PONTIFÍCIA UNIVERSIDADE CATÓLICA DE MINAS GERAIS
Programa de Pós-graduação em Relações Internacionais

Leandro Gomes Ferreira

FROM INNOVATION TO SOCIO-POLITICAL CHANGE
The European Union renewable energy innovation network mobilized for sustainability transition

Belo Horizonte
2021

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Tese apresentada ao Programa de Pós-graduação em Relações Internacionais da Pontifícia Universidade Católica de Minas Gerais, como requisito parcial para obtenção do título de Doutor em Relaçoes Internacionais.

Orientador: Prof. Dra. Matilde De Souza
Supervisor: Prof. Dr. Uwe Cantner

Área de concentração: Seguranca e Instituições Internacionais

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To my son, Ben
Para meu filho, Ben

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This is the opposite of education, which should aim to make people, no matter how smart or accomplished they are, learners for the rest of their lives. Rather, we now live in a society where the acquisition of even a little learning is the endpoint, rather than the begining, of education

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(Nichols, 2017, p.6)

ABSTRACT

Climate change is a huge problem for future societies, and one of the core sectors that can offer fundamental contributions to fight against it is the energy one. The transition toward a low-carbon economy necessarily touches upon enhancing the share of renewable energy technology (RET) in the sector. The European Union figures as a historical central actor on climate negotiations. The provisions toward RET are from 1970 and evolve until the XXI Century. Even though it lasts on a profound dependency on fossil fuel exporters. However, collective actions toward the share of knowledge and technology of renewable energies among the Member States had given autonomy of energy generation and can offer future contributions for the whole Union. As an objective, the thesis analyses the formation of a Renewable Energy Technological Innovation System (RETIS) base on collaboration between experts in the European Union and the coordination of political actors to enable an energy transition and reducing their economic and political dependency on Russia. As a theoretical framework, we developed the "Two scales framework" to deal both with public science and the politics of RET on an international level. We mobilise the Technological Innovation System, policy mix, different power and epistemic communities approaches to form the framework coherently. Our data was collected on different databases, such as REGPAT, SCOPUS, IEA, IRENA and Eurostat for descriptive statistics and social network analysis, and official documents for content analysis. We identified the evolution of the RETIS from 1989 until 2019 and their impacts on the European Union energy transition. We found out that the collective knowledge production of RET concentrates on Germany, France, Italy and Spain. Moreover, we observed that these Members are far ahead on the scale up to a new energy sector and the EU level. At the same time, some lagging countries, such as the Baltic States and others, still do not evolve at the same pace in terms of investment in RET and knowledge production. We concluded that there is an asymmetrical energy transition in the European Union based on knowledge production, investments and energy balances.

Key-word: Energy, Climate change, Technology, European Union, Energy transition.

RESUMO

Mudanças climáticas podem ser colocadas como um enorme problema para as futuras sociedades e um dos setores centrais que pode oferecer contribuições fundamentais para combatê-la, é o energético. A transição para uma economia de baixo carbono, necessariamente toca no aumento da participação da tecnologia de energia renovável (RET) no setor. A União Européia figura como um ator central histórico nas negociações climáticas. As disposições em direção à RET vem desde a década de 1970 e evoluem até o século XXI. Mesmo assim permanece uma profunda dependência dos exportadores de combustíveis fósseis. Entretanto, ações coletivas para a partilha de conhecimento e tecnologia de energias renováveis entre os Estados-Membros deram autonomia de geração de energia e podem oferecer contribuições futuras para toda a União. O objetivo desta tese analisa a formação de um Sistema de Inovação Tecnológica em Energias Renováveis (RETIS) baseado na colaboração entre especialistas da União Européia e na coordenação de atores políticos para permitir uma transição energética e reduzir sua dependência econômica e política da Rússia. Como estrutura teórica, desenvolvemos a "Estrutura de duas escalas" para tratar tanto da produção científica quanto da política do RET em nível internacional. Mobilizamos o Sistema de Inovação Tecnológica, a combinação de políticas, diferentes abordagens de poder e comunidades epistêmicas para formar coerentemente a estrutura. Nossos dados foram coletados em diferentes bases de dados, tais como REGPAT, SCOPUS, IEA, IRENA e Eurostat para estatísticas descritivas e análise de redes sociais, e documentos oficiais para análise de conteúdo. Identificamos a evolução da RETIS de 1989 até 2019 e seus impactos na transição energética da União Européia. Descobrimos que a produção coletiva de conhecimento do RET se concentra na Alemanha, França, Itália e Espanha. Além disso, observamos que estes Membros estão muito à frente na escala em direção a novo setor energético também no nível da UE, enquanto alguns países atrasados, como os Estados Bálticos e outros, ainda não evoluem no mesmo ritmo em termos de investimento em RET e produção de conhecimento. Concluímos que existe uma transição energética assimétrica na União Européia, baseada na produção de conhecimento, investimentos e balanços energéticos.

Palavras-chave: Energia, Mudanças climáticas, Tecnologia, União Europeia, Transição Energética

List of Acronyms

C	CNRS	Centre national de la recherche scientifique
	COP	Conference of the Parties
	COVID-19	Corona virus disease 2019
	CO2	Carbon Dioxide
	CPC	Cooperative Patent Classes
	CSP	Concentrated Solar power
	CTCN	Climate Technology Centre and Network
E	EBRD	European Bank for Reconstruction and Development
	EC	European Commission
	ECSC	European Coal and Steel Community
	EEF	European Energy Forum
	EERA	Energy Research Alliance
	EEPR	European Energy Programme for Recovery
	EIB	European Investment Bank
	EP	European Parliament
	EPO	European Patent Office
	ETS	Emission Trading System
	ETIPs	European Technology and Innovation Platforms
	ERA	European Research Area
	ERC	European Research Council
	EU	European Union
	EUFORES	European Forum for Renewable Energy Sources
	EURATOM	European Atomic Energy Community
	EUREC	Association of European Renewable Energy Research Centers
F	FFT	Fossil Fuel Technologies
	FP	Framework Programme
G	GERD	Gross domestic expenditures on R&D
	GHG	Greenhouse Gases
	GDP	Gross Domestic Production
H	H2020	Horizon 2020
I	IEA	International Energy Agency
	IPC	International Patent Classes
	IPCC	Intergovernmental Panel on Climate Changes
	IPR	Intellectual Property Rights
	IR	International Relations

	IS	Innovation Studies
	IRENA	International Renewable Energy Agency
K	KPI	Key Performance Indicators
	KTT	Knowledge and Technology Transfer
M	MDG	Millennium Development Goals
	MLP	Multi-level Perspective
N	NECP	National energy and climate plans
	NDC	National Determined COntributions
	NREAP	National Renewable Energy Action Plans
	NSI	National Innovation System
O	OECD	Organisation for Economic Co-operation and Development
P	PPP	Purchasing power parity
	PV	Photovoltaic or Solar Power
R	R&D	Research and Development
	RD&D	Research Development and Diffusion
	RE	Renewable Energies
	RET	Renewable Energy Technologies
	RETIS	Renewable Energies Technological Innovation System
S	SDGs	Sustainable Development Goals
	SET-Plan	Strategic Energy Technology Plan
	SETIS	SET Plan Information System
	SNM	Strategic Niche Management
	SSI	Sectoral System of Innovation
	SNA	Social Network Analysis
	STI	Science, Technology and Innovation
	STS	Sustainability Transition Studies
T	TEC	Technology Executive Committee
	TIS	Technological Innovation System
	TM	Transition Management
U	UN	United Nations
	UNFCCC	United Nations Framework Convention on Climate Change
W	WE	Wind Energy
	WCC	World Climate Conference
	WHO	World Health Organization
	WMO	World Meteorological Organization

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INTRODUCTION

In the last years, most has been discussed about climate change and its negative future impacts on the Earth if humanity does not change the way it interacts with the environment. Notably, two main policies are discussed, those related to adaptation and those related to mitigation. Adaptation measures rest on States where the effects of climate changes are already there. For example, Small Island States (SIDS) are geographical spaces where floods and destructive meteorological events often happen due to climate changes. Meanwhile, these societies have to find policies via international negotiations and public policies to alleviate their difficult situation. On the other hand, mitigation measures rest on all States because they are provisions to avoid or reduce the future impacts regarding climate change since it is a global event. Our study, among other characteristics, rests on the mitigation side research by dealing with one of the central sectors in the economy, energy.

Perhaps the Rio Summit in 1992 is a benchmark to understand the evolution of the world's concern towards climate changes (UNFCCC, 1992). After a long Cold War era, 1992 was the first time United Nations thought about global warming and climate impacts. Definitely, after the foundation of the Intergovernmental Panel on Climate Changes (IPCC) in 1988 and the foundation of the United Nations Framework Convention on Climate Change (UNFCCC- short Convention), negotiations around climate policies evolved at high speed. The first measurements were related to Agenda 21. Through 40 chapter, the Agenda pointed out the problems under environmental concern and countries should focus their environmental policies concerning future generations and advise the society on how to deal with current environmental problems. The rise of the temperature below 1.5 degrees, compared to pre-industrial times, was considered the major concern and continues on until today. Until the end of the XX Century, nations did not have reached conclusions that drastically would change climate negotiations. The energy sector emerged as a pinpoint in the climate discussion. But more than that, renewable energy technologies (RET) have a fundamental role if one really wants to advance on climate politics and guarantee average living conditions for future generations (UNFCCC, 2020).

The trade-off between climate change and energy security is at the core of our study.

While climate policies claim for the progressive efficient use of natural resources, reduce greenhouse gas emissions, and reduce fossil fuels use, energy policies claim to increase energy generation by different means and argue that RETs are still not stable enough to replace fossils. However, as will be discussed later on in Chapter2, one possible way to overcome this trade-off is with investment to turn renewable energy innovation more efficient, cheap and more diffused around the world. Policymakers are dealing with problems that are no longer a matter of opinion on which way to go, but they have to be based on scientific facts and normative goals for society (Haas, 1992a; Souza et al., 2014). The depletion of renewables has a high risk and requires large investments with an expected high degree of benefits for society (Mazzucato, 2015). It is a matter of States' action, and those which will have access to the renewable innovations more efficiently, also access a distinguish position in world politics (Avelino & Wittmayer, 2016).

As one might have noticed, innovations are also at the core of our study. By the progressive development of more renewable techniques, products and processes, they can offer some contributions to fight climate change and alleviate some societal problems. Moreover, in a systemic approach, innovations can distribute knowledge through different spaces nationally or internationally (Edquist, 2010; Carlsson, 2006) and support a comprehensive transition to a low-carbon economy. So, to establish some common ground, we offer a brief discussion about invention, innovation, technology and how these terms are connected with renewable energies and our main topic.

Invention can be sharply put as the process of generating ideas for new products or processes, while innovation is applying these inventions on the market and society (Fagerberg, 2004). This distinction is often made in many studies (Fagerberg, 2018; Rogers, 2010), and since they are closely linked, it is hard to make a differentiation. According to Schumpeter 1934, innovation would be sharply understood as ”new combinations” or the ability to carry these inventions into practice. The result of innovation can be a process, a product, a technique, or something else. Without putting it into practice as something meaningful for the market and society, the invention does not push the economy toward a new paradigm, and it does not acquire a market share or even is relevant for users every day. However, this process to make sense of invention is a process consisting of a considerable time lag, which is caused by the timely building of capacity for its introduction or the absence of capacities. This can be identified on the firm-level without the actual capacity to turn it on (Fagerberg, 2004) on the systemic level by the missing elements (we discuss this in Section 1.2), or the lack of institutions and organizations specialized in supporting it (Edquist, 1997a). Thus, there is a common long road toward the maturation of an innovation.

The path from invention to innovation is non-linear. It is best understood as a process of knowledge and technology creation and diffusion, which has been under scrutiny for a long time. Some economic scholars draw attention to industrial economics, and more focused on the firm level and on the Incentive-based Approach (Dasgupta & Stiglitz, 1980; Reinganum, 1989), by predicting and modelling innovation with perfect information and rational choices from the R&D department. Or Knowledge-based Approach (Nelson & Winter, 1982), by assuming bounded rationality to predict information and knowledge flow differently regarding the actors involved. Further, some scholars pointed out the existence of a system of innovations that pushes and might induce the process in which firms interact with other third sectors, high educational institutions, the public sector, civil society, among others (Rosenberg, 1976; Edquist, 2010; Hekkert et al., 2011). Some authors draw from psychology on an individual level the idea of shared learning inside a team as a process of creation (Cauwelier et al., 2019). Others take into account the process of training itself to understand patterns, assemble elements, and create thoughts (Kahneman, 2011). In any case, there are some common grounds about what makes one seek to assemble different elements, and later, innovation.

The steps to knowledge creation begin with the identification of a problem or a need (Rogers, 2010). This idea is named invention, something informal and with no economic or social application. The innovation process, as mentioned before, is an interactive and social process that takes years or decades to fulfil an innovation. The process assembles two main knowledge forms: codified (explicit) and uncodified (tacit). For knowledge codified, Nelson & Winter (1982) draw some conclusions about the influences that previous experiences bring about how to proceed. As well as the tacitness idea from Polanyi (1967), where the knowledge that people have is difficult to fully articulate and vary from individual to individual. The best people can do to create something is by the interaction of both types of knowledge (Rogers, 2010). The next step would be the convergence towards a researching activity on two types: a basic effort, by identifying foundations; or an applied level, by promoting answers to social and material problems (Rogers, 2010). Then, it is necessary to develop the knowledge so that the public audience can finally get in touch and use it as a new material tool or new institutional guidance. Finally, the commercialization and the creation of a market is definitely important in this manner. Otherwise, the knowledge remains as a prototype, not as an innovation or technology.

