. Low electricity prices from hydro-based power generation allow the creation of sustainable strategies without heavily relying on additional financial motives. Instead, focus should also be given on the electrification of the other sectors, considering the high interest from the actors of the system. In the case of Canada, it is showcased that regional differences have significant impact on the development of a universal strategy. Multiple

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bottlenecks are introduced due to uncoordinated federal and provincial legislation; while, depending on the involvement in oil and natural gas production, fossil fuel powerhouses show different levels of influence. The same can be said for Norway, although public funding towards private-public collaborations show a tendency to limit the strength of regime actors.

The systems examined in this research, with the application of the SIS and SF approaches, can be further analysed by using the multi-level perspective (Rip and Kemp, 1998; Geels, 2002), mapping frameworks (Nikas et al., 2017) and risk scoping through interaction of stakeholders (van Vliet et al., 2020). This potential enhancement of the SIS approach would contribute to a broader examination of the systems studied since the challenges regarding the diffusion of innovation would not be the sole focal point of the research, but other aspects could also be investigated, such as landscape factors leading to significant changes on the transportation sector. Another prospect would be the use of the SIS to also examine the interaction between the studied countries and international markets, so as to investigate the effect of global trading actors and networks to the diffusion of innovation in Norway and Canada, since transportation and especially maritime and air transport is closely related with international markets. Finally, the Systems of Innovation frameworks can be applied to design transformative policy pathways (Rogge et al., 2020; Geels et al., 2018a) since their usage as climate policy support frameworks (Doukas and Nikas, 2020) and as part of integrative approaches (Doukas et al., 2018) is continuously becoming more common.

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4 Brazil and Argentina Case Study: sustainable transport

4.1 Introduction

Despite the Paris Agreement setting the target to limit temperature rise to well below 2°C five years ago, fossil fuels still account for 81% of total primary energy supply and almost 67% of total final energy consumption globally in 2017 (IEA, 2018a). Consequently, according to the Production Gap Report 2019, fossil fuels, being responsible for 75% of global greenhouse gas (GHG) emissions and nearly 90% of CO_2 emissions, are the largest contributor to global climate change (SEI et al., 2019). Transport is among the sectors that are highly dependent on fossil fuels, with energy consumed relying almost exclusively on petroleum products (96%) in 2015 (Navas-Anguita et al., 2019). Progress has not been significant in recent years, with the share of petroleum products remaining at 94% in 2018. At the same time, fuel demand for transport is on the rise, with projections for 2050 estimating an increase of almost 75% for non-OECD countries, without major changes in the fuel mix, while OECD countries remain steady (EIA, 2019). As a result, transport is one of the fastest growing sectors in CO_2 emissions globally in the last decade, with emissions rising from less than 7Gt CO_2 in 2010, to more than 8Gt CO_2 in 2017, an increase of almost 15% (IEA, 2018). With transportation-related emissions projected to double by 2050 (Creutzig et al., 2015), decarbonisation of the transport sector requires a set of policy instruments to support low-carbon innovation (Geels et al., 2018b).

Electric vehicles are expected to play a vital role towards transport decarbonisation when coupled with high shares of renewable energy (Böhringer et al, 2020). Optimistic modelling scenarios indicate that widespread diffusion of shared electric vehicles (EVs) in the fleet could lead to a decrease of GHG emissions per km of up to 94% (Axsen and Sovacool, 2019). However, Koasidis et al. (2020a) highlight that there are national cases where, despite the high share of EVs, there has been limited progress in mitigating GHG emissions, with recent improvements being largely attributed to an increase of biofuels. Hence, biofuels are usually considered as an important additional solution to electrification for curbing carbon emissions (Siskos et al., 2018). This is especially true for regions in Latin America where the use of biofuels is rapidly growing, with Brazil and Argentina showing great potential in soy biodiesel (Janssen and Rutz, 2011), due to favourable climate and soil conditions (MAPA, 2006). Both countries are among the top largest producers of biodiesel, with Brazil also being the second and Argentina the third largest soybean producer in the world (da Silva César et al., 2019).

Brazil and Argentina were ranked in high places among global emitters, with the former being 14th and the latter 32nd in 2018 (Global Carbon Atlas, 2018). Despite both countries being treated as developing and therefore classified as non-Annex I (Viglizzo et al., 2019; Yıldırım et al., 2020)—even though there are growing arguments for Brazil to qualify as developed (Ari and Sari, 2017)—the high emission share cannot be attributed to the lack of ambition, since both countries have legislated intensive renewable energy policies (Pischke et al., 2019). Lack of significant progress, despite ambitious policy, raises questions over the effectiveness of such measures. Considering that transportation is the major CO_2 emitter in both countries (IEA, 2018a) and that biofuel efforts in the region can be found as early as the 1970s, it is imperative to formally study the historical evolution of the sector of Brazil and Argentina from a sustainability perspective, to properly evaluate mitigation policies without exaggerations (Eliasson and Proost, 2015).

Evolutionary economics (Nelson and Winter, 1982) have played a central role in exploring and understanding the dynamics that lead to systemic change (Dosi and Nelson, 1994) or economic growth (Nelson, 1995). In this process, co-ordination with market mechanisms is a key parameter towards technological change and innovation diffusion (Metcalfe, 1998). Innovation systems extend the concept of these evolutionary processes to include the role of

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actors, networks, and broader relations (Edquist, 1997) to create holistic and interdisciplinary perspectives (Song et al., 2020). In this study, we use the "Multi-Level Perspective" (MLP) (Rip and Kemp, 1998; Geels, 2002), a socio-technical framework to analyse technological transformations in the transport sector of Brazil and Argentina. We further couple MLP with another prominent Systems of Innovation framework, Technological Innovation Systems (TIS) (Carlsson and Stankiewicz, 1991), to investigate the evolution of a system as a technology evolves over time (Bergek et al., 2008), in our case biodiesel. The integration of the two frameworks is based on Markard and Truffer (2008), tailored to the needs of our case study.

From a methodological perspective, our aim is to use the MLP to study the historical evolution of the dominant regime of the transport sectors of Brazil and Argentina and understand how the dependency of fossil fuels was shaped in line of continuous pressures from oil, economic, and institutional crises from the landscape. We then employ TIS to understand the emergence of the biodiesel technological system, its interactions with other technologies, and the progress that allowed it to break through from a niche and become part of the regime. From this process, we intend to shed light on the historical evolution of the systems to provide valuable insights on policy implications that will inform future trajectories and decarbonisation strategies. Our analysis highlights that landscape pressures have provided windows of opportunity for technological change, with Brazil following a more sustainable pathway based on ethanol as an alternative fuel, which allowed the country to later build on cumulative knowledge and lessons learnt from the passenger vehicle sector to freight, while Argentina has locked-into a natural gas-based path. It also discusses that, with the recent expansion of the biodiesel industry, a key challenge for Brazil lies in keeping up the growing pace and unlocking the potential after reaching the 10% mandate amid concerns over food security if the mandate increases due to the lack of diversified feedstock, and for Argentina in balancing its biodiesel market between exports and domestic consumption.

4.2 Methods and tools

The multi-level perspective (MLP) (Rip and Kemp, 1998; Geels, 2002) is a qualitative framework that allows the analysis of socio-technical transitions based on interactions between multiple levels that influence technological change. This process aims to establish the pathways and identify the reasons between the change of the system from one socio-technical regime to another. The socio-technical regime constitutes an extension of the technological regime introduced by Nelson and Winter (1982) and refers to the dominant processes and the aligned actor activities surrounding these processes, in light of a set of formal and cultural norms (Geels and Schot, 2007). From a macro level point of view, the landscape, usually evolving much slower, has the ability to put pressure on the established regime, providing windows of opportunity for the breakthrough of innovative technologies. These usually emerge as niche technologies that evolve in a closed and protected market, taking advantages of pressures to destabilise the regime (Geels, 2004).

Sustainability transitions have received significant attention in the MLP literature, due to the importance of climate change effects that boost or hinder purpose-oriented transitions in a variety of different sectors (Smith et al., 2005; Geels, 2010;2011). From these sectors, transportation presents additional challenges in mapping the system due to the existence of multiple regimes depending on the focus point (Geels, 2012), for example in the road transport passenger mobility system (Hirschhorn et al., 2019). This is in contrast with more traditional MLP applications, where there is a clearer distinction of each component's boundaries, like electricity generation and diffusion of renewable energy (Moallemi et al., 2017). However, the contribution of MLP in analysing transport sustainability transitions is highlighted (Whitmarsh, 2012), triggering numerous recent studies covering a variety of areas, including historical analyses (e.g. Geels, 2005b; Roberts and Geels, 2018). Berkeley et al. (2017) focused on the niche technology of "battery-electric vehicles" and examined the attempt to disrupt a regime that is generally well established, while Sharmeen and Meurs (2019) studied the effect of smart mobility services in the governance of

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demand-responsive transit systems. On the other hand, Moradi and Vagnoni (2018), instead of focusing on a specific niche technology, opted for a regime-oriented approach to studying possible urban mobility transitions.

The technological innovation system (TIS) (Carlsson and Stankiewicz, 1991) is another process-oriented qualitative framework that helps investigate the evolution of a system as technology evolves over time (Bergek et al., 2008). It belongs in the field of Systems of Innovation that additionally includes the national (NIS) (Freeman, 1987; Lundvall, 1992; Nelson, 1993), regional (Cooke et al., 1997; Asheim and Isaksen, 1997) and sectoral (SIS) (Breschi and Malerba, 1997; Malerba, 2002) innovation systems that examine the interactions of different actors from a systemic perspective, each with a different focus and system boundaries. Specifically, TIS examines the creation and diffusion of technology as a result of networks of actors and interactions in a given set of institutional and infrastructural technological environments (Carlsson and Stankiewicz, 1991). For this purpose, the functions approach is proposed, where a set of functions correspond to essential components that contribute to the performance of the system (Johnson and Jacobsson, 2001). There are many different alterations of these functions in the literature, however with only minor differences from one another (Hekkert and Negro, 2009). In this study, we follow the functions adopted by Hekkert et al. (2007), which are presented in Table 19.

Table 19 TIS functions according to (Hekkert et al., 2007)

Function	Description
F1. Entrepreneurial Activities	Entrepreneurs that exploit new technological opportunities
F2. Knowledge Development	Research and development activities to produce new knowledge
F3. Knowledge Diffusion	Communication of R&D results among the actors
F4. Guidance of the Search	Specific goals and expectations that guide research
F5. Market Formation	Creation of a market environment (often protected) for new technologies to evolve
F6. Resource Mobilisation	Establishment of financial, human, and material resources
F7. Creation of legitimacy/counteract resistance to change	Acceptance or opposition of a new technology from key actors and interests

As was the case with MLP, TIS also received significant attention in transport studies, especially related to low-carbon vehicles (Köhler et al., 2013) or with a focus on specific alternative fuel technologies, like biofuels (Suurs and Hekkert, 2009), hydrogen (Suurs et al., 2009) and natural gas (Suurs et al., 2009). It is evident that the evolution of a TIS does not always ensure a sustainable transition, since there can be lock-ins into pathways that may be more efficient without necessarily reflecting deep decarbonisation transformations. Similar research trends are also present in more recent studies focusing on modern vehicle technologies, like e-bikes (Zuev, 2020) and driverless trucks (Engholm et al., 2020) or a variety of alternative fuels. Specifically, Hacking et al. (2019) studied the historical evolution and diffusion of hydrogen fuel cells in the UK, while Bach et al. (2020) provided a more sectoral approach focusing on hydrogen and battery-electric solution in the maritime sector of Norway. Biofuels also received significant attention, with Chung et al. (2018) studying the biodiesel sector of Taiwan and Furtado et al. (2020) analysing transitions related to second-generation ethanol.