Last but not least, the concept of technology incorporates both artefacts and knowledge. Artefacts are material objects products (i.e. hardware, solar panels, wind turbines...) or processes (i.e. software, digital control of wind turbines operation, techniques of installations...). Knowledge is an immaterial object and is partly found as competencies or skills embodying experts, can also be identified in academic writing, papers and drawings, or even embodying artefacts(Bergek et al., 2008a,b). For every generation of technology, there is an innovation process behind it. So, it is possible to use innovation and technology as interchangeable concepts embedded in the argumentation above. To mature and largely diffuse any innovation/technology takes time, requires investments, complex coordination of different actors, organizations and institutions (we discuss this in Section 2.2.3), and manipulation of society habits toward its legitimation and political and economic effects. These characteristics are difficult to be achieved and difficult to be tracked because: they might take years or decades; they are diffused with multiple actors and originally not coordinated in the early years; they are a result of chances. They maybe became more structured after some time, after governmental actions and collaboration between organizations, but one should turn this into a more institutionalized issue, so to speak.

Naturally, RETs went through all these steps because one can see photovoltaics panels and wind turbines on and off-shore worldwide (we discuss these technologies in 2.2.2). After Rio Summit in 1992, the boost around RETs pushes the innovation frontier, enabling, for example, the development and commercialization of photovoltaic (PV), concentrated solar panels (CSP), and on and off-shore wind broadly. Further, there is a feedback loop. When users become aware of the available technology, they start using and providing information to inventors and innovators with barriers, benefits, and desirable alterations in the technology. By and large, inventors and innovators have the opportunity to share and collaborate with others, and by this interaction, efficient manners come into play. The Smart-grid or Smart-city model are models of policies designed to increase energy demand coupled with the complexity of the energy grid under concerns with environment and sustainability (Zame et al., 2018). On a Smart-grid model, users are supplied with different energy sources, both private (PV, CSP, or wind turbine on rooftop) or via a renewable energy industry. The collaboration between different innovators from different industries might help policymakers to design a highly efficient energy grid.

Traditionally, this collaboration for renewable energy technology creation emerges locally or nationally. But in this study, we consider an international collaboration system composed of individuals, organizations and countries. Individuals are the experts, organizations are the firms, research groups and educational institutions, and countries are those in which the knowledge flows (as will be presented in 2.2.3). Firm sites might limit such products development, but a comprehensive result of knowledge production and diffusion is rarely difficult to contain inside a country's borders. Wagner (2006); Barabâsi et al. (2002) already discussed the growth of scientific and technological collaboration due to the least material limitations and easy communication and interaction, and Wagner et al. (2017); Graf & Kalthaus (2018); Binz & Truffer (2017) pointed out that international collaboration generates better outputs than national or individual. The reasons are typically the diversity of experiences, knowledge, performances, and the possibility to spread a certain view about the world. Co-patenting and co-authoring are ways to feed renewable innovation process from different places around the world, but that poses challenges regarding the coordination of inputs and outputs and further outcomes on an international level.

From now on emerges our research problem that guides this whole investigation. The European Union is certainly not a State, a country, or something of the genre. But ever since its foundation with the European Community for Coal and Steel in 1951 by the Treaty of Paris, through the European Communities in 1965 with the Brussels Treaty, and lately European Union from 1992 on with the Maastricht Treaty, the issue of energy is at the core of the integration. There have been several policies on this behalf to regulate and stimulate the diversification, growth and efficiency of the energy sector and market, in a sense that opens space for many firms and, recently, the introduction of the renewable industry on the EU level.

However, the energy issue is still a nested game within the integration and international relations. The top problem under concern is the high energy dependency[1] rates on fossil fuels both on local and international markets. EU consumes a lot of oil/petroleum for transport and oil and gas for the electricity sector. In 2019, renewables accounted for 15% of the total energy consumption; fossil fuels accounted for over 40%; natural gas around 25% and; nuclear around 13%. Thus, the EU society is highly dependent on non-renewable sources, which increases the level of emissions and the import energy dependency. The dependency degree varies in each country, but 96,8% corresponds to oil and petroleum imports on an aggregated level, while natural gas is about 89,7%. Russia is the top EU supplier with 46% for solid fuels, 41% for natural gas, and 26% for oil in 2019 (Eurostat, 2020b, 2019a; Energy Union, 2019). These numbers tell that almost all Member States have some energy trade agreement with Russia or elsewhere. Without it, it would be less possible to run the economy and society needs (we provide an extended discussion in section 2.2).

A possible way to overcome the EU dependency is by investing in renewable energy technologies and a new type of energy transition policy. The energy transition can be put as a process in which one enhances the share of renewable energy sources in its energy mix and reduces the share of fossil fuels. (Leach, 1992; van den Bergh & Bruinsma, 2008). On a EU level, it requires a massive cooperation between Member States to scale up RET, diffuse it and transform the energy sector. Above all, energy transition is about technology and innovation.

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[1] Gross available energy represents the quantity of energy necessary to satisfy the energy needs of a country or a region. The ratio between net imports and gross available energy indicates the ability of a country or a region to meet all its energy needs. This ratio is called energy dependency. In other words, it shows the extent to which a country or a region is dependent on energy import (Eurostat, 2020b)

For Europe, it requires more than just scale up RET, but enable collaboration between experts (Graf & Kalthaus, 2018) and coordinates EU and Members direction of policies toward some convergent goals for the energy sector. By convergence, we mean the fulfilment of the 2050 Roadmap or 2030 Energy Project characterized by the rise of renewables in the consumption energy mix, energy efficiency, and reduction of fossil dependency (European Comission, 2020), among other issues. EU has a big pool of climate and energy initiatives, projects, plans, and policies evolving since the early 1990s by incorporating different aspects on what is climate and energy problems and how to address them institutionally.

We identified three levels during the research process with several policies that support and push RET: International, European Union and National levels. EU provided several supports for innovations such as the Framework Programmes since 1984 (European Commission, 2020b), or climate and environmental decisions such as the old White and Green Papers in 1995 or the more recent European Green Deal from 2019, or even energy policies like the First Energy Package in 1996 or the more recent Energy Union project (Energy Union, 2019). National policies funded, regulated or support renewable energy emergencies such as traditional Feed-in Tariffs or national calls for innovation projects. International agreements, conferences, events, and organizations compiled the current environmental and energy concerns, directing the upcoming policy and political focus that also build upon energy transition. Some of them are directly related, some contextually related (this discussion is made in Section 3.3). It highlights the proliferation of policies and politics regarding transitions since the early 1990s, which after the Paris Agreement in 2015, became even stronger. The EU integration somehow traced a path in order to integrate and coordinate, in an efficient way, different levels, policies, and political demands in its energy transition.

Beyond that, the mixtures of policies on three levels allowed an interesting context for transnational collaboration. Again, since dependency is an EU problem, it tackles all Members in different degrees, and solving Germany's dependency but enhancing the French or Slovenian one does not help out. However, this is the reality. Different countries address climate and energy problems differently, which embodies their energy transition. So, there has been an uneven transition process among Members, and some of the reasons and probable impacts are discussed in Chapter4. Even though with a highly collaborative environment where experts from different scientific backgrounds and nationalities (among the Member States) collaborate to produce patents and academic papers, sharing experiences, experiments, products and processes in respect to RET among each other, the pace of energy transition is uneven. These collaboration efforts we call knowledge production. In terms of innovation, in a broad sense, we consider patents and academic papers (Graf, 2017). We count patents and paper for statistical purposes and also observe their co-authoring network in which the knowledge production actually flows. They are responsible to create the resources (Avelino & Wittmayer, 2016) that will be put into practice for National or EU energy transition.

Notwithstanding, only knowledge production is not enough to understand transitions. Renewables energies in the EU are also about geopolitics and power relations (Avelino & Wittmayer, 2016; Criekemans, 2018). Far from this traditional geopolitics assumption, the geopolitics of energy transition is about access to renewable sources, which are more or less well distributed across the globe. Frequently, the sun shines, and the wind blows, but it requires the capacity to mobilize it industrially, politically, institutionally and societal objectives. It is about renewable energy technologies and innovation with high public and private investments and a coordinated diffusion and destabilization of the old energy paradigm, which means from fossil dominant to renewable dominant. Each Member might have its sources of power to achieve this, but in an aggregated overview, they are really asymmetrical.

So far, the problem with the EU energy transition has been briefly addressed, and one might observe that there is a lot to be covered. Indeed. This study can also be seen as an innovation thesis to distinguish but complementary scientific disciplines: International Relations -IR, Innovation Studies - IS and Sustainability Transition Studies - STS. A tough scientific work was done over the almost five years of this research, and the next section summarizes the track chosen to be traced.

General methodology

This study has some different methods, techniques and tools. In part, because it comes from different disciplines, in part because our object required that. So we decided on a Methodological Appendix A where most of the methods, techniques and tools were described and, some of them, deeply detailed. In any case, when such an analytical process seems to be covered or hidden, please move to this Appendix, and one maybe finds an answer.

The merge of the three disciplines, IR, IS and STS, was done by overviewing their ontological and epistemological foundations. This discussion does not last long, but it is interesting to mention. We observed that they are connected by the Critical Realist ontological assumption, which assumes that reality exists and can be accessed by humans, although with some problematic bias and intellectual mechanisms. The result would be an investigation based on the ”widest possible critical examination” (Moon & Blackman, 2014, p. 1170) (Jackson, 2016).

Following the ontology, we drop into the epistemological assumption. Sustainability transition follows some normative approach that, at first sight, would be incompatible with

Innovation Studies. However, STS is derived from IS, precisely from those authors acknowledging the necessity of technological change to address societal problems (Markard et al., 2012; Rip & Kemp, 1998). In turn, they can be merged under the Constructionism epistemology. Although the reality is out there, meanings can be created from the interplay between the subject and the object (Moon & Blackman, 2014). Innovation can only make sense if it is really applied by society. Even though none IR classical theory is mobilized in the study, except by epistemic communities (Haas, 1992a), traditionally used to mobilize knowledge as an element of politics, the research design is grounded on the international flow of knowledge. Society can access the flow within a technology created to answer or contribute to societal problems. Innovation is a collective and social phenomenon (Graf & Kalthaus, 2018) that can be done at a non-traditional level - international - with different elements and tools - cross country co-authoring knowledge production.

The merged disciplines allowed the formulation of an innovative way to design researches, enabling us to move forward to our methodological elements. The general objective of this thesis is to analyze the formation of a Renewable Energy Technological Innovation System (RETIS) based on collaboration between experts in the European Union and the coordination of political actors to enable an energy transition and reducing their economic and political dependency on Russia goods. We breakdown some specific objectives: a) Develop a theoretical framework in which International Relations, Innovation Studies and Sustainability Transition Studies can be operationalized; b) Discuss the European Union convergence of climate change challenge into a discussion about renewable energy technologies diffusion and transfer; c) analyze the formation of the Renewable Energy Technological Innovation System (RETIS) and its consequences for climate and energy trade-off, and; d) analyze the geopolitics of energy transition within the RETIS.

Our research question is: **How the European Union coordinates the collaborative knowledge and technology developed in the Renewable Energy Technological Innovation System (RETIS) to disrupt its energy dependency and speed up its energy transition?**

Since there is a Methodological Appendix for descriptive steps, in terms of general methodology, the analysis starts in 1990 and goes until the most recent data around 2021, predominantly based inside European Union borders. The study was built in qualitative and quantitative methodologies. Therefore, quantitative data and analysis are predominant. We looked after reliable, safe and traditional databases to retrieve: energy statistics from Eurostat, International Energy Agency (IEA), International Renewable Energy Agency (IRENA) and Climate Watch; patents from OCDE RegPat 2020 version, and; bibliography from SCOPUS. After retrieving data, some descriptive statistics are presented based on patent count analysis and bibliometric analysis, and finally, a social network analysis is performed to understand the experts' collaboration and political dynamics. The complete description of all methods, techniques and tools, and key-words parameters to retrieve data can be found in the Methodological AppendixA.

Qualitative data and analysis are based on content analysis of: reports, and official communication and documents from European Union institutions; EU-lex for legal data; other findings in the literature, and; interviews performed with representatives from Directorate-General for Energy (DG ENER), Directorate-General for Climate Action (DG CLIMA) and Directorate-General for Research and Innovation (DG RTD) of the European Commission that demanded to remain anonymous.

The study is divided into 6 chapters, one Introduction, 4 discussing and analytical chapters, and a Conclusion. Once again, the Metholdogical Appendix is after all. This Introduction was responsible for presenting a broad and wide discussion of some basic concepts and introducing our research problem. Chapter 1 discusses our theoretical approach composed of theories from the Innovation Studies, Sustainability Transition, Political Science and International Relations. We discuss in the first section a disclaimer calling for more IR studies dealing with science, innovation and technology (SIT). Then we mobilize the discussion about radical innovations and technological changes and their connections with the Technological Innovation System (TIS) (Bergek et al., 2015; Hekkert et al., 2007; Carlsson et al., 2002). In turn, the selection of the TIS approach allows us to establish connections with international politics because technology links countries, but each country differently mobilizes its resources to create different power to fulfil transition (Avelino, 2017; Rotmans et al., 2001). We developed "The two scales/dimension framework" to organise the multiplicity of theories and approaches". The Low scale or Public science dimension deals with the collaboration between experts and the mix of policies that enable and support it. The Upper scale or Politics dimension deals with the geopolitics of energy transition and its different resource mobilization toward an energy transition, and the international struggle of power to reduce energy dependency and boosts energy transition.

Chapter 2 has a double mission. The first half deals with the trade-off between climate change and energy security and alternatives to tackle societal challenges, such as the energy transition. It presents the historical efforts to introduce more technological discussion in the Conference of the Parties and how climate change negotiations became a matter of renewable energy technology diffusion and transfer (knowledge and technology transfer - KTT). The second half localizes the EU within the international negotiation of KTT for renewables. Doing this defines the boundaries and limits of the RETIS, discussing and analyzing its structures. Each part of the structure is analyzed in a specific section as follows: the institutions, the trajectory of renewable energy technologies (RET), the market structure and the relevant actors. It is necessary to set up the background in which the TIS historically evolves.