The diversity of the case studies identified in the two frameworks proves the strength of systemic perspectives to capture the emergence and evolution of sustainable transitions (Markard et al., 2012; Köhler et al., 2019). Another

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important attribute of MLP and TIS is their versatility, which allows the application of multiple frameworks in a case study, synthesising different elements of a transition to establish coherent and robust narratives. Kim et al. (2019) combined MLP with a system dynamics model to analyse the transition of biofuels in aviation and assess possible future scenarios. Lilliestam et al. (2020) used TIS to study knowledge creation and diffusion of concentrating solar power (CSP), but also performed an industrial life cycle (ILC) analysis to focus on the technology itself. For the same reason, Nikas et al. (2020b) combined MLP with a life cycle assessment (LCA) of the technologies surrounding the Greek electricity generation sector to study the phase-out of lignite. Despite both MLP and TIS being considered part of a similar theoretical field with closely related concepts, Markard and Truffer (2008), integrated the two frameworks, arguing that this conceptualisation allows the exploitation of non-mutual advantages to provide a better understanding of radical innovation processes and socio-technical transformations. Due to their supplementary nature, the latter suggest that, when applying the integrated framework, interdependencies need to be considered to clarify the application domain of each framework. This allows adaptations of the integrated approach tailored to the needs of each specific case study. For example, Miedema et al. (2018) used the biomass gasification TIS as a possible green gas production route, and then applied MLP to explicate the sectoral configuration of the natural gas regime and the diffusion of renewable heat energy in the Dutch residential sector. In a different approach, Edsand (2017) used TIS to understand the slow diffusion of wind energy in the Colombian electricity sector and then MLP to examine the influence of the broader context in the form of pressures from landscape factors. In this study we use MLP to study the historical evolution of the fossil fuel-dominated transport regime of Brazil, and then of Argentina with references to Brazil, as well as broader landscape influences that affected their structure. We then couple this analysis with the application of TIS for biodiesel in the two countries to study the emergence and progressive evolution of this alternative fuel. Focusing on the TIS of biodiesel instead of a simple niche analysis allows a better understanding of innovation diffusion in line with interactions with different technologies, like for example the early ethanol initiatives in Brazil. At the same time, the MLP provides the opportunity to better understand the broader environment that features enabling factors for biodiesel expansion, leading to dominance of the two countries in the international biodiesel scene.

4.3 The case of Brazil

4.3.1 Regime

The Federative Republic of Brazil is the largest country in Latin America, covering an area of 8,515,767 km^2 and a population of around 200 million people (de Moura et al., 2017), that experiences significant demographic changes, including ageing and urbanisation (Carvalho et al., 2020). Historically, transport infrastructure in Brazil has been considered poor during the 1950s and 1960s, in terms of both road and railway conditions (Rodríguez-Pose and Arbix, 2001). In the following decades, infrastructure began shaping in its current form, following extensive deforestation and immigration of settlers in 1970, leading to the implementation of government-financed road projects (Brondizio and Moran, 2012). Favouring policy towards road development created an extensive road network and rapidly increased the vehicle fleet, but at the same time limited the development of railway, while ports started expanding after the 1990s (Padilha and Ng, 2012). Despite delays in the creation of transport infrastructure, oil exploration and production activities have been carried out since the late 19th century. In 1897, the first oil drilling was reported in Bofete, while in 1941 the first oil field was discovered in Candeias (Peyerl, 2019). This discovery paved the way for the creation of Petrobras in 1954, the most prominent and dominant actor in the Brazilian oil industry (Dantas and Bell, 2009), and the creation of the Brazilian Petroleum, Gas and Biofuels Institute (IBP) as a representative organisation of industrial companies.

In 1970, total energy consumption of Brazil accounted for 60,635.308 ktoe, with transport constituting a share of

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21,76% with 13,191.92 ktoe, coming second after industry (CEIC, 2018). During the following period, total energy consumption steadily increased, despite the oil crises of 1973 and 1979 and the lost decade of the 1980s in Latin America (Ramirez, 2000) that temporarily leveled consumption, with transport outgrowing the total trend, reaching a share of almost 28% by 1990. At the same time, transport has been the dominant CO_2 emitter in Brazil accounting for almost 40% of total emissions (EDGAR, 2017), thereby historically constituting an emissions-intensive sector. This can mainly be attributed to reliance on fossil fuels and especially oil products (Figure 23), due to the high share of road transport in total energy consumption by more than 80% (CEIC, 2018).

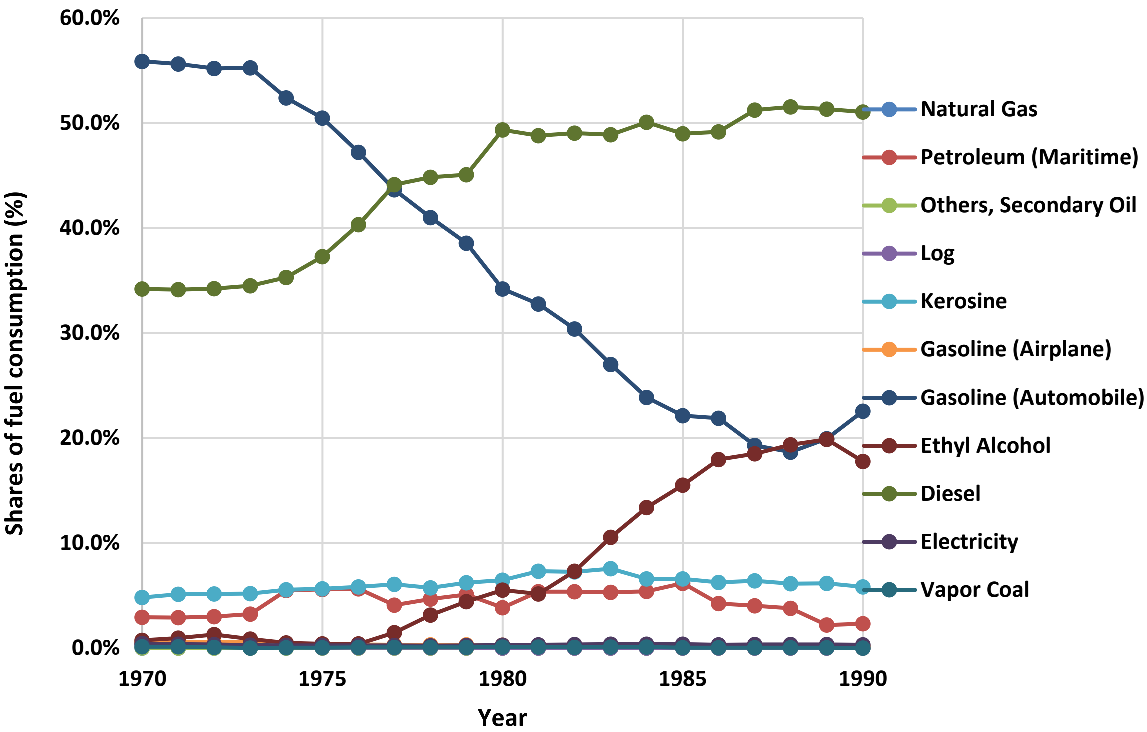

Figure 23 Share of transport consumption by fuel type

Source: (CEIC, 2018)

As Figure 23 suggests, in 1970 gasoline and diesel accounted for more than 90% of total consumption, with gasoline being the dominant fuel until 1977. However, in 1974, the start of a long-lasting decrease in the share of gasoline is observed with ethanol acting as a substitute fuel (Salvo et al., 2017; Luchansky and Monks, 2009). In the second half of that decade, the share of diesel significantly increased, stabilising at around 50% in the next decade. The two forces of growing demand and increase of biofuels in the form of ethanol played a role in the destabilisation of gasoline in the sub-regime of light-duty vehicles. On the other hand, diesel remained protected from this pressure since it was mostly used in freight transport and passenger buses. This led to the establishment of diesel as a dominant fuel used in the Brazilian transport sector, even though there is almost no competition between diesel and gasoline, unlike for example in Europe. Ethanol increase in the transport fuel mix highlights the potential of biofuels in Brazil. However, since ethanol is mainly a substitute for gasoline, focusing on different biofuels like biodiesel emerged as a challenge for the following period to allow the spillover of innovation from passenger vehicles to the other sub-regimes of transport.

The observed trends until 1990 kept on all the way to 2017, with the country still relying heavily on fossil fuels and especially oil products, with a share of almost 50%, to cover its growing energy demand (Figure 24). In 1997, Law 9478/1997 was passed, establishing a new framework in the distribution of petroleum royalties while introducing

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the National Petroleum Agency (ANP) (Postali, 2009) and the National Council for Energy Policy (CNPE), coordinated by the Ministry of Mines and Energy (Rosillo-Calle and Cortez, 1998). The increase of oil and gas reserves in the Campos basin in the late 1990s (Bruhn et al., 2003) shaped the dominance of oil in Brazil, since 85% of total oil production in the country comes from this province (dos Santos Silvestre, and Dalcol, 2009). However, a key advantage of the Brazilian energy mix is that electricity, ranking third, is produced mostly from hydropower with a share of more than 60%, while use of fossil fuels, mainly diesel, is limited to around 17% (Rocha et al., 2017; de Lima et al., 2018); this can be partly attributed to last decade's slowdown of total energy demand's increasing trend, fluctuating around the level of 225 Mtoe, a trend also observed in transport's energy consumption and emissions (De Oliveira-De Jesus et al., 2020).