Chapter 3 analyzes the RETIS. The social network analysis will be done retrieving statistics from our N group formed of patents and academic publishing collaborations inside the European Union. We reconstructed the networks for Patents from 1990 until the most reliable data, respecting the 4-5 years lag, which comprehends 2014[2]. For Publications, we start in 1989, the oldest data, until 2020. Since publication has a continuous flow, we did not have to respect some lag rule, which also explains the difference between the duration of each period. Patents time frame led to 28 overlaps and 9 periods (considering the years lag, 23 overlaps and 8 periods), corresponding to: 1990-1992, 1993-1996, 1997-1999, 2000-2002, 2003-2005, 2006-2008, 2009-2011, 2012-2014 and 2015-2019. Publications time frame led to 30 overlaps and 9 periods, corresponding to: 1989-1992, 1993-1996, 1997-2000, 2001-2004, 2005-2008, 2009-2011, 2012-2014, 2015-2017 and 2018-2020. We mobilized the policy-mix approach (Rogge et al., 2015) interacting with the functions of a TIS (Hekkert et al., 2011; Bergek et al., 2008a) to analyze the probable policies that might have created the context in which the RETIS develops over the years.

Chapter 4 analyzes the coordination of knowledge and technology to achieve an energy transition. We analyze the mobilization and manipulation of natural resources in order to acquire ”different power” and the challenges related to it. First, we discuss the dynamics of the social network analysis at a country level and how these epistemic communities created around the EU play a decisive role in informing the decision-makers to diffuse RET. Then, we put this power dynamic in the international context. Finally, we analyze the geopolitics of energy transition based on the mobilization of power and its resources (Avelino & Wittmayer, 2016; Criekemans, 2018) such as knowledge creation and other political and economic characteristics and its effects on the energy transition dynamic of the EU and its Member States.

The Conclusion wraps up the discussion and assesses the achievements and barriers found in the research developments. It also calls attention to further questions over the sustainability transition guided by IR principles, opening up new discussions and pointing to future research. The conclusion is followed by the Appendix aforementioned.

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[2] We also plotted, to check if the pattern was right, the tendencies for 2015 - 2019.

Chapter 1

INTERNATIONAL RELATIONS MEETS INNOVATION AND SUSTAINABILITY TRANSITION STUDIES

The chapter has the objective to discuss the theoretical foundations and the approach used to analyse the objects of study. The theoretical effort here is related to the attempt to incorporate Innovation Studies, a branch of Economics, into International Relations - IR. IR is a remarkable science in a globalized and deeply interconnected world, and the discussion of Science, Innovation and Technology (SIT) is pervasive in this reality. Among several approaches in economics, we seek one that is driven toward an international perspective of innovation and open up a political discussion for the process and consequences. Technological Innovation Systems (TIS), at the basis of Carlsson (2006) conception, has a global technological set. This means that the theory can go through States' borders and connect inventors, making them share common academic concepts and promoting similar knowledge. This is a prominent idea, in a sense that it can be totally related to the conception of *International*.

Notwithstanding, innovation scholars did not advance so much in this road, regarding TIS as a more national or subnational analysis them taking the international level seriously. Similarly, IR discussion of SIT tend to avoid the economic discussion, or because it can be taken as something exogenous, or because of a lack of a more quantitative approach that allows one to grasp more information about the international. However, from our perspective, dealing with innovation requires dealing with a comprehensive world in which economics has fundamental contributions. So, this chapter has an objective that becomes folded, meaning: on the one hand, to incorporate Innovation Studies into IR; on the other hand, to explore the international level and the political contributions (mainly discussing the duality between power/politics) of a TIS. To fulfil this, we have to present the foundations of Innovation Studies, how they open space for Sustainability Transitions Studies, and later, discuss how to incorporate this into IR.

1.1 Enlarging IR discipline

International Relations (IR) exists because their agents can structure the international to constrain their own actions and allows interactions. The discipline discusses political relations on the international level, and their contributions are critical to comprehend some international events. However, it constantly avoids discussions that require a more interdisciplinary perspective. Even more when dealing with economic knowledge and quantitative analysis. It would be something that could be left to technicians to resolve and propose models, then social and political sciences would take for granted (Winner, 1978). Science, innovation and technology (SIT) in IR is even rarer. Following the events of the II World War and the nuclear deterrence and (non)proliferation, it Ogburn (1949) was the first extensive study to present an effort to translate the technological problems and their interface with IR. Their seminal book ”Technology and International Relations” argues that this investigation would dominate the IR discipline. They were not wrong, nuclear weapons became famous at that time, and many important IR scholars such as Joseph Nye, Stephen Krasner, Susan Strange, Robert Keohane and Ernst Haas recognize this. Unfortunately, after a short period, they became silent about it and dedicated this to the sub-field of ’Defense studies’ or ’War and Peace studies’ (Mayer et al., 2014).

The table1.1 shows the small number of IR publications clearly dealing with ’technology’ and ’innovation’. The number of publications that intersect these two keywords with ’international politics’ and ’international relations’ are 1,607[1]. The first two columns take into account the number of publications per journal, considering SCOPUS quantitative ranking. The last two columns consider the number of publications for the most important journals in IR ranked by the impact factor available on SCIMAGO. The most influential journal in the IR discipline has only 1 publication. These findings highlight that IR, despite the importance of SIT for world politics nowadays, has little explored. Of course, other journals address this issue quite often, but they are not influential on the formation of the research agenda of IR in the XXI Century than those already mentioned.

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[1] We used the keywords: ’science’ AND ’technolog*’ Or ’innovat*’, and their intersection with ’international politic*’ and ’international relation*’ on abstract, titles and keywords. Then, further adjustments were made manually to select only relevant journals in respect to Political Science and International Relations according to SCIMAGO JOURNAL AND COUNTRY RANK

Table 1.1: Articles on innovation and technology published in major IR journals until April 2020

Top journals SCOPUS	Nº of publications	Top journals SCIMAGO	Nºof publications
Global Environmental Politics	22	American Journal of Political Science	1
International Studies Quartely	18	International Organization	2
Pacific Review	13	Quarterly Journal of Political Science	0
Mezhdunarodnye Protsessy	12	American Political Science Review	0
World Economy and International Relations	12	Political Analysis	1
Australian Journal Of International Affairs	11	International Security	7
International Studies Review	11	World Politics	5
Millennium Journal of International Studies	11	Journal of Conflict Resolution	0
Technology in Society	11	Journal of Peace Research	6
International Studies Perspectives	10	Western European Politics	0

Source: The articles were accessed via SCOPUS database in June 2020.

If the empirical acknowledgement has few attempts, the theoretical understanding of how technology and international politics are linked is even less. As Mayer et al. (2014) argues, ”the scope of IR’s academic interest neither matches the prominence of science and technology nor the extent to which they generate curiosity outside IR circles” (2014, p.15). A large literature was developed in IR categorizing the theoretical IR thinking and research (Hay, 2006), especially the book from Jackson (2016) ’The Conduct of Inquiry in International Relations’ that scrutinizes the philosophical wages into world politics discussion. Unfortunately, the complexity of the innovation and technology topics does not fit well on those categorizations. One explanation is the externalization of technology as a side effect of politics (Herrera, 2012). SIT is more endogenous to international politics than one can imagine. To be obvious, most of what we discuss today (weapons of mass destruction, international trade, climate change and so on) are tightly related because they are a permanent, constitutive part of the international idea.

A second explanation is a conceptual obstacle, where technology and innovation face rivalry against 'technological determinism' and 'social constructivism' (Mayer et al., 2014). The former is a more deterministic approach because it considers politics as a consequence of technology and expertise. Obviously, by removing all possible entrances of social practices, institutions and agency/structure, core elements for social sciences, it is rejected by a great part of IR scholars. Kalevi J. Holsti (apud Mayer et al. (2014), support the argument that technology and innovation have *any* effects on the development of Westphalian States or on the uprising of globalization waves. This is a single instance, but it represents how foundational scholars consider the discussion with more historical and consequential significance. On the other side, social constructivism acknowledges technology and innovation as a neutral tool that would be precisely to exercise power (an erroneous interpretation). Constructivism is followed by liberalism and realism, by "treating technologies as *Deus ex machina*[2](Herrera, 2012, p. 16)"

A third explanation is that SIT analyses are based on multiple causations, and IR academia are used to single causation (Weiss, 2005). Recapping a point discussed before, this topic is considered a social process, of course, but takes into account economic, cultural and technical factors. This falls into a high politicized context that often discusses the negotiation while, for example, global warming, starvation, fisheries stress and pollution of water are still on, and increases the rational calculation. This breaks down or delays the political discussion globally and takes away IR scholars that are not aware that technology does not end in itself. Securitization theory, which could be a prominently way to discuss technological change, eclipses the technological and material elements followed by an eternal social construction of reality based on discoursive conflict. Even if they have peculiar sectors of security (traditionally environment and economy, more recently energy and food) that require a fair weighting of material elements, it refuses to do so.

To sum up, scholars in IR have been criticised by the way theoretical traditions, named in a broad sense as Realism, Liberalism, English School, Constructivism and Poststructuralism, have a common ground by ignoring the technological world as a complex variable that should receive attention. It has recently raised some discussions of innovation diplomacy by identifying the factors that high-tech countries have on their side that allow collaboration and competition (Leijten, 2019). Or studies that address the traditional thought of science diplomacy (knowledge) as a 'soft power' element (Leijten, 2017), or even the idea of an international collaborative cluster of innovation (Hekkert et al., 2007; Binz & Truffer, 2017). However, since none of the authors are IR scholars, they produce exciting studies, but they still lack international power and politics components.

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[2] This is a Greek-Latin expression used in theatre contexts when a god come to solve the problem that originally was impossible to solve by humans. The same idea is applied to every situation in which someone's non-expected action changes the way.

The critics regarding the missing linkages between SIT and IR are long, but they were briefly described. But if one would search for decent works that scrutinized the topic, there are mainly two of those. The first one would be 'The elusive transformation: science, technology, and the evolution of international politics', which Skolnikoff (1994) access the interactions between technology and IR on a theoretical endeavour, followed by thematic chapters discussing the social factors that combined with technology lead to an evolutionary change. The approach rests on neorealism, based on self-help and balance of power, assuming the fact that technologies do influence the international system, but the preferences of States always remain the same. Even though there is a lack of discussion on how actually to change, based on the fact that Skolnikoff expects a 'global catastrophe' to change the foresee world order.

A second work would be 'The Global Politics of Science and Technology' by Mayer et al. (2014). Divided into two books, the first one introduces the idea of technology in IR by recognizing the difficulties of the discipline and offering some approaches for studying SIT from an IR perspective. This culminates in the conceptual framework of Techno-politics[3]. The second book offers a toolbox at first glance and tries to apply this concept to case studies. Different from Skolnikof, Mayer insists on a plural approach of the technology into IR theories pool. They care more about the material world and its constraints and the ideational and ontological issues important for IR theories. They drop into five main experimental approaches, such as (1) constructivist studies technology, (2) assemblage theories, (3) critical and subaltern approaches, (4) technological power, and (5) international techno-political economy.

The effort is still on, which is critical for developing a common understanding that SIT is inheritable a social process that has also to be carried on an international level. Notwithstanding, as one can notice, from 'SIT', only the S (stands for science) and T (stands for technology) are carried, even when discussing innovation diplomacy. The I (stands for innovation) is still underdeveloped. Under the 'international techno-political economy' approach, one can find suitable space for discussing innovation systems (this will be discussed later) that operate in a global system (Mayer et al., 2014). But it still lacks a theoretical endeavour to understand innovation activities and their linkage with world politics.

If, for SIT (especially innovation), IR discipline remains shy and shaded, for discussing sustainability transitions, this would be even more. There is a section (Section 1.2.1dedicated

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[3] "'Techno-politics' implies an understanding of science and technologies beyond the framework of social constructivism on the one hand, and technological determinism on the other. Neither are technologies simply byproducts or external to "social" relations, nor do sterile technologies merely determine social behaviour and political outcomes. Instead, the global politics of science and technology should be placed in a conceptual zone that enhances awareness of the complexity, contingency, hybridity, and dynamism present in the issue areas, research subjects, and empirical puzzles that are embedded in it" (Mayer et al., 2014, vol.2, p.2)

to explaining the scope of Sustainability Transitions Studies in this chapter, but right now, we can summarise the discussion by arguing that SIT can promote a sustainability transition that goes from the point where the society produces and consumes in detrimental ways for itself and future generations, to a point where it commits to the development of a society tied with environmental and social concerns(Markard et al., 2012). This idea requires a holistic understanding that innovation has a fundamental role in this process because it can turn our life more efficient, but at the same time, it will be impossible to disentangled politics, economy and society. Therefore, we go forward by arguing that, due to the international connectivity and interdependency, sustainability transition would only be possible to achieve if the cooperation among countries with this goal exists.

The difficulty to discuss a topic that is routinely carried by social sciences that is 'social change', can be supported by the fact that sustainability studies are connected to innovation. Herrera (2012) maybe was one of the first authors that, unintentionally, tried this linkage in his book 'Technology and international transformation: the railroad, the atom bomb, and the politics of technological change'. He pays attention to the fact that the international system (which is used not in a Realist sense) has historically evolved based on how technology was depleted in society. His perspective advances on the idea that innovations are political phenomena. He is aware that, besides understanding the influences, the process in which innovations are carried in the international level is more important. The given context and tendencies highlight the countries' investments for innovation and provide firms with the incentives to act within. Finally, he considers the socio-technical system by explaining that technology linked to international politics is a special kind of variable, which does not follow the common logic of actor and role being the same, or by the jargon, in an eternal mutual co-constitution of reality. Socio-technical systems are path-dependent, and when they lock possibilities, they unlock others.

This socio-technical change is connected somehow with Schumpeter's aphorism about creative destruction (this will be discussed later in the next section). A multipolar system provides incentives to increase the generation of innovations (Kennedy, 2010). This could be a more realist's argument connected to the historical warlike rivalries among kingdoms in the past and States nowadays, making actors seek improvements in the military sector. This meaning, if correct, would induce countries to invest in innovation solely because they want more power of destruction, linking a process of creation of knowledge to a process of highly defence concerns. However, the eminence of war similar to those in the XX Century does not exist, and institutions can somehow constrain actors and their economic interdependence (Edquist, 1997a; Keohane, 2005), So, what would drive more innovations could be linked to the fact that wealth and economic growth can be made through this process. Because science aware people and society that our current habits facing the environment are not sustainable, or as a way to offer something that makes someone's life easier (Leijten, 2017).

As one may notice, this first section is a disclaimer that presents some arguments that IR does not take into account SIT as an endogenous and scrutinized issue. This is one of our endeavours. Innovation occurs in the international and is pervaded by politics, not only economics. Also, as we argued, IR lacks theoretical formulations dealing with SIT and requires contributions from disciplines that originally, or in larger time, deal with this manner. The idea of technological change and technological paradigms (Rip & Kemp, 1998; Dosi, 1982) are central discussions that drive the efforts made by entrepreneurs, firms and the market, but also by institutions and political actors. They are together in a system that can engage sustainable transitions. The proposed theoretical approach, which will be forwardly described, is formed by different approaches. It brings complexity, but at the same time, the studies on sustainable transitions are quite new, even more for both Economics and International Relations (Köhler et al., 2019; Criekemans, 2018; Drezner, 2019; Kemp et al., 2007; Hekkert et al., 2007).

1.2 Innovation studies and innovation systems

This section presents important definitions of Innovation Studies and how they were incorporated into the Sustainability Transition Studies. In the first subsection, we discuss core concepts such as invention, innovation, inventor, knowledge and diffusion, systems of innovation and technological change. In the second subsection, we define Transition Studies, such as the levels of a transition, interaction of actors and motivations to transit.

Innovation is not a new phenomenon. It is actually something that happens in society since remote times and allows it to move forward, thinking different, experiencing something, and providing to humankind more comfort and more efficient labour. This was also what Joseph Schumpeter thought. This study will be incomplete if it does not mention the crucial contributions or, more precisely, his seminal works. It is possible to affirm that it was one of the most structured and original approaches to study the entangled relation between long-term economic and social change by focusing on the crucial role of innovation and what surrounds it. From the traditional neoclassical strand of economics, which focuses on equilibrium and static models, he moved and further influenced scholars to look at a more progressive and entrepreneurial form to mobilize resources to create change by entrepreneurs and take place in a historical time. Schumpeter died around his 67 years (1883-1950), leaving a legacy on Economic Studies that is found at the baseline of our forward approaches in IS and STS, and eventually, his much interest in innovation either as a process of creative destruction (aka Schumpeter Mark I, or the process of ’widening’) or a creative accumulation (aka Schumpeter Mark II, or the process of deepening)(Breschi et al., 2000).

Innovation Studies is a branch of Economics and, for our purposes, we take the approach from Evolutionary Economics (Freeman, 1989; Nelson & Winter, 1977), but as it will be noticed, claims for multidisciplinary field research. One can argue that the field started to emerge by the 1960s based on the works of Joseph Schumpeter in the USA, where he stayed on working at Harvard University until his death. There are countless contributions during this early period, but more focused on technology, and less on the innovation as a broad sense, and many prominent scholars to innovation literature were there[4](Fagerberg & Verspagen, 2009). Also, at the same time in Europe, the Science Policy Research Unit (SPRU) was formed in 1965 at the University of Sussex, and it was one of the greatest contributions to develop studies that can address economic and social change. Originally they were based on a cross-disciplinary orientation. Christopher Freeman, one of the greatest contributors to the idea of innovation systems later, was responsible for diffusing this new field of research across Europe.

On the economic approach, it is possible to argue that knowledge and technology are considered a phenomenon of passive adjustment to economic pressure mediated by markets and factor prices (Rosenberg, 1976). Rosenberg (1976) made advances in this idea, arguing that also social structures and cognitive skills drive innovation. Likewise, the understanding from Edquist (1997a) that formal institutions have important effects in the innovation process, recognizes, based on a common sociological understanding of institutions[5], that they often determine the possible paths that an innovation process can follow. Certainly, as Freeman (1987); Lundvall & Dosi (1988) noticed, they have a huge impact on the formulation of an innovation system and how knowledge and technology are depleted in the market. Thus, from the very beginning, innovation activity is understood as an activity of thinking the world differently and creating spaces for structural change in reality (Dosi, 1982).

Since then, innovation studies have kept expanding and constantly receive influences from other disciplines such as geography (Binz et al., 2014), sociology (Rogers, 2010, originally from 1962), history (Bijker et al., 1987), and political sciences (Dyer & Page, 1988). But regarding the latter, since innovation studies started in economics, scholars often take power and politics or as an exogenous factor or ignore how power and politics shape and drive the development of innovations. But also, on the political science side, few studies connecting innovation and politics has been done. This is a little intriguing because innovation, as mentioned before, constantly deals with structural changes, which also is a core topic for political

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[4] Hounshell (2000) acknowledge an extended account of US contributors

[5] In a broad sense, institutions can be put simply like sets of common habits, routines, established practices, rules, or laws that regulate the relations and interactions between individuals and groups.

scientists (Raven et al., 2016). Some of the explanations for this problem are described as: a difficulty to understand the lobby and actors' social and political interests in this manner (Meadowcroft, 2009); and maybe the difficulty to understand the emergence of innovation and their diffusion, and the bargain involved in this process (Raven et al., 2016). In a more comprehensive context, the innovation process will be slow and controversial, allowing actors to build resistance against change through time by using different strategies to counter-claim, such as mobilizing society, reducing investments, and creating barriers to diffusion. Hence, innovation studies still require more scholars to think about it from a different perspective, and one of the contributions of this study is to offer some pieces of evidence of political factors that could contribute to understanding the process. Even though the level of analysis will be international, which emphasize even more the lack of contributions to this field of study. International relations still lack internal logic regarding theories, factors, and methodologies to scrutinise much more systematically (Mayer et al., 2014).

To begin this endeavour, it will be necessary, from now on, to present and discuss core definitions for IS that touch upon our inquiry. In the Introductory chapter, we differentiated between innovation and invention, but we should shortly recap their meanings to make a logical presentation. Inventions can be simply put as the generation of ideas for new products or processes (Fagerberg, 2004), while innovation requires the effort to transform the ideas by coupling all the necessary factors into something for the market to commercialize (Lundvall & Dosi, 1988). In our perspective, this would be something meaningful for society, and our goal is a sustainability transition that incorporates innovations. Sometimes invention and innovation are closely tied, but in general, there is a considerable time lag between the two, going from years to decades. This happens because inventions are, in short, different ideas that can be carried out by institutions such as research centres, R&D departments in firms and institutions of education. Everyone can come up with an idea, randomly and detached from material efforts, but to transform it into innovation, it would require new combinations of different types of knowledge, skills, and other factors to be introduced on the market and to make sense for the society (Fagerberg, 2018; Malerba, 2002).

Also, it is important to notice that innovations are sometimes bond into a path-dependency relation, which means it is a continuous process where innovations from the past opened up circumstances for the following ones (Fagerberg, 2004). The right way to conceive an innovation is understanding that it is a heterogeneous thing and only by the accumulation of some knowledge over time, something was possible to be depleted on the market and society. A single innovation can be a result of interconnected innovations that in the past were not possible to be assembled, but with some effort and constant persistence, one was able to overcome the threshold. As mentioned before, this process, according to Schumpeter

(1934), can happen in many different ways. It can be technological and organizational, in different sizes and extensions vary from radical (creative destruction - Schumpeter Mark I - widening) to incremental ones (creative accumulation - Schumpeter Mark II - deepening). Schumpeter Mark II is commonly characterised as an accumulation of the prevalence of the current technological paradigm[6], Schumpeter Mark I is often characterised by a disruption in the technological paradigm, with the new entry of firms and entrepreneurs filled with new innovations[7] that were not seen before. Technological change and further structural changes can occur following both patterns of innovation. Our focus here is on the Schumpeter Mark I since we are dealing with radical changes.

Any type of innovation, incremental or radical, occur within a technological regime, as first pointed out by Nelson & Winter (1982), where firms in a certain sector reflect on their routines how things are actually done. Some critiques have been applied on this idea, accused of providing a lock-in view on the development of the market and a deterministic view of technological and social changes. Later, Rip & Kemp (1998) were responsible for updating the concept of technological change by also addressing sustainability factors, where this regime (or paradigm as they originally argued) becomes outdated and have to be replaced by a new one. This will occur because of radical innovations that challenge this old paradigm and gradually replace it. This also happens because of a complex interaction between the different levels of an innovation process. They introduced the idea of micro, meso and macro levels of analysis, regarding micro as niches where innovations are done, and they have to be protected. Otherwise, they will suffer a lot with the market selection; meso as the institutions that govern and drive innovation, and; macro as externalities or as factors that actually are often difficult to control or predict their occurrence (idem). Technological change can occur only by understanding how those factors work closely to create a window of opportunity for radical innovation fulfilment.

Incremental innovations are also important, but there is some consensus to which extent one can consider them. Radical innovations are at the core of innovation studies. Some studies want to predict their occurrences (Arts et al., 2013) other would like to trace the process (Geels, 2011), other will identify the effects of its entry into the market, society, firms, institutions, etc. Radical innovations can occur under many labels, such as ’discontinuous’, ’disruptive’, ’breakthrough, ’revolutionary’ and so on, which gives another complication regarding the fact that the literature often refers, with different labels similar process on the

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[6] By technological paradigm, Dosi (1982) argues that it consists of a set of specific models, patterns and institutions and other elements that are embedded in such a technological process that constantly influences the direction of innovative activity and diffusion.

[7] A redundancy can be noticed when using the term ’new innovations’, but this uses may allows a understanding of innovations sometimes more advanced than those that we currently see. Something perhaps disruptive.

bundle of Schumpeter Mark I (Kovacs et al., 2019). There is no convergent and coherent definition, which makes difficult to identify in the reality if a single technology can rather be radical or incremental because the terminology is still unclear. It is quite common to measure innovation based on patent data and bibliometric analysis to identify the common characteristics of the radical labelled one. Depending on the scientific field, radical innovations are studied and defined in a very distinct way (Gopalakrishnan & Damanpour, 1997).

But the theoretical differentiation of those terminologies is important to understand the radical character of renewable energy technologies. We make a short distinction between some of these terminologies. Radical innovations have a transformative characteristic because the novel ideas introduce a drastic change in the current regime. New legislation, infrastructure, and other elements can be impacted by the innovation and will suffer some modifications. Some scholars identify the openness of a new trajectory and the following consequences from this impact (Dosi, 1982). Others would identify the combinations of existing technologies and new technologies in the creation of something (Story et al., 2011). Discontinuous technology often brings the idea of a brake on the current path. It changes how the market, society, and users handle a technology by introducing a substitute. The revenues for firms and the benefits for the society are unknown at the first moment, which requires a time factor to evaluate their impact (Kassicieh et al., 2002). Disruptive innovations, in fact, have no radical component. They are a renovation or updating of current technologies to fulfil customers' needs better. Somehow, this would be identified as a disruption of an existing trajectory (Christensen, 2013). Finally, breakthrough innovations or inventions (in this case is also possible) would be quite a few because they do not offer marginal improvement, but actually, they discover and create new opportunities and have a large impact on technology, market and society (Arts & Veugelers, 2015).

Some common elements are stressed, and all definitions are incumbent, such as novelty and impact elements. For the former, radical innovations definitely require something original regarding its contemporary time, something that no one has done before. It does not matter if the result will be based on an update, a combination or something really new (very rare). For the latter, the impact has to be weighted as something that reaches different spaces and provokes structural changes. Our objective here is not to propose a new definition but to present the foundations of this discussion that could compromise the audience's understanding that might have contact with some of these ideas before. As a form to wrap up the discussion and avoid further misunderstanding, all the possible terminologies are taken as radical innovations. This is so because, at the heart of RET, based on the fact that society still largely uses fossil fuels, they are possible to be addressed as radical innovations disregarding the multiple terminologies (Mazzucato, 2015; Rogge et al., 2015;

Fagerberg, 2018; Rip & Kemp, 1998). Despite the fact that radical innovations are uncertain and with a high risk, they demand a lot support to still exist and evolve through time. And they require 'mission-oriented policies' (Mazzucato, 2013) to avoid the traps that a potential novelty could fall. Those traps are related to the impossibility to move forward the sprouting phase because the market and society already sentenced it to nonexistence. Therefore, policymakers would have to design policies, and political actors would have to be really active, and both public and private sectors finance the project and get the revenues.

As became evident from the preceding discussions, innovation has a systemic nature, which certainly is one of the most important concepts for the process in an interconnected context. It would be more difficult to innovate if inventors and innovators do not have access to external sources. Thus, it is a collective achievement (Freeman, 1987). Innovation system - IS (or elsewhere system of innovation - SI) is a generic terminology that can come up with radical novelties or the accumulation of small and non-contradictory technologies. For our purposes, a good definition is provided by Edquist: "all important economic, social, political, organizational, institutional and other factors that influence the development, diffusion and use of innovations" (2010, p. 182). Agents are linking each other in this system and forming a network. Intentionally or unintentionally, general or peculiar creation of technologies are the main outputs of the system. But the innovation itself is a part of the process and is attached to the constraints and contradictions of the system (Markard & Truffer, 2008) and could be a challenge to consider whether an innovation is part of the system.

Edquist (2010) scrutinized in a coherent way the key characteristics and structures that are often present in a system. He argues that the system of innovation is constituted of its components and the type of relationship among them. Organization and institutions are the main components. Organizations are material structures made with an explicit purpose, represented by actors, firms, research centres, universities and others. The institutions would be traditionally defined as commonly established practices, routines and regulations that define the type of interactions between individuals, groups and organizations. Finally, the function of a SI would be the pursuit of innovation processes. In every type of SI approach, holistic and interdisciplinary content is determinant because the main goal is to identify different elements and variables that help someone comprehend the phenomenon. They carry more for an evolutionary perspective which requires a time frame analysis of its expansion or retraction, level of importance of some units and their strong or weak tie. Since the process of innovation is contradictory and often requires the surrounding sources or embedded in an environment that offers stimulus, it is non-linear, and capturing this dynamic demands analytical effort. Finally, the SI approach reaffirms the role of institutions rather than assuming their exogenous determinants on the innovation process. In turn, they can enable or disable actions and processes.