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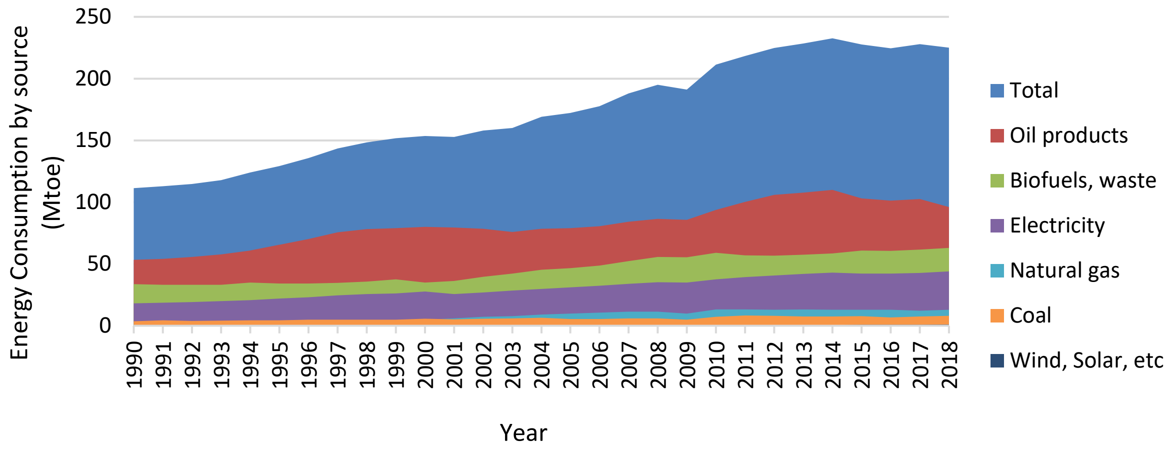
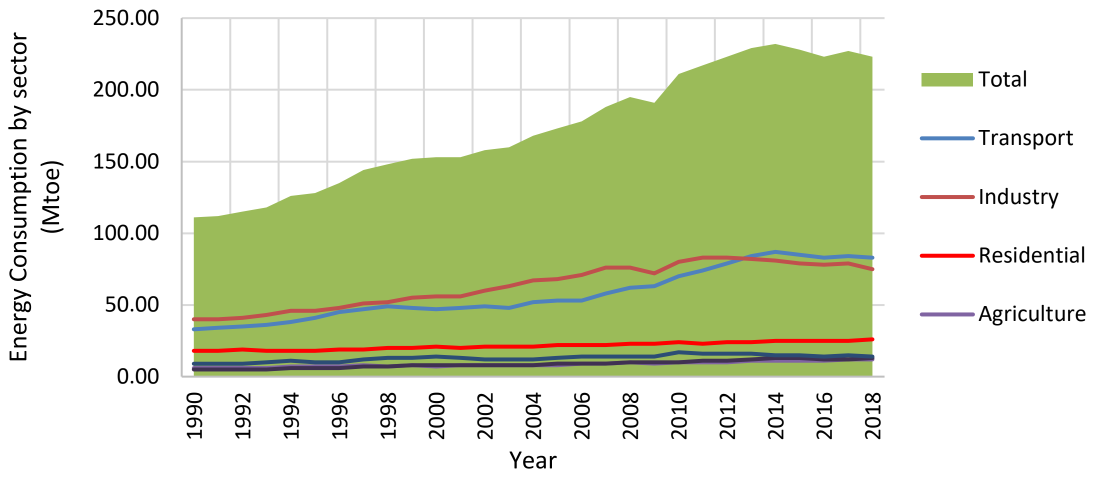
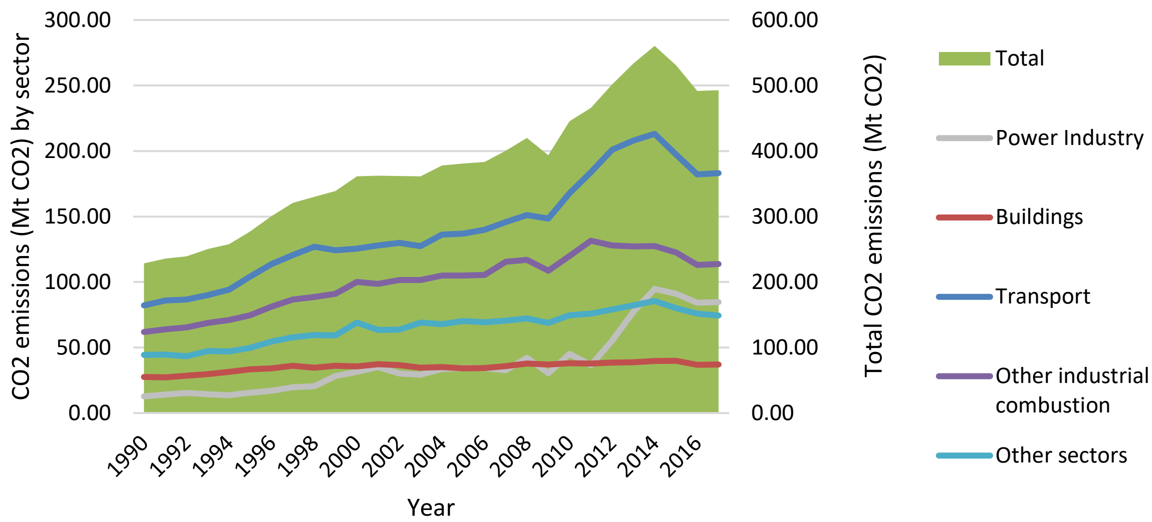


(a)



(b)



(c)

Figure 24 Energy consumption by (a) fuel, (b) sector and (c) CO_2 emissions by sector in Brazil (excluding AFOLU)

Source: (IEA, 2018a); EDGAR v5.0 database (Muntean et al., 2018)

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Despite the recent stabilisation in absolute numbers, the share of transport in the total energy consumed reached almost 37% in 2017, surpassing industry in 2013 for the first time since 1970. At the same time, total CO_2 emissions slightly decreased over the last years, with transport failing to follow this trend and remaining steady, with a share of almost 50%. This highlights that ethanol progress attempted in the previous decades were not consistently continued with other biofuels, since their share increased slowly since 2000. This increase started forming into shape in 2005 with the introduction of Laws No. 11097, No. 11116, and the following resolutions that established the use of biofuels and biodiesel, promoting targeted blend mixes (Pousa et al., 2007) as part of the The Brazilian Biodiesel Program (PNPB) (Rico and Sauer, 2015). Low carbon fuels play an important role in achieving carbon intensity reduction (Lepitzki and Axsen, 2018), despite controversies surrounding biofuel emissions accounting (Rajagopal and Plevin, 2013). With transport consuming almost similar amounts of energy with industry, yet producing almost double the amount of emissions, addressing emissions intensity comes as a great challenge for future policy scenarios.

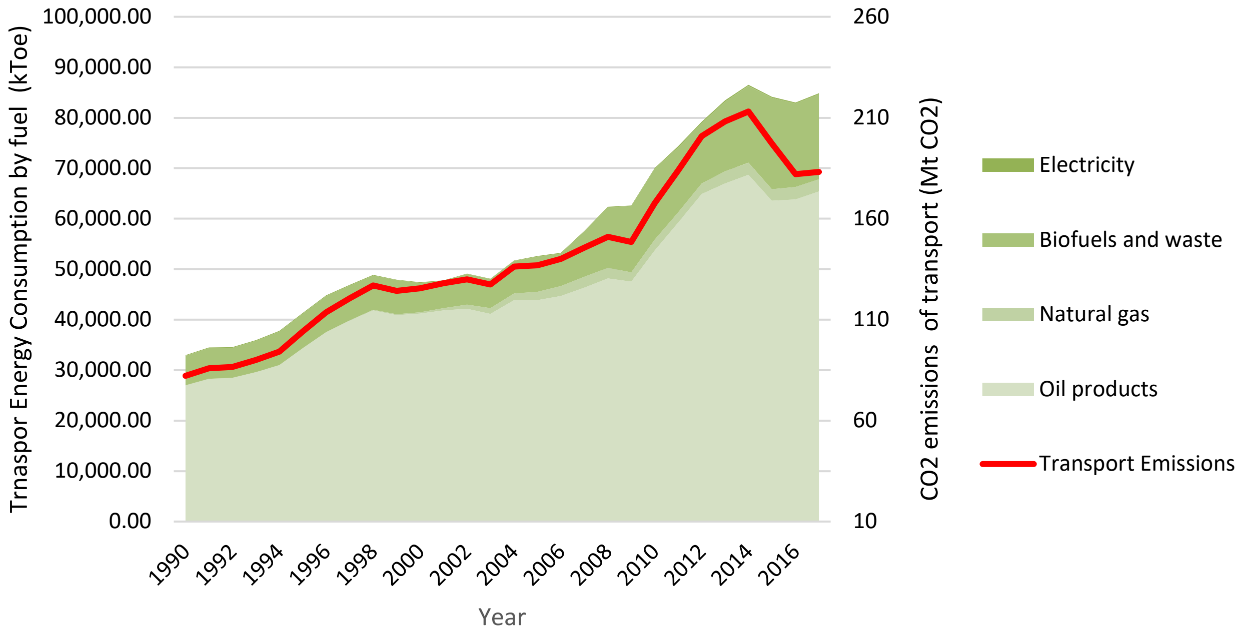

Figure 25 CO_2 emissions of transport in comparison with transport energy consumption by fuel and in Brazil

Source: (IEA, 2018a); EDGAR v5.0 database (Muntean et al., 2018)

Figure 25 compares transport emissions with the energy mix of the sector, showcasing that from 1990 until 2005 carbon emissions steadily increase, following a similar trend with transport energy demand. This highlights the limited growth of ethanol in this period that failed to have any impact in changing the emissions trend. Emissions strayed from the previous pattern only after 2005 when the aforementioned laws about biodiesel came into force (especially after 2008) and most importantly with the increase in the LDV fleet after the introduction of more efficient flex vehicles in 2003 (Nogueira et al., 2015), which consequently led to the increase of biofuels shares. However, following the financial crisis of 2008 a significant increase in energy demand was observed, covered mainly by oil products used in various means of transport, enjoying subsidies in oil prices compared to the high taxes in gasoline (Hallack et al., 2020). Coupled with the Regulatory Mixed Regime (Laws 12,276/2010, 12,304/2010 and 12,351/2010, supplementing Law 9.478/1997) that allowed public companies like Petrobras to exploit the abundant reserves such as the Pre-salt region (Almada and Parente, 2013), progress and influence of biofuels was limited, failing to improve emissions mitigation. In 2008, key actors of the system including private companies like car manufacturers pledged support in biofuels by selling cars with more sustainable blends, like ethanol (E85) and

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other blends including biodiesel. As a result, half of new vehicles sold that year used purer forms of fuel (Jayed et al., 2011). Along with the severe 2014 economic crises, this contributed to another increase in the share of biofuels in transport, and a significant decrease in emissions after 2014.

In 2017, as a result of the 2015 Paris Agreement and in order to meet the country's submitted Nationally Determined Contributions (NDC), the Brazilian National Policy on Biofuels (RenovaBio) was introduced to provide biofuel producers with financial incentives, expecting a substantial increase in production volumes (Grassi et al., 2019). The program aimed to establish a universal market for biofuels with a trade mechanism avoiding the need for producers to directly negotiate with distributors (Denny, 2020). A key advantage of such initiative is that it does not focus solely on a certain fuel, but rather boosts different types, including advanced biofuels, since part of the market includes the commercialisation of carbon credits caused by the switch from fossil fuels to biofuels (CBIO) (Salina et al., 2020).

4.3.2 Landscape

Landscape factors have played a very important role in the formation of the current dominant regime in the Brazilian transport sector and the emergence of innovation, by either providing windows of opportunities or creating cracks in the established technologies.