There are some possible ways to seek an inquiry using the systemic approach. The distinction between the elements that formulate the system and their boundaries are crucial to address a coherent analysis. The National System of Innovation (NSI) (Lundvall, 1992; Freeman, 1989) would be a classic possibility. It allows scholars to dive deep into the dynamics of national actors to build the framework or the network and their inner interaction. A different approach would be the Sectoral Innovation System (SSI), which considers a specific industrial sector (Malerba, 2002). Or elsewhere, the Regional System of Innovation (RSI) could be a less broad approach compared to national because it considers regions inside the country (Cooke et al., 1996; Howells, 1999). Likewise, the Technological Innovation System (TIS) reveals the system that develops around a single technology but does not necessarily respect regional or national borders (Carlsson et al., 2002; Bergek et al., 2008a).

These analytical possibilities are quite popularized among innovation scholars. But our focus is on those which could present prominent contributions to the analysis of sustainability transitions. This means studying the structural changes that innovations, technologies and knowledge have on society. The key contribution of innovation system analyses to the study of sustainability transitions is, we argue, that it provides policymakers with a tool for identifying system weaknesses. In other words, uncover the characteristics and structures of the system that promote or barrier the development of a change. Considering the options, the TIS approach seems to contribute in this manner, and it will be discussed later in this chapter. For now, we should move for a discussion about the field of transition studies and their core concepts and discussions.

1.2.1 Sustainability Transition Studies

According to Markard et al. (2012), it is possible to grasp the roots of transition studies[8] with some promising ideas by the end of XX and beginning of the XXI Centuries. The concepts of technological paradigm and technological regimes (Dosi, 1982; Nelson & Winter, 1977), systems of innovation (Freeman, 1987; Edquist, 1997b), multi-level perspective (Geels, 2002; Rip & Kemp, 1998), transition management (Rotmans et al., 2001), sociology of technology (Bijker et al., 1987) and technological systems (Carlsson & Stankiewicz, 1991; Bergek et al., 2008a; Hekkert et al., 2007) are taken as important pillars because they often refer to the idea of a technological change based on economic and societal elements. By repeating the same steps as Markard et al. (2012) and performing a fast bibliometric analysis on SCOPUS Elsevier, we found out that the field count with 5,417 publications, with an important

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[8] There are lots of possible terminologies, but the field is commonly nominated as Sustainability Transition Studies, sustainable transitions research or transition studies

growth around 2004 to 2005, which makes the field of research really new if compared to old disciplines like economics, sociology or law. The Sustainable Transitions Research Network (STRN), funded in 2009, is a digital network to connect scholars and stimulate knowledge exchange, which also launched the most important journal for scientific publication, the *Environmental Innovation and Societal Transitions* factor of 7.514 in 2020. Although the area is still under development, it has already shown some strong contributions in science, and at the same time, fostering decision-makers based on this urgent knowledge (Fagerberg, 2018; Köhler et al., 2019; Avelino & Wittmayer, 2016).

Kemp (1994) and Rip & Kemp (1998) were one of the first dealing with technological changes (with a broader understanding of technological regime shift and transitions), then, there has been a rise of interest in innovation policy employing concepts such as transformative innovation policy (Steward, 2012), eco-innovation (Kemp et al., 2007), mission-oriented policy (Mazzucato, 2015) or policy mix concept (Rogge et al., 2015) as a way to promote social-technical changes regarding environmental goals. But the difficulty is found when States need to find an equilibrium between economic growth and environmental degradation. More precise, it deals with the idea to generate economic growth with less and less damage to the world that we live, and move to an economy where the environment will actually be taken into account as our primary goal to defend (Smith et al., 2010).

STS absorbed innovation studies because it is concerned with incorporating new ideas in the market and society. But transition studies advances by arguing that innovations, as a process, should comprise societal challenges at its core (Köhler et al., 2019). Considering the resources depletion (clean water, oil, forests, energy resources and food stock), loss of biodiversity and climate change as common problems of the XXI century, under this perspective, these problems cannot be addressed by incremental improvements and technological fixes (Mazzucato, 2015; Rip & Kemp, 1998; Markard et al., 2012). Traditional technologies in respect to electricity access, means of transportation or sanitary are intertwined with the lifestyle of a certain society and their institutional peculiarities such as regulation, politics, business models and others (Rip & Kemp, 1998). Energy supply, water supply and transportation are taken as *socio-technical systems*. Those systems are formed by a network of actors (e.g. individuals, firms and collective actors), institutions (e.g. societal and technical norms, regulations and practices), material artefacts, and knowledge (Rip & Kemp, 1998; Geels, 2002). These elements interact so that they provide specific outputs for society, and some are really tight on each other that they tend to be dependent on the prevailing of the network/system.

This complex relation requires a more comprehensive and holistic approach. Because transition studies have to pay attention to people's interaction with the technologies surrounding them and their impacts in the world (society, economy, politics and environment) (Köhler et al., 2019; Smith et al., 2010; Avelino & Rotmans, 2009), so, ”a central aim of transitions research is to conceptualize and explain how radical changes can occur in the way societal functions are fulfilled” (Köhler et al., 2019, p.3). So, the mission of sustainability transition, aside from the general scientific contributions, is to offer tools, data and models for decision-makers to stimulate sustainable transformations in society that has technology as one of the main means of ”doing things”. But at the same time, the initiatives and policies are analyzed in a sense to serve as a follow up for policymakers and create social pressure (Markard et al., 2012). It is still problematic to talk about a sustainability transition because it is clearly subject to self-interpretation and may change over time. So, to avoid an over-explanation, our meaning of sustainability or sustainable lays on our perspective argued until now.

Conceptually, exists a separation of level of analysis in micro (niche), meso and macro. Each level is composed of its own dynamics meaning that the micro-level stresses the creation of knowledge and technology, the presence of controlled and protected niches of innovation. At this level, inventions happen quite often, and sometimes they fulfil or are rapidly discarded. It can be seen as an analysis of the routine of a firm to direct its R&D budget (Nelson & Winter, 1977), or the work solo of a research centre to provide rapid answers for the market (Geels, 2011). The meso-level stresses the interaction between private and public actors around the creation and diffusion of technology under certain institutional constellations (Köhler et al., 2019). The macro-level could be described as the externalities or the events and factors out of control that can drastically change the path toward a new innovation (Smith et al., 2010)l[9]. The majority of approaches on Sustainability Transition are concentrated at the meso-level because the focus is on the interaction of technologies and society (Köhler et al., 2019; Markard et al., 2012), but it is impossible to avoid spillovers into or from micro and macro-levels. This makes the field conjugates several characteristics and paradigms that stress this complex relation:

- Multi-dimensionality and co-evolution;
- Multi-actor process;
- Stability and change;
- Long-term process;

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[9] It is important to understand the distinction of STS levels when comparing with IR levels of analysis because they often are not the same because the dynamics are different. However, they can be adjusted to fit one another by emphasizing the similarities of their range of explanation. This will be discussed later

- Open-endedness and uncertainty;
- Values, contestations and disagreement;
- Normative directionality[10].

First, multi-dimensionality and co-evolution, and Multi-actor process are connected so that socio-technical systems consist of multiple elements and actors, as already mentioned before, and all of them play a force in a non-linear and interdependent process. Second, stability and change, and long-term processes are core issues in transition research because changes are taken as a long process that can take decades to unfold, but that constantly faces the force of the stability of incumbent actors and path dependence. Thus, analyse a transition requires the division of phases and an inner dialectic focus. Third, open-endedness and uncertainty are in respect to the multiple pathways to pursue and the prismatic uncertainty, for instance in national plans or lack of resources, also a social acceptance that could drawback in an unknown point. Fourth, Values, contestation and disagreement, and normative directionality consider the legitimation struggles that such a transformation can bring, for example, the current business model of powerful but 'dirty' industries and their lobby on the legislative process that shocks with embedded sustainable values. Or even the absence of regulations, standards or innovation policies that can cause free-rider problems or even users without support (Köhler et al., 2019).

With this brief introduction about transition studies, we can now present the main conceptual approaches to design a study. There are 4 prominent theoretical frameworks in the field of sustainability transition studies:

1. Multi-Level Perspective (MLP): the foundations combine evolutionary economics, sociology of innovation and institutional theory. The transition comes based on three main levels micro (niches), meso (socio-technical regime), and macro (socio-technical landscapes). Transitions happen by the interactions between the levels that eventually opens a window of opportunity where the change can occur (Geels, 2002; Rip & Kemp, 1998).
2. Strategic Niche Management (SNM): combines ideas from the sociology of innovation and evolutionary economics, but with the premise that innovation often happens in protected and special spaces that constantly avoid the market selection or social legitimation. The study focus on the demonstration of projects that, according to their high

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[10] For a detailed explanation on how all of these elements can be mobilized in a transdisciplinary transition study, please read: Köhler et al. 2019

quality, promote a good trajectory and social networks (Geels & Raven, 2006; Schot & Geels, 2008).

3. Transition Management (TM): a combination of complexity science and governance studies. It has a character more prescriptive, and policymakers can shape transitional processes by four sequential steps: Strategic activities, Tactical activities, Operational activities, Reflexive activities (Loorbach, 2010; Rotmans et al., 2001).

4. Technological Innovation Systems (TIS): mobilizes ideas from innovation systems theory and industrial economics, which means that a system is made of technologies, actors and institutions. The focus is more on the emergence of novelties and the diffusion of knowledge between entities of a network (Hekkert et al., 2007; Bergek et al., 2008b; Negro et al., 2012; Markard et al., 2015). This approach is adequated for this study and will be discussed later.

MLP was on the foundation of the Sustainability Transitions field, so commonly happens some confusion between the levels of a socio-technical system and the MLP levels. To make sure about the definition of socio-technical system, one of the common problems scholars have, is to identify its extensions in terms of technology, boundaries and levels. Once again, the socio-technical system is an analytical tool based on the material factors (technologies, agents and organizations) and the relations among them (knowledge flow, investments, and social relations). It can be observed in several levels and sublevels, but it is more about the research design than solely material elements.

To embody a transition, the process must be a radical shift in Schumpeterian terms of creative destruction. Commonly, scholars of Sustainability Transitions understand this process related to high levels of aggregation, including changes of structural and institutional conditions under which emerging innovations can be up-scaled in a given context (Loorbach, 2010; Rotmans et al., 2001), the struggle for power, disruption and reshape of the current regime (Avelino & Rotmans, 2009), the building of a new system (Musiolik et al., 2018), an active role of the private and public sectors to support green technologies and innovations (Mazzucato, 2013, 2015), an innovation system oriented to diffuse a new innovation or technology (Hekkert & Negro, 2009; Markard et al., 2015), and many other possible characteristics. In the first studies, the focus was on some sectors of the economy (e.g. energy, water, food, mobility and agriculture) and the impact of novelties in some national borders. These were some of the contributions of TM (Loorbach, 2010; Kern & Howlett, 2009), but they also open up some space for governance and policy context analysis. Recent studies have broadened the focus on societal systems, regions, and international connections, acknowledging the interaction between human and non-human aspects. But for the side of a truly international perspective that considers the spatial and geographical interconnectivity of the actors, there has been not enough (Bento & Fontes, 2015; Bergek et al., 2015).

MLP has been mobilized quite often to design inquiries (Geels, 2002; Sovacool, 2011; Geels et al., 2017; Smith et al., 2010). These studies are more concerned with some sociological understanding of variation-selection-retention mechanisms behind technological change. Based on the three levels already mentioned, they try to understand the relations of agents to produce innovations through standardised and preexisting levels and functions. It is also referred to as socio-technical change where technologies play an important role within the society and in the other way around. But at the same time, it disregards the logic of action and its performativity (Labussière & Nadaï, 2018), which is a great weakness, if considered the goal to understand causations of such a process that goes overtime. Also, they never get into the so-called landscape or regime based on the international connection but stays at the same level of lock-in between national institutions and innovators. Since the theory proposes a more holistic view, when it intends to propose an international perspective, it forgets the international phenomena (Labussière & Nadaï, 2018; Markard et al., 2015). After some critics (Geels, 2011), the MLP remains with some core ideas, such as the relationship between the levels but moving away from a trajectory and lock-in, and embodying a relational approach that takes into account functions of actors and their influences through time. Also, technology itself is no longer a 'tool'. Instead, it is taken into account the assemblage of different elements such as public and private sectors, universities, institutions and organizations, and users, for example, considering in each one the agents or actors capable of interfering in the dynamic process (Labussière & Nadaï, 2018).

For the SNM approach, the research became a micro-level approach focused exclusively on the protected and specific market spaces and how they, in a bottom-up process, grow, stabilize or decline within the socio-technical regime. There have been some studies to highlight the transnationality of those niches (Wieczorek et al., 2015), but it still lacks a conceptualization on how international niches made up with national niches within controlled markets. The TIS perspective Carlsson & Stankiewicz (1991) argues that it already has a global scope in its original conceptualisation due to its absence of a geographical limit. But it is still unclear about the conditions for actor access in a multi-scalar phenomenon.

Eventually, the approaches of Transition Studies remain with some problems in respect to their global perspective. Coenen et al. (2012) argues that mainly TIS and MLP, which would be analytically dominant in the field, have some naive conceptualizations, but if compared to the others, both are improving relatively fast. The process of maturation of the field requires better incorporation of the international politics and level of analysis (in IR sense) and its dynamics. Some scholars have pointed out some contributions on the global nature of innovation ideas (Wieczorek et al., 2015; Binz & Truffer, 2017) or even how to merge socio-technical regimes at a global level scale (Fuenfschilling & Binz, 2018), but more can be done. So, one of the contributions of this study is to bring the international level (embodied in the IR discipline) to contribute to the sustainable transition discussions, mainly for two reasons. The first one is the already mentioned miss-conceptualization of the international level in transition studies. The second one is to incorporate international politics in the field. This is necessary because transitions have a global perspective, (Binz & Truffer, 2017; Binz et al., 2014; Carlsson et al., 2002), but the context where it happens is not only under the controlled space of a State it is also international, which makes the rules of the game to change (Edquist, 1997a) and contextual international politics can redirect the process.

1.2.2 Politics and power in transition studies

In the last sections, we affirmed that STS is rooted in Economics/Innovation Studies. However, since our approach is to take technological change as a socio-technical change process regarding the existence of actors with different opinions and individual goals, transition studies became an inherently political process. Therefore, it must be invoked political science and its central discussion about power and politics. The influences that a transition makes in a society is not only around what type of technology is in or out. It is about the reflections that a system of technologies interacting with society and scaling up. Consequently, this provides the generation of new systems of technologies that pressure again for a further step (Avelino & Rotmans, 2009).

So, to cover this gap, scholars in innovation and transition studies decided to look beyond the analysis of public policies and provide more systematically thoughts about political processes and how they can model policy outcomes, (Köhler et al., 2019). From the field of political science came up lots of contributions (Kern & Rogge, 2018; Kern, 2015a, for a overview), namely advocacy coalition framework (Geels & Penna, 2015), discourse coalition (Kern, 2011), technological legitimation (Bergek et al., 2008b; Binz et al., 2016), system building (Hess, 2014; Musiolik et al., 2012) as some examples to mention. Each approach has its peculiarities, and the choice between which one to use is part of the research focus. Unfortunately, they sometimes pay less attention to the political outcomes (negotiations, motivations and interests) and more to the policy outputs (policy instruments) (Köhler et al., 2019). The argument is based on the insights that technological change actually has some effects on the political interests of the actors (Markard et al., 2016). If a technology that is truly meaningful for the use of society come into play, it can lead to some institutional modifications, mainly changing the way agents interact with each other (Edquist, 1997a).

In turn, institutions have a decisive role in shaping opportunities for new entrants in the socio-technical system and how they will perform their entrepreneurial activities (idem).

The concept of policy mix proposed by Rogge & Reichardt (2015) has some contributions to transition studies that could help overcome the narrowed vision of political processes. The definition of policy mix is simple: "a combination of several policy instruments" (Rogge & Reichardt, 2015, p.3). But at the same time, they recognize that to grasp what happens in the real world of the technological transitions, more attention has to be given to the process of formation of such a policy instrument and politics (Kern & Rogge, 2018; Reichardt et al., 2016; Rogge et al., 2015). According to (Rogge & Reichardt, 2016) and in order to offer a good contribution of the policy mix for Transition Studies, it is necessary to bring into the analysis three basic requirements:

- Capture the complexity by identifying the characteristics of the object under investigation (Flanagan et al., 2011).
- Incorporation of the policy process. This includes the identification of social actors and their interactions with the societal problem (Edmondson et al., 2019).
- Consider the strategic component. Transitions happen with a long-time horizon in a non-linear sequence of events (Markard et al., 2012).

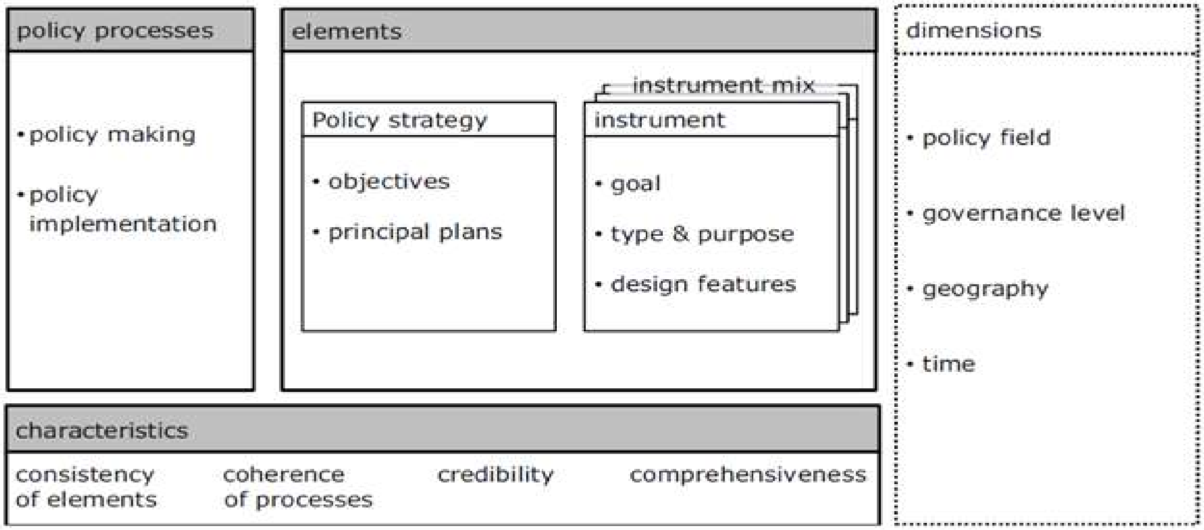
Every policy mix is formed by three building blocks: elements, policy processes and characteristics. Each one of them also has components that offer a comprehension of the political process for sustainable transitions. Figure1.1 summarizes it.

Hence, we follow Rogge et al. (2015) in their definition of policy mix focusing on sustainability transitions as:

> Para um espaçamento simples (...) we define the policy mix as a combination of the three building blocks elements, processes and characteristics, which can be specified using different dimensions. Elements comprise the (I) policy strategy with its objectives and principal plans for achieving them and (II) the instrument mix with its interacting policy instruments. The content of these elements is an outcome of policymaking processes. Both elements and processes can be described by their characteristics, including the consistency of elements, the coherence of processes, credibility and comprehensiveness. Finally, the policy mix can be delineated by several dimensions, including policy field, governance level, geography, sector, technology, value chain position, innovation phase, actor and time. (Rogge & Reichardt, 2015, p.9)

Who and how one supports research activities is a natural discussion in innovation studies. Because the track where the low carbon technologies will go through depends deeply on

Figure 1.1: Building blocks of policy mix for sustainable transition



Source: (Rogge & Reichardt, 2016, p. 1629)

the incentives via public programs and projects, and entrepreneurial activities (Rogge et al., 2015; Flanagan et al., 2011). Policy mix in the RE innovation process has a double effect, according to Graf & Kalthaus (2018), they support research activity and also support more international cooperation. Most important to the last point, countries already embed in international collaboration networks can strengthen their connectivity.

The policies can be technology push, demand-pull or even systemic. Technology push is motivated by externalities in economic terms or technological spillovers that lead to underinvestments in RD&D, such as subsidies for both public and private sides (Haščič & Migotto, 2015; Cantner et al., 2016), and these investments could be national or even international. They can come as regulations such as Intellectual Property Rights (IPR) and technology transfer. Or, in a general way, they can come as investments in education, science and technology and their exchange. Demand-pull increases demand by creating niches or new technologies. From an economic perspective, it attracts new actors to the innovation process and benefits from economies of scale (Kemp et al., 2007). Feed-in-tariff is an example of this. From a political perspective, this could be an answer to the current political, social missions and needs (Kyoto Protocol and Paris Agreement compromises, or IPCC awareness), and also a motive to promote more cooperation in the micro-level (science niche) or at the state level (reinforce the demand for more environmentally friendly technologies) (Rogge & Reichardt, 2016). Last but not least, systemic policies can come as infrastructure provisions or cooperative RD&D grants, for example. Also, they can be seen as regulations in the market or environmental and energy laws. They are also policies to promote thematic debates, cooperation programs and the formation of clusters (Rogge & Reichardt, 2016; Wieczorek &

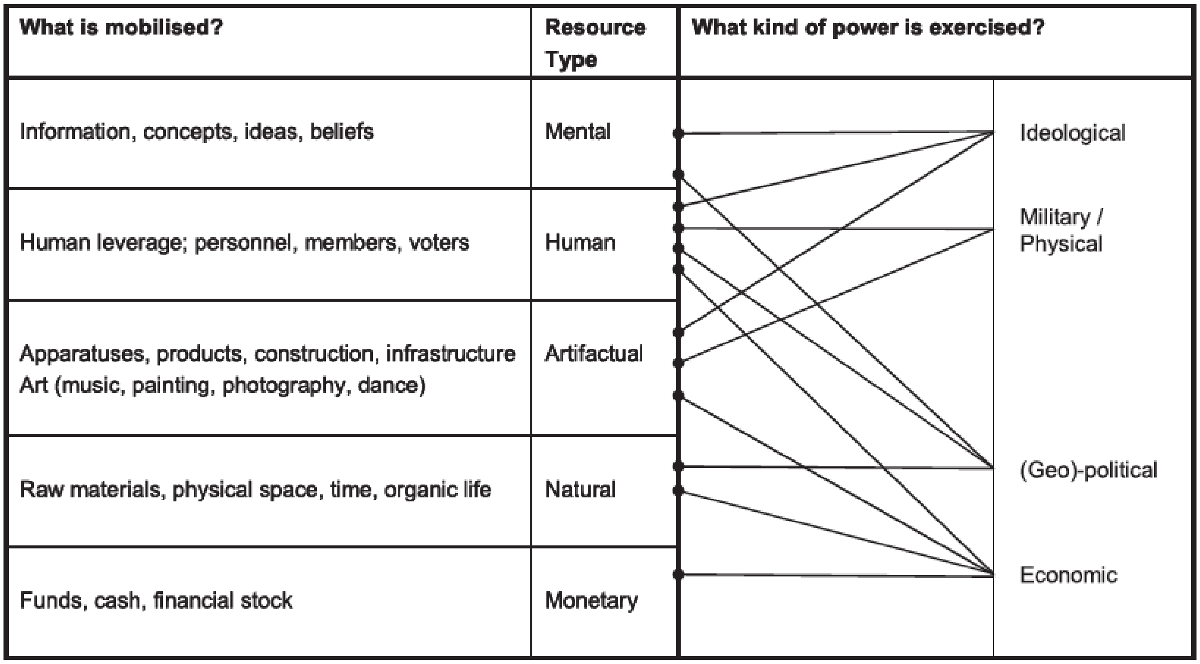
Hekkert, 2012).

In every sense, policy mix is about the coordination of random and separated actors and institutions in the convergence of the same mission, in this case, a sustainable transition (Rogge & Reichardt, 2016). This coordination can also be understood as a collection of available resources or creation of them and their use to something meaningful, in our case, for transitions. Transitions are unprecedented and complex, and at the same time, requires speed due to the negative effects of climate change. On the one hand, they need to provide information for policymakers to destabilise the existing configuration as fast as possible and speed up the transitions. At first glance, this seems to be simple because, since this will be a common will, they would not face resistance. But, on the other hand, the complexity of this situation starts when the actors and institutions engaged in the political process for change are alongside the resistant and opposite policies. This could bring two results: (I) in order to produce a transition, the political endeavours in favour of sustainable missions are limited by the material and ideational forces, or; (II) this complex combination can produce unintended or undesirable effects (Rogge & Reichardt, 2016; Edmondson et al., 2019).

In this situation, the variable power seems to have good contributions to the development of this theoretical framework. Taking this as an important reflection, what makes technologies come up is the disposition of resources to pressure a system and provoke a transition. Beyond that, it is about to provoke changes that require sources of power, the exercise of it and how they actually mobilize the elements in the network to disrupt the current system. Köhler et al. (2019) stresses that transitions are inherently political processes, there will be winners and losers, and actors will disagree considering the directions of transitions, the means, and the strategies. Our meaning of power is rooted in the idea that power is not possessed by someone, or ”generated in and through the reproduction of structures of domination” (Giddens, 1984, p. 258). And even with similarity with the Parsonian approach, a system mobilizes resources to fulfil certain altruistic goals (Parsons, 1963), since the transition is a process full of different and perhaps contradictory objectives and opinions, the actors involved often do not think similarly. Time is an important variable in the analysis, and our understanding of power has to take into account the long-term dynamics.

Power is defined in the current study as: ”The capacity to mobilize resources is ‘owned’ in the sense that one can ‘have’ this capacity and ‘own’ resources and it is exercised in terms of actually mobilizing resources (Avelino & Rotmans, 2009, p.550)”. To discuss power, we focus on some elements regarding transition studies: the resources; the mobilization of the resources; the exercise of power, and; the cause/consequences of this process. Beginning with resources, as a classical approach, it can be broadly defined as ”persons, assets, material or capital, including human, mental, monetary, artefactual and natural resources” (Avelino &

Figure 1.2: Typology of resource mobilization power



What is mobilised?	Resource Type
Information, concepts, ideas, beliefs	Mental
Human leverage; personnel, members, voters	Human
Apparatuses, products, construction, infrastructure Art (music, painting, photography, dance)	Artifactual
Raw materials, physical space, time, organic life	Natural
Funds, cash, financial stock	Monetary

Source: (Avelino, 2017)

Rotmans, 2009, p.551). There is no hierarchy between the resources, and all of them can be mobilized according to the needs, interests, objectives or shared conceptions and ideologies of the agents. However, which resource is more influential in a transitional process is an empirical matter related to the research design. For our purposes, natural resources, material, capital, and knowledge seem to play an important role. Figure 1.2 presents the correlation between the resources and the kind of power exercised.

Second, institutions define how those resources can be mobilized, and actors guide themselves with this in mind (Avelino, 2017). The mobilization of resources can occur in multiple ways (some examples are presented during the presentation of policy mix). The way actors and institutions mobilize their information, personnel, natural resources, knowledge, technologies, funds and investments can be accessed by the plans and programs that efficiently take into account sustainable objectives. These plans and programs can be of two categories: constitutive, in a sense that they demand the creation of certain resources, or; dispositive, in a sense that they collect the resources available to dispose of in a certain social objective (Rogge & Reichardt, 2016; Avelino, 2017).

Third, power can be exercised to stabilize or provoke changes by structures to coerce actors' action (Giddens, 1984)s. The perspective of power in STS is quite often not so pervasive by structures of domination or constraints (Avelino & Wittmayer, 2016), because the goal is not stability in the end (as a traditional discussion between agent and structure in social sciences). The power literature commonly focuses on *power over and power to*[11], but Avelino & Rotmans (2011) propose a typology of power relation named as *Different power to*, which generates three possible power dynamics: sinergy, antagonism and neutrality. To simplify the explanation, this relation occurs with two actors 'A' and 'B'.

- Sinergy: it means that both actors have different power and they exercise to enable and support one another;
- Antagonism: it means that both powers restrict, resist or disrupt one another, and;
- Neutrality: it means that both powers do not affect significantly each other.

The meaning of this typology is that power is not exclusive and actually can be mobilized in different ways or created via additional resources. This typology opens space for three different forms that actors exercise their power in a transitional process. Avelino (2017) proposes a specifically distinction between *Reinforcive*[12]*, Innovative and Transformative* power. Table 1.2 presents a short description of the three forms of power and their indicators.