In the period between 1967 and 1973, known as the "Brazilian miracle", the country's economy showed significant economic growth with increases in GDP and labour productivity (Mateo, 2018). This prosperous period relied on low oil prices and Brazil acting as the main oil importer from OPEC countries to then supply the developing world. With the emergence of the oil crisis in 1973, the increase of oil prices and consequently the difficulties in development led the country to reevaluate its energy strategy in the face of a huge trade deficit (Perry and Kern, 1978). To address these challenges, the Brazilian Government turned to the exploitation of its own natural resources, supporting Petrobras in exploration activities, while also increasing energy security with hydropower electricity, with these actions succeeding in mitigating the negative effects of the crisis (Vernon, 1976). An output of these mitigation actions was the launch of the national program ProAlcool which aimed to substitute imported oil with ethanol produced from sugarcane to promote and scale up the use of flex-fuel cars that can run with blends including ethanol and gasoline (Nieuwenhuis and Wells, 2003; Cavalcanti and Jalles, 2013). Therefore, ProAlcool acted as a practical example of an output created by cracks landscape pressures caused to the regime, opening a "window of opportunity" for the expansion of environmental innovation and policies aiming to mitigate emissions (Tongur and Engwall, 2017), while at the same time addressing the challenges caused by the crisis. The result of this large and sudden landscape change resembles the combination of pathways described by Geels and Schot (2007) and Geels et al. (2016), with ethanol and gasoline following a reconfiguration pathway characterised by the symbiotic nature of the two technologies in the LDV regime, while diesel remained dynamically forcing reproduction processes in the freight regime.

The end of the dictatorship and the establishment of a democratic government in 1985 came with the challenge to overcome problems related to external debt and inflation caused by the military regime (Mateo, 2018; Nassif et al., 2020), which in turn also created disputes in 1989 over policies surrounding biofuels. ProAlCool received significant criticism from society due to its ties with the military regime (Stattman et al., 2013), as well as pressures from global actors, who claimed that the drop in oil prices made ethanol an expensive fuel, undermining the original motivation behind the program (Hall et al., 1992). The government attempted to prolong the existence of the program by lowering prices, but at the same time an increase in sugar prices reduced the potential for expansion in production, forcing the government to downplay ProAlcool, by limiting the shares in the blend. These limitations in the expansion of ethanol acted as an example of how pressures from landscape can affect a sustainable alternative that managed to break from niche into the regime and which attributed to the economic

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growth of a country for almost a decade. In fact, progress in the field of biofuels is hardly attributed to ethanol in recent years (Figure 3), since the lower energy content of ethanol, by 30%, effectively forces a threshold on the price of ethanol compared with gasoline (Pacini and Silveira, 2011).

Until 2010, the Brazilian economy has been rapidly developing, with citizens experiencing significant increases in their per capita income (Andrade and Garcia, 2015). In Brazil, this economic growth is correlated with significant increases in total energy demand, a correlation that is well established in multiple case studies in literature (Al-Mulali et al., 2016), with transport consumption almost doubling from 2003 to 2013 (Figure 24). This period was followed by one of the most severe economic crisis in 2014 leading the country to a period of political and financial instability (Raul Boschi and Pinho, 2019), with the economy shrinking by 3.8% in 2015 (Rasella et al., 2018). This crisis, however, coupled with the 2008 recession and like the effect of the oil crises previously observed, had the potential to provide another window of opportunity for the emergence of sustainable reforms (O'Riordan, 2013). In fact, the increase of biofuels has already restarted in recent years (Figure 25) and is expected to continue with RenovaBio, while CO_2 emissions have stabilised after a long period of continuous growth (Figure 24), with transport emissions showing significant decrease in the aftermath of the crisis. In these conditions, given the dominance of oil in transport, biodiesel can find the necessary opportunity to establish innovative processes (Malerba and Orsenigo, 1997) and break into the existing regime.

4.4 The case of Argentina

4.4.1 Regime

The Argentine Republic is the second largest country in Latin America after Brazil, covering an area of 2,780,400 km^2 and a population of almost 45 million people, experiencing steady population growth and urbanisation (Pou et al., 2017). Transport infrastructure in Argentina started in the final years of the Spanish colonisation of America, but major transformations took place only after 1857, based on national and British capital investments and technology expertise. During the following period, emphasis was given on railroad and the opening of a seven-mile line connecting Buenos Aires with local villages (Pulley, 1966). The growth of the railroad network continued in the 20th century until the 1960s, when privatisation of railroads led to poor maintenance and paved the way for the growth of the automotive industry and the road network (Monk, 2013). However, even in recent years, road infrastructure is still considered of poor quality (Escanés and Poó, 2018). Therefore, infrastructure, especially in metropolitan regions, faces significant challenges nowadays that extend to all transport means and require the strengthening of maritime and port systems as well as the improvement of rail and road networks (Roccatagliata and Keeling, 2011).

In the period before 1990, the energy sector of Argentina including oil, natural gas and electricity was dominated by public entities, with the government and key institutional actors like the ministry of energy and mining (Waterworth and Bradshaw, 2018) supporting the use of natural gas since 1956 (Collantes and Melaina, 2011). A year later, the Argentinian Institute of Oil & Gas (IAPG) was established to represent the interests and support the activities of oil and natural gas companies. During the 1980s, natural gas was further promoted with the government incentivising the conversion of the car fleet to use compressed natural gas (CNG) (Vassallo, 2018). This triggered industrial and regional development, since a dominant actor in the oil and natural gas sector was the public Yacimientos Petroliferos Fiscales (YPF), who distributed gas in many developing markets in the country, through the—also public—Gas de Estado (GdE). Financial problems led to the privatisation of both companies, with the state selling 31% of YPF on local and international markets (Minor, 1994). This was part of broader changes and efforts to increase competitiveness of the economy, which eventually changed the status of the regime through privatisation of public companies and infrastructures (Honoré, 2004), and regulatory development to

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increase microeconomic efficiency, which was mainly achieved with the enactment of State Reform Law 23,696 and the following decrees in 1989 (Lipovich, 2008).

Even though these activities changed the structure of the market, energy consumption continued relying heavily on oil products (Figure 26). However, a key difference between the dominant regime of Brazil and Argentina is that, in the latter, natural gas is also a prominent fuel, steadily following oil in final consumption especially after 2000. This has caused the dominance of fossil fuels in the Argentinian regime, with oil products and natural gas accounting for almost 75% of total energy consumption (IEA, 2018a). At the same time, total demand has been steadily rising, almost doubling in 2018 compared to 1990.

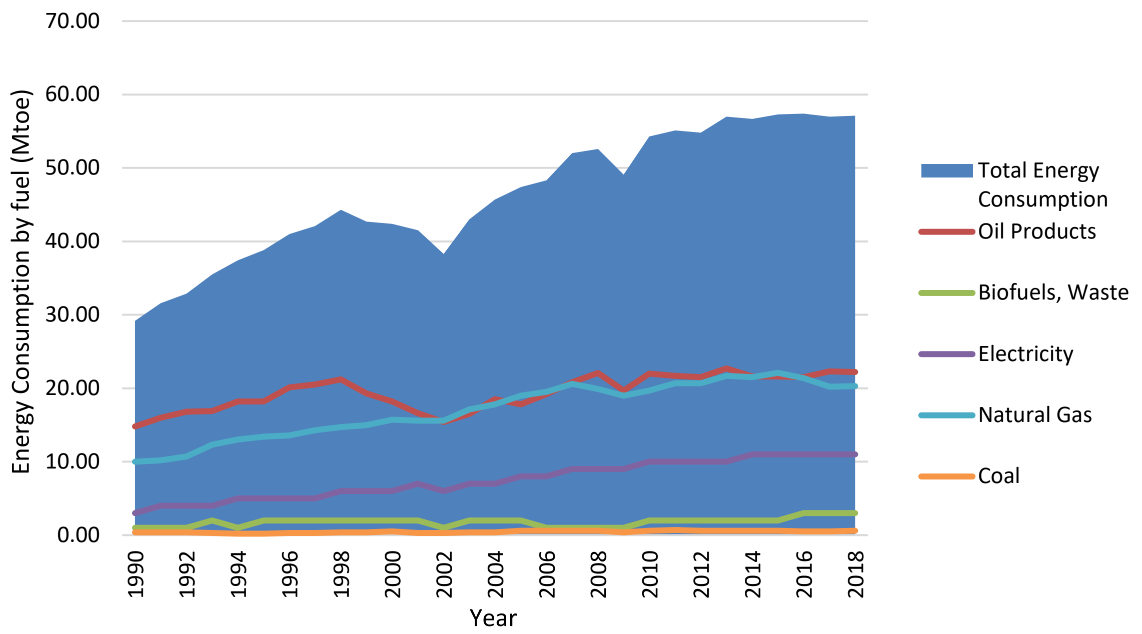

Figure 26 Energy consumption by source in Argentina 1990-2018

Source: (IEA, 2018a)

Contrary to Brazil, in Argentina energy consumption is more evenly distributed among transport, industry and the residential sector, with transport being the dominant sector historically and nowadays (Figure 27). In 2018 transport consumed 18.1 Mtoe of energy, which constituted almost 32% of total energy consumption. This share has been almost steady since 1990, with minor fluctuations since transport follows an increasing trend of total consumption with similar growth rates. Occasional disruptions in the increase can be observed as a result of the multiple financial crises faced by the Argentinian economy, which equally affected total and transport demand. These consecutive crises, starting in 1998, caused a huge decrease that, then followed by the 2009 and 2013-2014 crises, never allowed energy consumption to fully rebound, remaining steady in the last decade, at or around the 60 Mtoe milestone.

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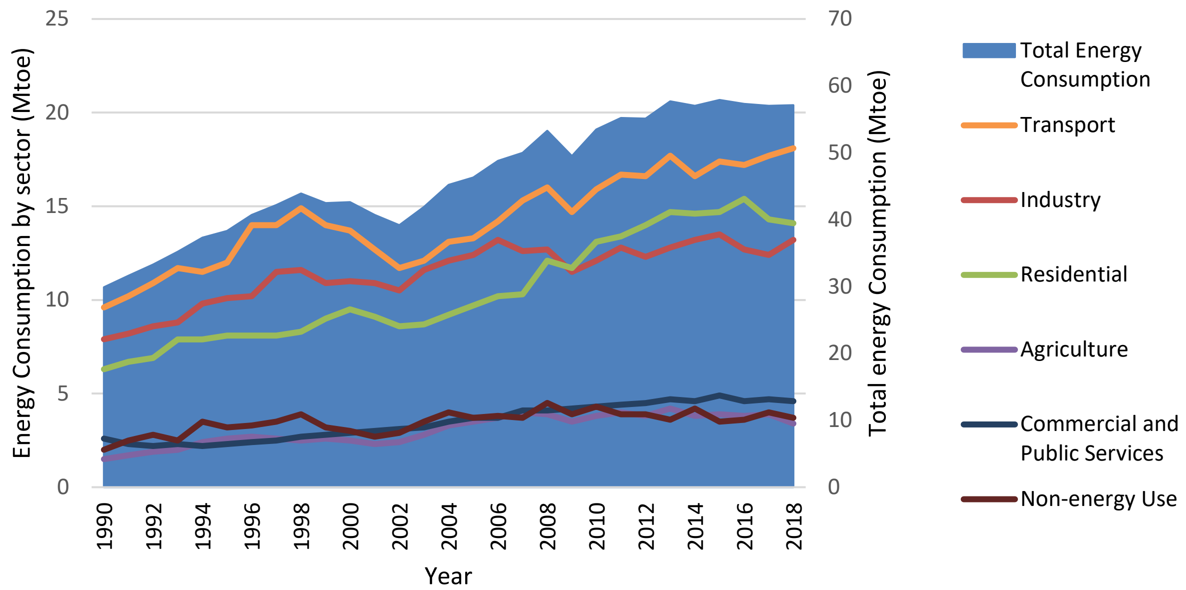
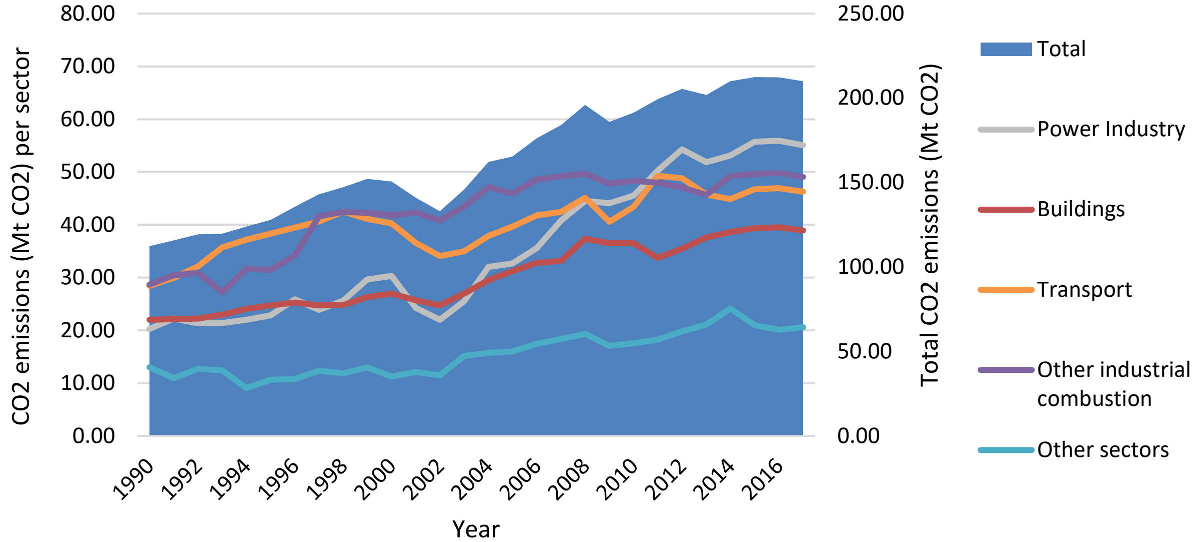


(a)



(b)

Figure 27 Energy consumption by sector (a) and CO_2 emissions by sector (b) in Argentina (excluding AFOLU)

Source: (IEA, 2018a); EDGAR v5.0 database (Muntean et al., 2018)

Like energy consumption, distribution of CO_2 emissions is more evenly spread among the different sectors, with transport accounting for 22% of total emissions in 2017, even though it is not the dominant emitter, due to rapid rise of the power industry's emissions. In Brazil, it was highlighted that transport's dominance in CO_2 emissions was even more commanding than the dominance in energy consumption. However, in Argentina the situation is completely different, with transport being less intensive due to its long-lasting use of natural gas in mobility, which is more efficient than other fossil fuels (Chong et al., 2016). Therefore, even though transport emissions have increased since 1990, this trend was slower than total emissions'. However, since natural gas is usually described as a short-term transition fuel (Hekkert et al., 2005; Safari et al., 2019), heavily relying on such a fuel can lock the system into a pathway unable to achieve decarbonisation in the longer run (Nikas et al., 2020b).

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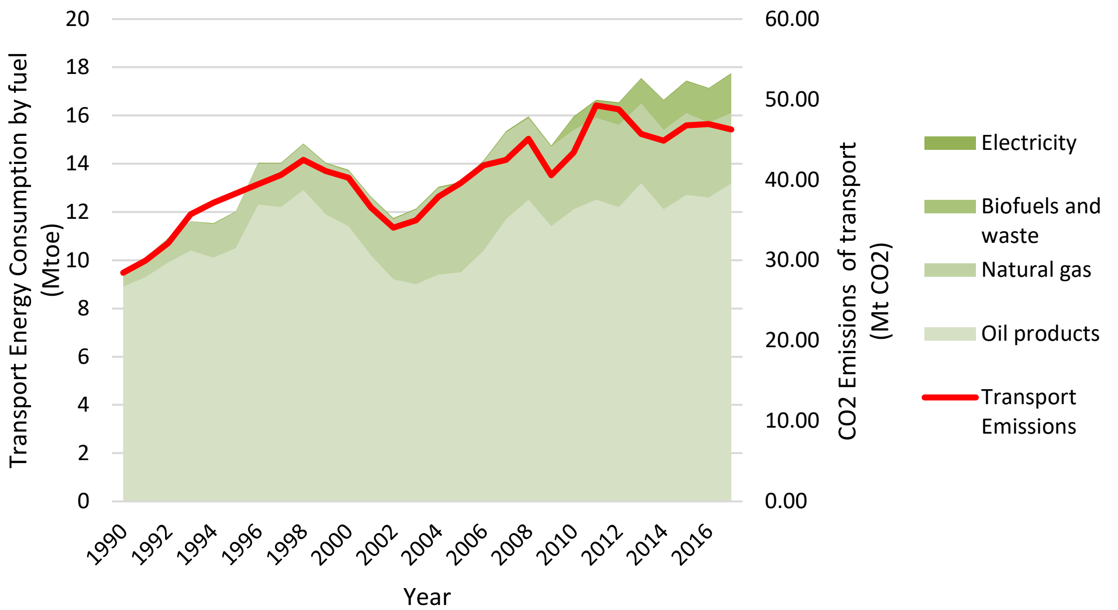

Figure 28 CO_2 emissions of transport in comparison with transport energy consumption by fuel in Argentina

Source: (IEA, 2018a); EDGAR v5.0 database (Muntean et al., 2018)

This is highlighted in Figure 28 where transport CO_2 emissions are correlated with the energy mix of the sector. It is evident that the fossil-fueled dominated regime, with internal combustion engines using either oil products (diesel, gasoline) or natural gas, has created a technological lock-in that is difficult to escape (Åhman and Nilsson, 2008). In fact, the only progress in mitigating CO_2 emissions is observed within the latest decade after the breakthrough of biofuels in 2010, when they started to enter the energy mix on the demand side as part of the boost attempted by 2006 Law 26,093 aiming to increase domestic biodiesel demand by 2010 (Mathews and Goldsztein, 2009). In the same year, Law 26,190 was also passed to shift electricity production from fossil fuels to renewable energy sources (Bragagnolo et al., 2014), while in 2007 Law 26,197 strengthened the authority of the state and local government over the management of hydrocarbons, indicating a turn of national policy towards sustainability. These legislative efforts were very important, since, up to this point, despite significant biofuel production in the country, Argentina based its economy on exports, limiting the amount of self-consumption (Sadorsky, 2012), thus failing to establish visible emission mitigation results. More recent efforts introduced the expansion of Law 26,093 to set higher mandates of 10% biodiesel in diesel and 12% ethanol in gasoline as of 2016 (Das, 2020).

4.4.2 Landscape

The Argentinian economy has experienced great divergence from, even setting a rare exception to, the expected flow of capital among rich and less developed countries (Reinhart and Rogoff, 2004). This paradox can be traced to the late 19th and the early 20th century, when Argentina was one of the richest countries until the Great Depression in 1929 (Taylor, 2018), after which it saw its growth of the previous period halt without managing to fully recover afterwards (Rocchi, 2005). The crisis led Argentina towards path-dependent import-substitution policies that created numerous development constraints and restrictions until market liberalisation in 1976, and the expected instability afterwards due to loss of governmental support (Teitel and Thoumi, 1986; De Pablo, 1977;

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Richaud et al., 2000). As a result, from 1975 to 1990, Argentina faced a great recession in the form of international debt and consequently high interest rates that altered the constitution of employment, shifting workforce from industry and agriculture to services (Hopenhayn and Neumeyer, 2005), while also creating the need towards the end of this period for systemic changes in the form of privatisations, as observed in the regime.

Following this crisis, natural gas started gaining ground in transport (Figure 28) due to the subsidies provided by the government for CNG. In line with the increase in the use of natural gas, its economy also prospered from 1990 to 1998 mainly due to foreign investments that were absent in the previous years, the tying of Argentine peso to the US dollar (Convertibility plan) and significant amount of exports (Kehoe, 2003). Dependence on foreign powers, however, made the country vulnerable when these capital flows suddenly stopped, due to exogenous parameters like the Russian Crisis of 1998 (Calvo et al., 2003), which added to previous external perturbations like the Tequilla Crisis in Mexico 1994 (Boschi, 2005). The result was another deep recession affecting debt, the banking sector, as well as exports of agriculture products, especially towards Brazil. Despite controversies surrounding the depression, and regardless of whether overvaluation of peso or weak fiscal policies were the main drivers of the crisis (Bleaney, 2004), it is clear that in the transport sector a key beneficiary of the situation was natural gas. Due to the following devaluations, the price of natural gas was favourable, leading to an increase in demand in 2002 and 2003 (Collantes and Melaina, 2011), with an increase rate of almost 44% between the two years, significantly higher than the trends observed in the previous decade (Figure 28). Therefore, it is evident that these consecutive crises provided the window of opportunity for natural gas to become vital part of the transport regime, in a break similar to that of ethanol in Brazil. However, since windows of opportunity merely provide the cracks in the regime for different niches to enter, it was through policy initiatives in the early stages of the two technologies that paved the pathway that the two countries followed; a more sustainable option for Brazil, in contrast to a fossil fuel-based solution in Argentina. The difference is further highlighted in the reconfiguration pathway (Geels and Schot, 2007; Geels et al., 2016) that Argentina followed, compared to the combination of pathways in the case of Brazil. CNG cars, consuming a fossil fuel resource, were easily adopted in the regime in a symbiotic setting. This solution triggered further adjustments, with natural gas emerging as a key part of the dominant regime. However, these non-disruptive adjustments avoided creating deeper architectural changes towards sustainability, as was the case with the more radical pathway that Brazil followed. This highlights the importance of raising actor and institutional awareness for innovation even in the early stages of diffusion (Larsen, 2011).