Transformative power and reinforcive power are opposite in this sense because they tend, on one side to transform, and on the other to stabilise. Transformations are necessary, but reinforcive means are also important to help new structures be perceived by actors and inform them about 'what is new and how to do now'.

This section intended to present and discuss the foundations and advances of a new field of research. As many times argued, STS investigates the modification over time in a socio-technical system and its effects in the economy, politics and society. Therefore, social sciences have lots of contributions to pay in this sense, and we incorporate the discussion about power and politics. Our goal is to give the next step into this multidisciplinary field by adding the international level into consideration and international politics. Before we move into this goal, it will be necessary to present, define and justify the choice of the Technological Innovation System as a matched approach regarding our theoretical goal. The next section is going to deal with this.

1.3 Technological Innovation Systems - TIS

First mentioned by Carlsson et al. (2002), they defined Technological Innovation System (TIS) as "a network of agents interacting in the economic/industrial area under a partic-

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[11] These are the most relevant typology of power for sustainable transitions. Haugaard (2002) discuss several meanings for power and Partzsch (2017) presents how to conceptualize power in environmental politics and transition studies

[12] On Avelino & Rotmans (2011), they refer to this as constitutive power, but to avoid confusion among another typologies of power and social interactions they proposed the term Reinforcive power

Table 1.2: Typology of power and indicators

Forms of exercise	Definition	Indicators
Innovative power	The capacity of actors to create new resources	The comprehensive effort to create or discover new resources (knowledge and technology). Changes in the interaction of actors and institutions (Avelino & Rotmans, 2011).
Reinforcive power	The capacity of actors to reinforce and reproduce existing structures and institutions	Institutional changes. Changes in the regulatory framework.
Transformative power	The capacity of actors to redistribute resources. Or replace old with new one and change the way they are distributed	The development of new institutions. Changing in systems. Transitional efforts. The capacity of actors to develop new structures and institutions moving to a new political and economic paradigm.

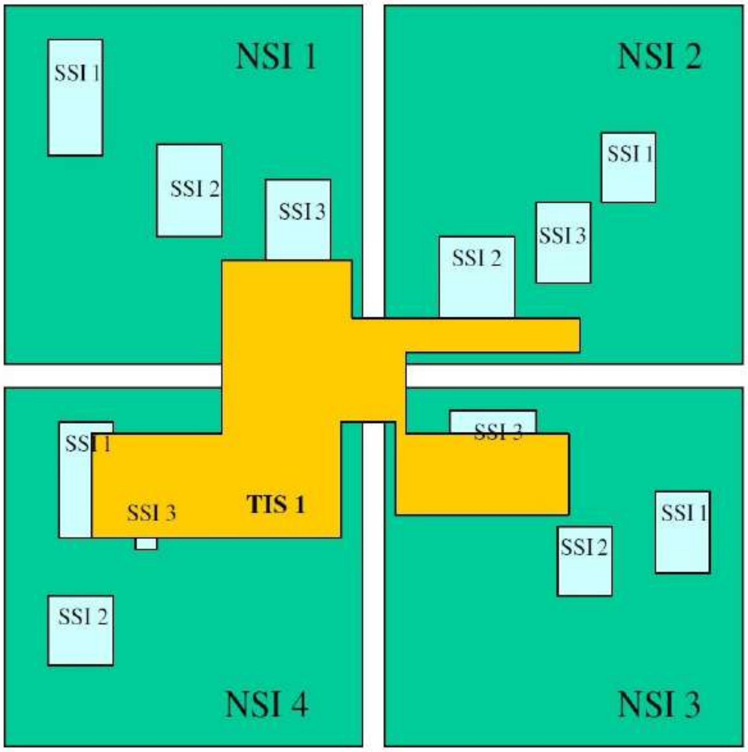
Source: Based on Avelino (2017); Avelino & Rotmans (2011)

ular institutional infrastructure (...) and involved in the generation, diffusion, and utilization of technology." (Carlsson & Stankiewicz, 1991, p. 94). It is a fair definition, but it is definitely embedded in the Industrial Economics perspective, and, for the objectives of this study, it does not capture the aspects that we would like to highlight. Essentially, our meaning of TIS has to incorporate the socio-technical aspect, such as the interdependencies between the actors and institutions of the system (this will be covered soon). So, Markard & Truffer (2008) with this comprehensive idea, proposed a definition that seems to solve this gap in the literature, as follows:

> A technological innovation system is a set of networks of actors and institutions that jointly interact in a specific technological field and contribute to the generation, diffusion and utilization of variants of a new technology and/or a new product. (Markard & Truffer, 2008, p.611)

The definition seems to provide a good start for discussing innovations that have a transnational or international aspect. According to the Figure 1.3, the TIS was designed to carry about the dynamics intertwined among NSI and SSI (innovation system theories mentioned before). Since this, TIS can be a useful analytical tool to develop a research that considers the international perspective. This is a discussion based on the design of the study, and for this reason, we consider innovation as part of the system. 'T' from TIS stands for technology, and as we argued before, technology and innovation have a similar meaning, and it is quite important to take it as something endogenous (Markard & Truffer, 2008; Markard et al., 2015; Hekkert & Negro, 2009). In this sense, as a knowledge result, the technology is not limited by the States' borders but can travel across countries and connects different people that are previously oriented to this.

Figure 1.3: Boundary relations between NSI, SSI, and TIS



Source: (Hekkert et al., 2007, p. 417)

The last disclaimer on this preliminary conceptualization of TIS is related to our following international approach mentioned before. The contribution of this study lies in the inclusion of an international level to conduct analyses of technological change within a TIS. There is a strong upcoming necessity to promote more studies about the internationalization of innovation systems because the international society considers the interdependencies between countries as a fundamental assumption of world politics and economy (Carlsson, 2006). And it is not only about the R&D activity between firms, but the fact that through international networks, technology becomes increasingly globalized, and the opportunities for innovation can enhance (Pavitt & Patel, 1999; Pavitt, 2002). The national approach does not lose its power of action, however, instead of acting isolated, it must be introduced in a network with a high flow of knowledge (Fromhold-Eisebith, 2007).

Lots of critics have been attributed to TIS regarding the spatial element because when it comes to the empirical part, the mention of international connectivity does not exist, making some scholars think that this is just another form to call comparison between NISs (Coenen et al., 2012; Binz et al., 2014; Bento & Fontes, 2015). But, of course, there are differences between the two approaches, and space really matters for TIS (Dewald & Truffer, 2012; Wieczorek et al., 2015), because it tends to connect different types of elements in a network that have some correlations that go beyond the national boundaries. We bring into the analysis the international connectivity between the actors and move forward to an analysis of the political strategies and coalitions of the actors, as with their political network overlapping the learning network or the other way around (Markard et al., 2015).

Therefore, innovation is a collective and social activity in a contextual situation. The success of this one is determined by how the system is built up (Musiolik et al., 2012), their functions or activities (Hekkert et al., 2007; Bergek et al., 2008a), providing analysis about political implications (Bergek et al., 2015), problems on the system (Hekkert & Negro, 2009) and its future consequences. This concept stresses that the diffusion of information among actors is a key feature of the innovation process and is the main function that defines the degree of the interactions between them. But before explaining the communication between actors, it is important to discuss how to identify the TIS, their structural components and their analytical boundaries, in other words, the system building. System building is a core concept and originated from the TIS literature within the Transition Studies. Musiolik defines it as:

> (...) the deliberate creation or modification of broader institutional or organizational structures in a technological innovation system carried out by innovative actors. It includes creating or reconfiguring value chains and creating a supportive environment for an emerging technology in a more general way. (2012, p. 1035).

Since innovation in our terms is a collective action, many actors and rules that contribute to the system's structure are inevitable. Therefore, after these first conceptual disclaimers, we should move to presenting the core concepts of a TIS.

1.3.1 Core concepts of the TIS approach

The delineation of the boundaries is somehow blurred because lots of elements can be in or out according to the research design (Coenen et al., 2012). For this reason, it is fundamental to consider the breadth of the technological field, their vertical scope, whether a spatial of particular technology/knowledge or even a temporal focus (Markard et al., 2015; Bergek et al., 2008a). These decisions are epistemological and critical to focus the researcher and research. But naturally, since the process of any system formation is contradictory, the boundaries are set in an iterative way regarding the case study.

The first requirement is about the level of aggregation of the study. This means including too much to get a better picture or specifying to get a detailed one. This means that it is possible to narrow the technology (PV or Biotech) to understand their dynamics(Cantner et al., 2016; Bergek & Jacobsson, 2003; Graf & Kalthaus, 2018). Or it is possible to have a broader starting point (renewable energies that incorporate wind, solar and biomass, or IT) (Bergek et al., 2008a; Johnson & Jacobsson, 2001). A second requirement would be focused on the range of applications of technology. This means deciding around the final use of such a technology, for instance: IT at home or IT to data science. This would help specify more and more the elements in the TIS structure, which can be closely observed. In any case, the study's focus may not reflect the reality of the system, and the iterative characteristic has to play a decisive role, as well as in every research, has some original objectives and contributions to state of the art (Bergek et al., 2008a).

After defining some of the epistemological foundations, the TIS approach also reinforces the difficulties in identifying this system's components or building blocks. Straightforwardly, those are the actors and rules (Hekkert et al., 2007), and later, their analytical arrangement (Bergek et al., 2008a). Hekkert et al. (2011) propose four main components:

- Actors: the variety of relevant actors is large. It can be a well-known expert or commonly involve organizations that contribute to a specific technology, varying from public to private, from generators to adopters. Categorically they are:
    1. Scholars
    2. Knowledge institutions
    3. Educational organizations
    4. Industries
    5. Market actors
    6. Government bodies and Supportive organizations
- Institutions: they are constraints that shape interactions that can be formal or informal. Traditionally, formal institutions are easier to map, but informal ones often strongly influence the innovation process. Categorically they are:
    1. Supporting legislation of the focal technology

    2. Collective interactions of actors
    3. Market structure

- Networks: the central idea of the innovation system framework and what determines the geographical limits and actors. They could be identified as:
    1. Links between actors in a given technology
    2. Advocacy coalition
    3. Epistemic communities
- Technological factors: the technological structures of artefacts and infrastructures in which they are integrated

Maybe setting the structure is already a big part of the job. Because the identification of those actors is a massive data collection to fulfil an analytical arrangement. This would be important to understand which components inside the structure are considered to be fundamental or secondary. The arrangement has to go through:

1. Identification of technologies
2. Actors involved
3. Spatial and temporal limitations
4. The creation and diffusion of knowledge with the structure
5. Market formation
6. Politics and policy goals
7. Medium actors
8. Network analysis

The arrangement provides a time frame that has differences by the time, and this is when the evolution of the TIS has to be analysed. TIS, at first glance, has no boundaries if one takes the World as an open space. But to design an investigation, it is necessary to define some limits regarding space where the theoretical assumption will take place. The network under analysis is defined by the type of technology, geographical position, and absorptive capacity of each actor. So that, ”despite the potential existence of a ubiquitous global opportunity set, innovation activities are not uniformly or randomly distributed across the global landscape" (Binz et al., 2014, p. 6), and by the end of the process tracing, the network or the system itself can be identified as predominately local or national.

Moreover, every TIS has to function in peculiar ways. This means identifying the functions (also can be mentioned as activities or process)[13], and as a breakthrough step, measure how they function in a certain manner. The functions help us with insights according to the innovation process and their contradictions toward a sustainable transition. There are different ways to approach these functions (Hekkert et al., 2007; Hekkert & Negro, 2009; Markard et al., 2015; Bergek et al., 2008a; Binz et al., 2014), and we advance by identifying 6 functions of a TIS. Table 1.3 summarises the functions with their definitions followed by their probable international indicators. This last column was based partially on the studies of Coenen et al. (2012); Bento & Fontes (2015); Binz et al. (2014) and partially on the requirements to fulfil an international political analysis of the TIS.

Table 1.3: Functions of a TIS

Function	**Description**	**International indicators**
Knowledge Development	This is the core of every TIS. This function comprises different but indivisible activities, such as: knowledge creation, the process of 'learning by searching' and 'learning by doing', and; knowledge diffusion, which is the exchange of information through different types of nodes and linkages, encompassing 'learning by interacting' and 'learning by using'. Every TIS has its own way to perform its own process and evolution.	Bibliometrics; patents; R&D plans; the number of international academic meetings; trade of equipment and technical consulting.
Influence on the direction of search	Activities within the innovation system that can positively affect the visibility and clarity of specific wants among technology users fall under this system function. It is a combination of firms' will, mission-oriented policies and also social demands.	Expectation of growth, regulatory pressures; political interventions; (in)formal international concerns; scientific state of the art.
Entrepreneurial activities	The existence of entrepreneurs in innovation systems is important because experimentation is a process of social learning and evolution. More than obvious, many ideas will fail, and some will achieve something, but the system does not stagnate.	Number of new entrants; the number of experiments with the new technology, and; patents.

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[13] This distinction is important here by the fact that the term functions, for some, automatically reminds the "functionalist" thought in Social Sciences. In this section, there is going to have a dedicated space to discuss this paradox as Jacobsson & Jacobsson (2014); Hekkert et al. (2007) already disclaimed.

Function	Description	International indicators
Market Formation	New technologies have to compete with incumbent one. Sometimes there is a call for temporary niche markets for specific technology applications, which the government or other agents in the innovation system often do. Also, the evolution of the market depends on some maturation by time and building of the dynamic.	Number of introduced niche markets; specific tax regimes for new technologies; share of domestic and foreign companies and; trade statistics.
Resources Mobilization	Resources can be mental, human, material, financial or natural, and they are necessary as a basic input to all the activities within the innovation system.	Interviews with experts; the amount of venture capital; R&D personnel; and skilled labour.
Legitimation	It is about the social-political acceptance and compliance with relevant actors in the TIS to make a focal technology diffuse and naturally depleted.	alignment of the TIS with the regulatory framework; supporting political projects; social movements; newspaper tendencies; parliamentary votes.