After 2003, the Argentinian government made an effort to promote exports, including soybean that since 1970 has taken advantage of the non-existent domestic market and started gaining ground against beef and wheat, which were the main exported commodities (Richardson, 2009). This rise in exports took a severe hit in 2012 with the government's decision to nationalise YPF, thereby creating significant tensions with traditional markets for biodiesel, like the European Union (mainly Spain), and Mexico, who was also a shareholder in YPF. Specifically, by 2010, Spain represented 53% of the country's exports and a key investor in YPF (Moreno et al., 2013). The Spanish government characterised this decision as irrational and unjust, stating that it could lead to diplomatic conflicts in fear of further nationalisations, while Repsol, whose interests have been mostly hit, threatened to take action against YPF and future allies (Costamagna et al., 2015; Moreno et al., 2013). After this conflict that resulted in anti-dumping duties from the EU, Argentina had to adjust its strategy, maintaining its international orientation by looking at new markets like North Africa, but also focusing on self-consumption through appropriate mandates (Naylor and Higgins, 2017). These recent obstacles arising from landscape factors are bound to shape Argentina's future pathway regarding biofuels as a means of sustainable transition.

4.5 The Biodiesel Technological Innovation System in the two countries

The use of biodiesel as a more efficient fuel has been receiving significant attention in recent years; however,

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efforts to establish an alternative to the original diesel-powered engine have a long, and hence challenging, track record in the field. Even back in 1900, Dr Rudolph Diesel tried to run an original diesel engine with vegetable oil (Bozbas, 2008). Nevertheless, the term "biodiesel" was not officially coined until 1988, even though the fuel patent dates back to 1937 (Aytav and Kocar, 2013). Thereafter, due to its biodegradability in high shares, compared to conventional fuels, biodiesel has been considered a more sustainable alternative with multiple political, financial, environmental, agricultural and even health and safety benefits (Milazzo et al., 2013).

Global energy demand for vegetable oils is increasing rapidly, but this is mainly attributed to the increasing dominance of food use rather than industrial and biofuel activities (Rosillo-Calle et al., 2009). The fact that soybean oil production in Brazil and Argentina is increasing faster than food demand means that production is more than capable of covering domestic demand. Additionally, the use of genetically modified organism applications experiences significantly better acceptance rates in Latin America than for example in Europe, further assisting the production of soybean (Castanheira at al., 2014). For these reasons, soybean production in Latin America, and especially Brazil and Argentina, has received great societal acceptance, avoiding the biofuel controversy suggesting that their expansion could reduce food availability and increase food prices, negatively impacting food security (Negash and Swinnen, 2013). However, the expansion of the biofuel market in recent years presents additional challenges in balancing, through proper policy initiatives, negative impacts like deforestation and food security, without burdening producers (Janssen and Rutz, 2011).

In this section, we delve into the functions of the technological innovation system of soybean biodiesel in the transport sector of Brazil and Argentina to identify the enabling factors that allowed the emergence and break into the dominant regime after pressures from the landscape, and focus on interactions with other alternative technologies that determine future pathways.

4.5.1 Entrepreneurial Activities and Market Formation

As previously highlighted, the favourable conditions of the broader Latin American region allowed Brazil and Argentina to be part of the most prominent soybean biodiesel producers globally. Despite their shared dominance, the two countries have major differences in the structure of their markets, mainly due to the export-focused operations in Argentina, discussed in the landscape analysis, in contrast with the Brazilian approach that focuses on domestic consumption. These differences are also present in the entrepreneurial activities in the two sectors (Function 1). In Argentina, three domestic and three global companies (Aceitera General Deheza, Molinos Rio de la Plata and Vicentín, and Bunge, Cargill and Dreyfus, respectively) control 87% of the sector's activities. Export tax mechanisms as well as tax differentials, while not affecting small farmers, provided a great incentive for larger companies to produce for the export market (Tomei and Upham, 2009). This shaped a very inelastic market of biodiesel, making it difficult to establish stable domestic demand, and further promoted exports. As a result of this environment, many of these companies proceeded to mergers and joint ventures to increase their strength in the market (Leguizamón, 2016).

On the other hand, in Brazil, the sector is more diverse with at least ten companies and smaller producers (Wilkinson and Herrera, 2010). This diversity allowed the Brazilian companies to use different shares of raw materials like castor and palm oil. However, the majority of production, including smaller producers, was based on soybean with 78% and animal fats with 18% in 2008, as part of PNPB. With 96% of all feedstock coming from the two largest agricultural activities in the country, this indicates a failure of PNPB to diversify the cultivation of other oils, which was a key goal of the program (Padula et al., 2012). The process of allowing smaller family farmers to participate in the market (Function 5) was through auctions that were performed under ANP and the Social Fuel Stamp (or Seal), a form of certificate that granted such producers the priority to sell (De Oliveira et al., 2019). Petrobras was the main buyer of these auctions, as a key distributor of biodiesel, further strengthening the

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company's position, raising questions on whether the scheme can provide a sustainable role in the market for family farmers despite the existence of regional positive outcomes (Marcossi and Moreno-Pérez, 2018). In fact, PNPB only partially achieved its goal of achieving broader social inclusion (Padula et al., 2012), since not so many jobs were created as expected, especially in the North and Northeast due to limitations in securing steady input supply (Rathmann et al., 2012). The lack of diversity in the feedstock, as well the push-out of family farmers in the production create additional challenges for the future pathway of the sector. Until recently, only soy had the ability to scale production to meet demand and yield earnings, while other feedstocks like palm oil remained less viable. So far, this did not affect food security since the ratio between soybean and soybean meal prices remained steady, with biodiesel only consuming excess oil from the market (Rathmann et al., 2012; Nogueira et al., 2016). However, increase in demand may reverse this situation, questioning the availability of oilseeds without compromising food security in a sector dominated by soybean. In fact, it has been recently reported (Fick and Jackson, 2020) that concerns over the ability to meet demand forced ANP to maintain the mandate in its current 10% level (Figure 29) instead of 12% that was pledged. Usually, studies indicating a significant reduction of emissions from biofuels refer to blends with high concentration (e.g. B100), with the positive effects being more limited in lower shares (Rathmann et al., 2012). On the other hand, recent modelling activities indicate that the decarbonisation of the freight sector should focus on advanced biofuels with or without carbon capture and storage (Köberle et al., 2020). Considering the concerns raised in our study, following such a pathway requires efforts to increase efficiency of alternative oils instead of solemnly depending on soy to intensify agricultural production while at the same time meeting the appropriability conditions to increase production without threatening food security.

Despite differences, both countries' approaches allowed the share of biodiesel in the energy mix to increase, through mandates of the legislative efforts highlighted in each country's regime (Figure 29). In Brazil, it was the support towards a more diverse sector, while in Argentina the joint ventures created resilience to price changes allowing a better adaptation of the companies in the market (Timilsina and Chisari, 2013). Following the mandates, the share drastically increased in 2009 for Brazil and in 2010 for Argentina and then steadily kept this growth rate until 2018, reaching almost 10% of biodiesel in the mix. As discussed in Section 4, this refers to the limit set by the Argentinian government, while Brazil still has the ability to further improve.

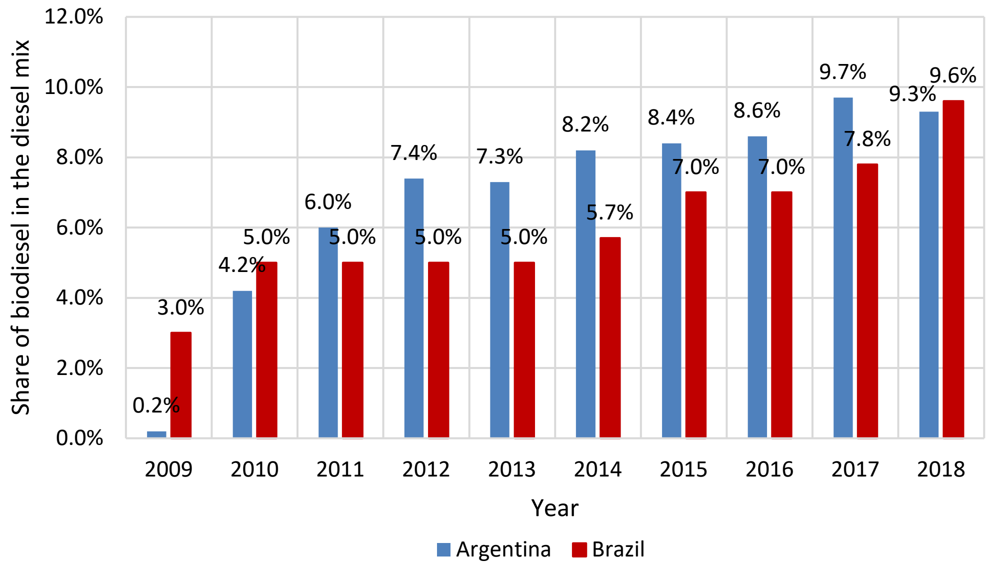

Figure 29 Share of biodiesel in the diesel mix of Argentina and Brazil in 2009-2018

Source: (USDA, 2020)

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The establishment of the mandates and the legislative initiatives in favour of biofuels around 2006 had a direct impact on the production volumes of the two countries but also in domestic consumption (Figure 30). In this recent formation of the market, we can observe three key differences between the two countries. First, while the Brazilian market is still rapidly rising, Argentina has been displaying stabilisation with periodic declines, since 2010. Second, while in Brazil produced biodiesel is mainly consumed domestically (USDA, 2020), in Argentina exports constitute the dominant destination of the production. And, finally, the only sector consuming biodiesel in Argentina is road transport; in Brazil, despite road being the dominant market, there is also some increase in rail transport consumption (ANP, 2020). Innovation spillover from road, which is the main transport sector, towards different sub-sectors is vital for the long-term sustainability of transport (Koasidis et al., 2020a). In Brazil, the only occasion where a small decline is observed, happens in 2014 with the political and economic crisis discussed in the landscape. This impact was minimal with the increase being even more rapid following the crisis. In contrast, in Argentina, after long periods of instability, the YPF-related conflict with Spain and other major importers of Argentinian biodiesel created significant volatility in the production volumes, with recovery efforts still struggling. This had no effect in the domestic market, which showed small signs of increase. Coupled with the decreases in production, this periodically increased the share of domestic consumption, as an answer to limitations in exports. However, Argentina seems to require a coherent biodiesel-related strategy with a clear focus concerning the long-term international orientation (Naylor and Higgins, 2017) and domestic consumption.

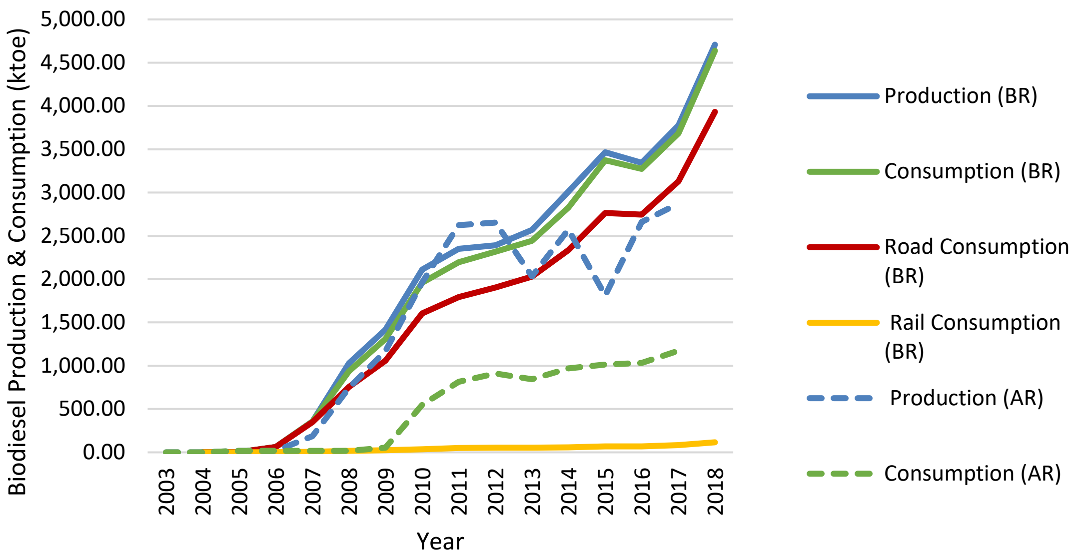

Figure 30 Biodiesel production and consumption in Brazil and Argentina

Source: (ANP, 2020)

Market formation is also dependent on the changes in other alternative fuels. In Brazil, another key biofuel, as highlighted in the regime analysis, was ethanol with major supporting policies like ProAlcool, which is not the case in Argentina. A key advantage of biodiesel is that there is no direct competition with ethanol since the latter act as a substitute for gasoline. This allowed the expansion of the biodiesel TIS, with production volumes in Brazil almost quadrupling since 2019. At the same time, ethanol also showed an increase of 36% between 2009 and 2018 (Figure 31), which is notable considering that the first ethanol initiatives started back in 1975. Ethanol in Argentina is also starting to increase, although produced quantities are still small to be able to provide a valuable insight, rather than a tendency.

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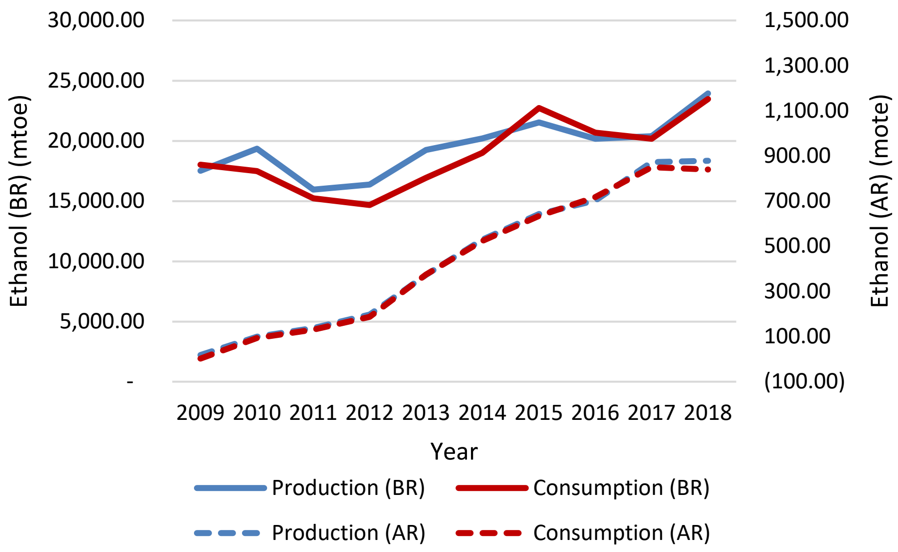

Figure 31 Ethanol production and consumption in Brazil and Argentina

Source: (ANP, 2020)

With the expansion of biodiesel diffusion being necessary, a key concern emerges from analysing the drivers of the market formation until now. Specifically, the reasons behind the introduction of ethanol as we observed in the landscape of Brazil was the substitution of oil imports. Similarly, biodiesel production seems to be driven less from environmental benefits, rather than political and financial motives, due to pressures from associations like ABIOVE and powerful lobbies operating in the soy sector (Wilkinson and Herrera, 2010).

4.5.2 Knowledge Development, Knowledge Diffusion and Guidance of the Search

In Brazil, the first official policy supporting ethanol was back in 1919 followed by institutions and regulations to support the use of the fuel (Stattman et al., 2013). In the following period, many research institutes and universities—like the Sugar and Alcohol Institute, the National Institute of Technology, the Oil Institute of Ministry of Agriculture, and the Industrial Technology Institute of the state of Minas Gerais—attempted to promote research related to the use of different vegetable oils to potentially be included in the energy mix (Function 2). The oil crisis and relevant opportunities provided for innovation and research focused on the use of palm oil, a path not further pursued with the improvement in oil prices after the crisis (Bergmann et al., 2013). In 1980, along with ProAlcool, a program for the promotion of vegetable oils, ProOleo, also took place to reduce oil import dependency by increasing local production (Johnson and Silveira, 2013). Again, decrease in prices harmed the viability of the program, which was replaced with the National Energy Program from Vegetable Oils (OVEG) to test different mandates (Function 4).

These early research efforts of Brazil, especially with ethanol on the sub-regime of passenger vehicles, contrary to Argentina that progressed in the sector much later, paved the way for the spillover of innovation utilisation in the sub-regime of freight with biodiesel in recent years, providing the opportunity to build on cumulative knowledge (Function 3), one of the key aspects in knowledge diffusion (Malerba, 2005). In 2005 and 2006, the two countries both legislated for the expansion of biodiesel with PNPB in Brazil and Law 26,093 in Argentina that have been extensively discussed in the respective regimes and both established mandates to increase the share of biodiesel in the mix. As a result, both countries are nowadays considered powerhouses in the field of biofuels. Part of this

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success is also attributed to agricultural research, like the Brazilian Agricultural Research Corporation (Embrapa), who promoted the exploitation of underused areas for agro-industrial project zones, especially in the region of Cerrado (Nehring, 2016). Such efforts established the dominance of soybean oil in the knowledge base of the countries, due to its abundance and low prices, which subsequently lowered biodiesel production costs, which are mostly dependent on raw materials (Lamers et al., 2008). This was vital for the economic feasibility of biodiesel, since lowering costs is a key challenge, which coupled with the high indirect environmental costs of fossil fuels could make biodiesel a very attractive alternative (Perin and Jones, 2019).

4.5.3 Resource Mobilisation and Creation of legitimacy/counteract resistance to change

The introduction of PNPB and Law 26,093 were a major effort towards the promotion of biodiesel both in terms of resource mobilisation (Function 6) and establishing social acceptability (Function 7). In the region, due to the abundance and low prices of soybean oil, such projects generally receive great attention from the media. The benefits of biodiesel have therefore been widely communicated to the public, leading to great acceptance and community engagement, which in other cases is very often a main barrier to the diffusion of biofuel-related innovation (da Silva Filho et al., 2018). On the other hand, the oil and automotive industry is another incumbent, who could resist deep transformational changes, like adoption of electric vehicles (Stokes and Breetz, 2018). Their main concern derives from the fear that biodiesel could replace the conventional engines, thus leading to diminishing profits (Chin et al., 2014). However, the use of soybeans in the region with the currently established mandates does not require significant modifications in the engine (Hassan and Kalam, 2013), while the use of biodiesel mostly in freight transport reduces the threat on such actors. The acceptance of biofuels in society allowed the legislative efforts to be effective both financially and regarding the engagement of human resources. In fact, as already highlighted in the market formation discussion, both small producers (including local farmers) and bigger companies participated in the biodiesel sector. This broad participation allowed the wide use of financial incentives, mainly in the form of taxes (Padula et al., 2012), establishing a powerful market that also attracts private investments, especially for example in Brazil with the recent introduction of RenovaBio (Salina et al., 2020).

4.6 Conclusions

This research aimed to analyse the historical evolution of the transport regime in Brazil and Argentina and the pressures and opportunities created by the wider landscape context, in order to understand the conditions that allowed the emergence of biodiesel as a dominant technology in recent years. For this purpose, we employed two qualitative Systems of Innovation frameworks, MLP and TIS, that enabled us to study the socio-technical transitions of the two countries and the diffusion of innovation inside the systems. Specifically, the MLP was used to analyse the fossil fuel-dominated regime and the historical changes occurred due to pressures from landscape factors and alternative innovation technologies. The TIS analysis allowed us to study the formation of the biodiesel innovation system in line with the insights provided by MLP that influenced the evolution of the technology as well as the interactions between different alternative fuels. Applying the two frameworks in a nuanced, integrative approach, instead of a conventional historical analysis, allowed us to uncover knowledge that can help guide the transition and subsequently better explain the factors behind technological and systemic change (Nikas et al., 2017).

In the MLP analysis, it became evident that landscape factors in the form of different crises (oil, recession and political turbulence) had a significant impact on the shaping of the transport regime, especially considering institutional, legislative and fiscal adjustments that had to be performed in the regime to adapt to these pressures. As a result, the two countries followed significantly different trajectories, with Brazil pursuing biofuels and especially ethanol, while Argentina strayed towards natural gas as a result of the global oil crisis and the domestic

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economic crises. Therefore, even though windows of opportunity provided the necessary destabilisation shocks in the respective regimes, it was the Brazilian policies that led the transition to a more sustainable pathway early on, while Argentina was locked-into a fossil fuel-based pathway, with the consecutive financial problems of the country in the following years creating difficulties in pursuing disruptive innovations. The trajectories of the two countries started showing signs of alignment only after 2005-2006, when they both invested in the expansion of the biodiesel industry. In Argentina, it was the 1998-2002 economic crisis that led to the promotion of biodiesel, while in Brazil after the initial increase in 2005, a second increase was also observed in 2014 after the severe political and economic crisis. This new and most recent window of opportunity enabled the expansion of the biodiesel industry, making Brazil and Argentina two of the most prominent producers of soybean biodiesel worldwide.

Understanding the reasons behind the success of biodiesel in the two countries is an important task towards informing future sustainability pathways that focus on deeper transformations, since from 1990 onwards mitigation of CO_2 emissions that is not correlated with decreases in energy demand is found to only happen in recent years, along with the increase of biofuel shares. This is the same, yet uneven, case in both countries, despite the significantly different historical trajectories they followed. Among the two countries, the cuts in transport emissions are greater in Brazil than in Argentina, where after an initial decrease they tend to stabilise. These deviations are attributed to the different approaches followed regarding the mandates of biodiesel in the energy mix. Argentina rose faster to a share of 10% in the mix, while Brazil followed a steadier increase. The fact that Argentina legally pursued and reached the 10% limit, in the form of a mandate, is the reason behind the stabilisation of emissions afterwards, while Brazil has the potential to further improve the efficiency of the sector by increasing the share in the energy mix. Therefore, a key to decarbonisation of both sectors lies in driving biodiesel consumption growth after hitting the 10% milestone, considering that production still relies on taxation incentives to be financially viable. Part of these different policy approaches in the mandates can be traced back to the nature of the two countries' economic activities, with Argentina placing significant importance in exports, while Brazil enhanced the domestic market increasing domestic consumption. In light of the landscape pressures arising from the crisis between Argentina and Spain after the nationalisation of YPF, we argue that balancing between exports and domestic consumption is a key challenge for the Argentinian sector as the transition unfolds in the future. Additionally, to be able to cope with threats of food security from the expansion of biodiesel to meet the increased demand from the higher mandates, the two countries need to focus on diversifying the feedstock used and create productions of scale for other oils instead of only depending on soybean.

Our research can be enhanced by adding further layers of insights from different Systems of Innovation frameworks, through for example coupling the MLP-TIS integration used in this study with the system failures (Woolthuis et al., 2005) and transformational failures (Weber and Rohracher, 2012) frameworks. Like recent such integrative applications in the transport (Koasidis et al., 2020a) or other sectors (Koasidis et al., 2020b), this can allow to better explore potential barriers that can lead to failure to keep up the expansion of biodiesel in line with changes in direct and indirect production costs in both alternative and conventional fuels. Building on policy implications provided in this study, the outputs can be used in to inform modelling assumptions and activities (van Sluisveld et al., 2020) to design transformative policy pathways (Rogge et al., 2020), given the increased interest of innovation systems in climate policy (Doukas and Nikas, 2020) and energy modelling studies (Nikas et al., 2020a).

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5 Key Takeaways and Discussion

The socio-technical system lies at the core of the emerging field of sustainability transitions. Methodological frameworks focus either on the transition of sectors, conceptualised as socio-technical systems (Markard et al., 2012) and the changes towards meeting sustainability targets, or on the incremental diffusion of radical innovation from a process-oriented technological perspective. Acknowledging that the borders of each system are defined on a case-by-case level (Markard and Truffer, 2008), it should be noted that this collection of studies comprises different countries, methodologies and/or research questions that focus on sectors, technologies, or combinations thereof. However, some generalised comments can be made on a comparative basis to consider global dimensions of the transition and inter-sectoral linkages (Lindberg et al., 2019; Andersen et al., 2020) to enhance insights for modelling activities of PARIS REINFORCE and better inform the development of transformative policy mixes in Task 4.6.

In the first study, the historical evolution of the low-carbon pathway of the Greek electricity system is examined. The sector acts as a starting point of the set of socio-technical analyses before moving onto other sectors, considering that electricity supply already undergoes significant systemic changes due to the existence of robust alternatives (Sovacool et al., 2018). Lignite has long dominated Greece's electricity system, boosting economic growth and energy security, given the abundant domestic resources. As a result, the country's analysis can provide insights into other coal-dependent regions in pursuit of a sustainable decarbonisation strategy (e.g. Poland). In line with its national and international commitments to climate action and sustainable development, Greece is currently facing the urgent need to transform its energy system, overcome its technological lock-ins, and transition to a low-carbon economy. Drawing from the need to secure a sustainable transition that considers the impacts of a lignite phase-out on local economies, this case builds upon the Multi-Level Perspective framework and further focuses on the phase-out of the dominant fossil fuel, rather than solely exploring the phase-in of new technologies. By delving into the landscape that established lignite as the mainstream energy resource in Greece, as well as the factors sustaining its dominance and resistance to change despite niche technologies and innovations challenging the regime, we discuss how the envisaged decarbonisation can be socially just and effective across multiple sustainability dimensions. Finally, based on current national pledges, the danger to lock-into a delignitisation but not a decarbonisation pathway is stressed considering the over-reliance on natural gas. As a result, instead of being used as a transitional fuel, extensive use of natural gas establishes deep roots inside the regime, with the potential to even become the dominant regime. A less aggressive behaviour of natural gas also appears in the transport sector in Argentina with an innovation shift to CNGs as a result of the oil crises, aligning natural gas symbiotically with the Argentinian transport pathway. The similarities on these markedly different case studies that appear on distinct time periods indicate the ability of natural gas to break-into and even dominate regimes since, as a fossil fuel, it is closer to the fossil fuel industry and status quo while more environmentally friendly than other conventional fuels. When designing decarbonisation policies that plan to utilise natural gas as a transitional fuel, countries need to be aware of the fuel's versatility to avoid creating additional technological lock-ins that would be harder to overcome.

In the second study, we move from power generation to the harder-to-decarbonise industry sector. Industrial processes are associated with high amounts of energy consumed and greenhouse gases emitted, stressing the urgent need for low-carbon sectoral transitions. In this case, the energy-intensive iron and steel, cement, and chemicals industries of Germany and the United Kingdom are analysed, two major emitting countries with significant activity, yet with different recent orientation. Considering the status of these two countries as industrial powerhouses, policy results can be extrapolated to other European countries (e.g. iron and steel experts in Austria

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also reach similar conclusions in a stakeholder engagement exercise in D4.3; see also Labella et al. 2020), while technological concerns from this case are of relevance to the global industrial system. Our socio-technical analysis, based on the Sectoral Innovation Systems and the Systems Failure framework, aims to capture existing and potential drivers of or barriers to diffusion of sustainable industrial technologies and extract implications for policy. Results indicate that actor structures and inconsistent policies have limited low-carbon innovation, with the system appearing more static on the decarbonisation front compared to the other cases, also evident from the steady emission intensities; small reductions are caused mainly by reduced activity rather than technological improvement. A critical factor for the successful decarbonisation of German industry lies in overcoming lobbying and resistance to technological innovation caused by strong networks in the regime. By contrast, a key to UK industrial decarbonisation is to drive innovation and investment in the context of an industry in decline and in light of Brexit-related uncertainty. A key concern driving actors' behaviour in the industrial system is the fear of carbon leakage. Both national and supranational institutions, out of fear of shifting demand to emerging industrial countries, provide emission allowances, which consequently act as a barrier against stricter regulatory policies that could provide the necessary motive for triggering a low-carbon pathway. Apart from institutional policy hesitation, the static progress of the sector is caused by the lack of established alternatives to the dominant state-of-the-art processes. Using BATs increases overall efficiency but is limited in the ability to achieve long-term targets which require radical innovations, like CCS and hydrogen. However, these technologies are still in very early stages of development and diffusion. CCS, when implemented at scale, face societal resistance and lack of legitimacy, shifting efforts to a much anticipated "hydrogen economy" transition. Such a transition needs to go hand-by-hand with that of electricity production; renewable energy will enable the production of "green" hydrogen and create a pathway for decarbonising industry without launching massive CCS projects. As a moderate approach, "blue" hydrogen solutions could be sought based on natural gas, with similar risks of locking-into a gas-based pathway, as observed in Greece's electricity generation sector.

The transport sector, which was the focus of the third case, is of particular interest from a socio-technical perspective due to the different dimensions existing in the individual sub-sectors; alternatives already exist for decarbonising the light-duty vehicle regime (e.g. EVs), while aviation is more similar to the industrial sector in terms of the lack of alternatives. Still, transport is associated with high amounts of energy consumed and greenhouse gases emitted, since most transport means operate using fossil fuels, creating the urgent need for a rapid transformation of the sector. In this third study, we examine the transport systems of Norway and Canada, two countries with similar shares of greenhouse gas emissions from transport and powerful oil industries operating within their boundaries. Our socio-technical analysis, based on the Sectoral Innovation Systems approach, attempts to identify the elements enabling Norway to become a pioneer in the diffusion of electric vehicles through policy, as well as the differences pacing down progress in Canada. In both countries, low-cost of energy has shaped different transitional pathways. In Norway, the abundant hydropower potential decreased the cost of maintaining and using an EV, acting as an adequate motivation even when state-led financial incentives decreased. On the other hand, access to cheap fuels created hesitation of EV adoption in Canada. Therefore, as with industry, decarbonising electricity generation to provide cheap energy is the cornerstone of supporting transport transitions. By utilising the System Failure framework to compare the two systems, bottlenecks hindering the decarbonisation of the two transport systems were identified. Results indicated that the effectiveness of Norway's policy is exaggerated, since efforts have focused mainly on electrification. Only recently spillover effects towards green shipping were observed. Regional and federal legislative disputes (mainly in Canada), the activity of oil companies and the lack of sincere efforts from system actors to address challenges have led to non-drastic greenhouse gas emissions cuts, despite significant policy efforts in both countries. Cross-sectoral innovation realisation is key to transport decarbonisation, since even in Norway with a fast diffusion of EVs, sectors outside the light-duty vehicle borders require different approaches and technologies, ranging from biofuels as a

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supplementary strategy to EVs to hydrogen fuel cells, with clear linkage to the hydrogen-based transition in industry.

Biofuels have long been debated as a technology contributing to the transport sector's decarbonisation, especially in sub-sectors where upscaling electrification innovation is challenging. The fourth comparative case builds on the particularities of the transport sector, to examine the role of biofuels in Brazil and Argentina, two countries that have long been top biofuel producers. In this case, we employ an integrated innovation systems framework to study the historical evolution of the dominant regime in the two countries' transportation and the recent emergence of the biodiesel technological system to provide insights and policy implications for future trajectories and decarbonisation strategies. In these counties, contrary to Europe, diesel is used in heavy-duty vehicles. As such, knowledge produced in biodiesel innovation can inform on transport decarbonisation outside the EV scope. Our analysis highlighted that landscape pressures have provided windows of opportunity for technological change, with Brazil following a more sustainable pathway based on ethanol as an alternative fuel, which allowed the country to later build on cumulative knowledge and lessons transferred from the passenger vehicle sector to freight, while Argentina has locked-into a natural gas-based innovation path. We also discussed that, with the recent expansion of the biodiesel industry, a key challenge for Brazil lies in keeping up the pace and unlocking the potential after reaching the 10% mandate amid concerns over food security and the lack of diversified feedstock, and for Argentina in balancing its biodiesel exports and domestic consumption. These challenges have global impacts in terms of transport decarbonisation strategies. Trade-offs between increased production of biofuels, food prices and land use change emissions should be considered on a global scale. A rapid diffusion of biofuels in a region (e.g. Europe) could cause increased biofuel production levels beyond the capabilities that balance these trade-offs, especially considering that biofuel production in Latin America is driven by financial and not climate/ environmental motives.

Single-sector approaches in socio-technical analysis provide valuable insights in the early stages of a transition or innovation diffusion. As the transition unfolds, and with key milestones fast approaching, including the 2023 Global Stocktake and the submission of the updated 2030 NDCs, whole system analysis and improved frameworks for studying transitions across multiple sectors begin to receive significant attention in the sustainability transitions field (McMeekin et al., 2019; Andersen and Markard, 2020). This collection of case studies across multiple sectors, and with a diverse set of tools improves the understanding of inter-sectoral transitions and trade-offs based on empirical evidence from different countries in a comparative manner.

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