Source: Based on Hekkert et al. (2007); Binz et al. (2014); Bergek et al. (2008a); Bento & Fontes (2015)

We synthesize the number of functions based on the design of the research. Depending on the TIS variation approach, this number can vary until seven with the addition of 'development of positive externalities' [14] (Bergek et al., 2008b), or even eight elsewhere (Planko et al., 2016). By identifying the functions of a TIS, the problem with the high level of abstraction, which is one of the common critics of Transition Studies, is partially solved.

> When the technology matures, the TIS also grows due to an increasing knowledge base, new entrants, growing networks in terms of size and density, and specific institutional arrangements that come into place. In addition, when a TIS grows, the rate of technological progress generally increases, leading to increased chances of success for the technology in question (Hekkert & Negro, 2009).

Some studies have addressed the fundamental importance of legitimation and how it contributes to and co-evolves with the system building, and whether they support or not develop other system functions (Planko et al., 2016; Bergek et al., 2008b). Because it deals with the

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[14] Bergek defines the 'development of positive externalities' ('free utilities') as: "It reflects the strength of the collective dimension of the innovation and diffusion process. It also indicates the dynamics of the system since externalities magnify the strength of the other functions." (Bergek et al., 2008b, p. 6)

absorption of critics, manipulation of expectations and how the product in focus is depleted in the society and became useful or not (Binz et al., 2016).

Each actor who participates in a network has different interests and objectives, and they are searching for access to resources to achieve their individual goals (Markard et al., 2015; Coenen et al., 2012; Hekkert et al., 2007). But they are linked because of their common technological factor. Their links can vary from formal to informal, short to long-term, mono or multidisciplinary, and other variations. This is the core of TIS, and understanding these factors and collecting empirical evidence are the analysis goals. The development and diffusion of knowledge (which is a function for TIS) happen because the actors organize themselves consciously or unconsciously in a network to provide information among them (Bento & Fontes, 2015; Binz et al., 2014).

The knowledge itself is nothing without communication, more precisely, without the interaction between actors in a network. And considering a previous approach, all of this happens in a socio-technical system that can be changed. TIS has received some critics regarding its difficulty in explaining sustainable transitions or technological changes (Markard et al., 2015; Kern, 2015b), accused of being inertial and just portraying static situations and emerging TIS. But the TIS was designed to identify the structures that actually constrain the movements of the actors. Identifying these elements and their probable interaction would be possible to understand the network's weaknesses and contradictions. This is an important step that offers some reasons for developing a certain technology at the international level. (Hekkert & Negro, 2009; Labussière & Nadaï, 2018)

1.3.2 TIS weaknesses and energy transitions

Since its conceptualization, the TIS has been applied to analyse emerging technologies in a variety of economic sectors such as water, energy, transport and food(Markard et al., 2012, 2015). Since TIS scholars left behind the market failure approach, their goal was to identify the failures of a system and how to cope and overcome them. Overall the studies have been offering contributions to discuss energy sustainability failures so far. They are often dealing with problems in the legitimation process, (Bergek et al., 2008b; Binz et al., 2016), institutional failures (Markard et al., 2016; Hekkert & Negro, 2009), global connectivity (Carlsson, 2006; Coenen et al., 2012; Wieczorek et al., 2015), diffusion (Negro et al., 2012; Bento & Fontes, 2015), formation of the system and building of capacities (Johnson & Jacobsson, 2001; Kukk et al., 2015), among other issues related to renewable energies.

The energy transition can be simply explained as a process in which one enhances the share of renewable energy sources in its energy mix and reduces the share of fossil fuels (Leach, 1992; van den Bergh & Bruinsma, 2008). IPCC reports and other important research centres in the study of the environment often argue about the terrible effects that climate changes will have on future generations, and energy is found at the heart of this discussion (IPCC, 2011). Because a high level of emissions of GHG in the atmosphere happens from generate to consume of energy. In this process, lots of difficulties are pointed out, such as the lack of technological artefacts, short energy grid, low investments of renewable technologies, fossil fuel lobby, legitimation of public opinion, among others (Negro et al., 2012). In the last decades became clear that the formulations of energy and climate policies should encourage some resolutions for these difficulties, and innovation and diffusion of RET are based on this. This links energy transition discussion to TIS since the approach encompasses the emergence and diffusion of technology in a network (Markard et al., 2015).

From a national perspective, TIS can provide good recommendations (Johnson & Jacobsson, 2001; Musiolik et al., 2012) because the coordination of policies, actors and other elements of the network is in respect to the regulations of a country and their government objectives. However, when it comes to an international perspective, coordination problems are different and often require more political efforts to be solved. Negro et al. (2012) in their seminal paper 'Why does renewable energy diffuse so slowly? A review of innovation system problems' raised some points that might address some failures that EU countries are still dealing with from an innovation system perspective. The first one is the automatic dependence of the current economic system on the energy system, and transforming it can also cause an economic transformation. Fossil fuels offer a continuous feed of energy, with low risks of blackout or not enough resources (Junior et al., 2011). Another point is about the struggled relationship between the current energy system and the emerging RET. While the RET proved themselves to be more efficient on the firm level (Rexhäuser & Löschel, 2015) or even for societal purposes due to the emission reduction targets (Sheffield, 1997), they are considered radical innovation and require investments at high stacks. Finally, they identified that some institutional problems account for more than 50% of the cases. These are related to the lack of discontinuity and long-term regulations, inconsistency of policies, lack of subsidies, contradictory regulations, and lack of legitimacy. As well as the problematic situation of guiding the research and coordinating with institutions of education due to limited interactions between universities and cooperation between the private sector and the educational.

Although really consistent and with important evidence, the study of Negro is based on the use of a large number of failures from the system. This gives some unnecessary complexity to the analysis for two reasons. First, the failures raised are not convergent in the IS literature. Second, the number of variables and indicators may not be well discussed. To keep coherent with our 6 functions approach already described, we follow the inquiry of

Jacobsson & Bergek (2011), based on the identification of weakness that help us to understand the RET innovation and their forthcoming depletion, and also on the empirical evidences found by Hekkert & Negro (2009) the different types of TIS and their development based on their structure. Table 1.4 presents a summary of the probable weaknesses that a TIS can find by analysing the RET system.

Table 1.4: Weaknesses of a renewable energy TIS

Function	**Weakness**
Knowledge development and diffusion	Different concentration of investments on development or diffusion, which are inseparable. Limited connectivity between actors in the educational sector and research institutions. Limited connectivity between firms and educational institutions, and research centres.
Influence on the direction of search	Not clear information or even identical information between actors. Lack of societal incentives (demands and social movements). Lack of central and common guidelines.
Entrepreneurial experimentation	Limited number of entrepreneurial experimentation. Profit-seeking and Risk-averse actors are dominant. Lack of policy intervention.
Resource mobilization	Identification of the correct resources. Build the correct resources (e.g. human capital). Efficient use of the resources.
Market formation	Absence of regulatory framework to provide future market. Limited power grid connections. Different national regulations. Limited allocation of physical space. Standardization of the resources used and products sold. Markets that do not support the price and cost for RET.
Legitimation	Contradictory discourse. Advocates and lobbies for the fossil fuel industries. The unpopularity of actors.

Source: Based on Jacobsson & Bergek (2011); Hekkert & Negro (2009)

The literature also points out that there is a range of weaknesses that can be identified and assessed regarding the context and reality, and also on the stage of development of a TIS as well as one or two weaknesses may not be found in a given analysis because they simply change after time. This happens because new policies and actors often enter and drop the system, encouraging or retracting new strategies and goals (Jacobsson & Bergek, 2011; Johnson & Jacobsson, 2001). Of course, when considering an international perspective, other difficulties may exist in identifying the weaknesses.

So far, we have presented a constellation of definitions, concepts and approaches that can be used to create the framework for analysis. The next sections will be responsible for linking all of them. It is important to take this next step by setting the energy transition and their relation with international politics. Then we provide an initial and underdevelopment correlation between the concepts raised from innovation and transition studies and their connection with international relations.

1.4 The geopolitics of energy transition

At this point, it must be clear how the issue of sustainability transition (especially the energy one) has an international political perspective. But before identifying how can all the previous theoretical formulations make sense for international relations, it seems necessary to understand when and how energy touches upon international politics.

Energy security and climate change are commonly seen as or complementary or a trade-off discussion. This has some historical backgrounds. The Industrial Revolutions had a great impact on the way people used to live and do their activities. By the end of the second phase, in the late XIX Century, the knowledge pool was increased due to the invention of combustion motors. A revolution that counted with efforts from chemistry, physics and mechanics, for instance. Also, the conception of electricity made by Benjamin Franklin, electromagnetism by Michael Faraday, and the lighting bulb by Thomas Edison opened up a long road for new inventions in history. Have access to energy became a synonym of economic development and growth because, which made the countries pursue technologies able to generate energy in high quantity, but without considering the detrimental impacts on the environment (Junior et al., 2011; Nersesian, 2016).

The idea of excessive use of natural resources to generate energy, specifically fossil fuels, turned into a true environmental problem for the world by the end of the XX Century. Policymakers have seen this as a trade-off between energy security and climate change. This became evident since Eco 92 in Rio de Janeiro went through Kyoto Protocol and the Paris Agreement. Therefore, incorporating the environment as a major discussion in the economics of energy and energy politics is mandatory (Najam & Cleveland, 2005). On the climate change side, fossil fuels are the main factor that explains the elevation of the world's temperature due to GHG accumulation in the atmosphere. Burn these fuels liberates CO2 and creates non-natural modifications on the lands, death of animals, stress on fishery systems and pollution in general (Junior et al., 2011).

On the energy security side, fossil fuels have a fundamental role in the generation of energy. They are more stable (rare blackout moments), is relatively easy to have access to the resources and an extended energy grid in most countries. On the contrary, renewable energies became popular and evolved to the point that the technologies can actually replace fossil fuels. During the generation, they emit less GHG and have a long duration with less maintenance (Brown & Huntington, 2008). The duality between complementarity or trade-off emerges as follows. On the one hand, when an energy matrix is conceived, it couples the technologies to generate energy available in a country and when policymakers increase the share of renewable sources, energy security actually is a great ally to fight against climate change consequences. This means that they are complementary and driven by the same goal. On the other hand, when the mix is more fossil fuel dominant, even if the energy security measured by a high level of accessibility and affordability, the level of emissions also increases because of the energy generation process. This means that they are a trade-off (Chapter 2.1 provides a comprehensive discussion about it) (Brown & Huntington, 2008; Junior et al., 2011).

Since this type of technological change involves high risks of opportunity combined with large investments with returns for the society, this puts States as the fundamental actor (Mazzucato, 2015; Nersesian, 2016). Public and private investments are welcome, and they have to take into consideration the social goals such as larger accessibility of energy but combined with sustainable technologies. To solve the trade-off, it requires political decisions to establish priorities, facing contradictory discourses and interests. However, since climate change is a problem shared by all the countries, in the long term, it becomes impossible to offer political, economic and technological answers without involving the countries' neighbours (IPCC, 2011). Energy security can be seen as an international problem. Since some countries have an interdependence relation of energy trade (Ferreira, 2017; Högselius, 2018), they would require a stable supply chain. These assumptions seem to be able to set the debate of energy transition on the international level.

A probable answer from the International Relations side would be to treat it as a cooperation problem, precisely a multilateral one (Ruggie, 1992). One can depict the political problem by identifying the political actors involved in the negotiation process and their probable interests. However, the challenges of a global energy transition lay on a lower level of analysis as wells, and, due to the nature of our object, cannot be solved only via observing the multilateralism phenomenon. As argued before, IR scholars commonly ignore the impacts of technology and innovation on the material world (Leijten, 2019; Mayer et al., 2014). If we follow this common sense, regarding innovation as a side effect, an exogenous variable, or simply not disregarding, part of our object of analysis, which is the flow of renewable energy technologies/knowledge among countries, would not exist. At the core of IR discipline lies the 'change' in the society, political system, politics and so on, with the duty to make peace among nations and create a better world. Intrinsically, despite the different terminologies of international society or system, we deal with a system life cycle (Herrera, 2012). We are dealing with the historical and material depletion and diffusion of innovation in society and whether and how they can impact (combined with other factors or not) power distribution and reshape the political game.

According to our previous discussion about power in transitions, those who have access to renewable technologies more efficiently reach a distinguished position in world politics (Avelino & Wittmayer, 2016). Besides some similarities, this has nothing to do with the traditional balance of power approaches in IR (Diniz, 2007), where States empower themselves via military or economic factors, driving to a zero-sum game. Because power in this sense does not precisely consider the trade-off in energy transition and the necessity of an aggregated answer from international to local. Moreover, they emphasize the role played by technologies in international politics by traditionally taking weapons of mass destruction as a first topic, focusing on military engineering, nuclear technologies and the raise of assets necessary to enhance the defence of a State (Mayer et al., 2014). This might include energy and climate change, but their inner orientations tend to be more on the international security side.

Alternatively, IR scholars have been scrutinized the energy phenomenon as a geopolitical issue. They have addressed contributions about the dependency on oil and coal and the consequences in the world order (Yergin, 2011; Klare, 2002), on the energy security side (Sovacool, 2011; Brown & Huntington, 2008) and geopolitics (Högselius, 2018). However, they have hardly touched upon the implications of renewable energies for world politics. In the last years, various geopolitics aspects of renewable energies have been taken into account, and they are not ignoring the intervening of innovation and technology (Criekemans, 2018; Scholten et al., 2020; O'Sullivan et al., 2017). There are few studies, but at least they open some for discussion. Criekemans (2018); Scholten et al. (2020) categorically affirm the tremendous difference between the traditional geopolitics of energy and the new geopolitics of renewable energies. Scholten et al. (2020) presents six factors that impact on the geopolitics of renewable energy.

1. Abundant and dispersed nature of renewable energy sources and less oligopolistic global market;
2. Renewable sources support a shift toward a more resilient energy system varying between centralized facilities and decentralized, household or local generation of energy;
3. Highlights the critical use of rare earth metals and the competition in this market and the influence on the energy one;
4. The expected electrification of the energy system;
5. Changes in the energy trade and the market;

6. The intrinsic creative destruction innovation pattern (Scholten et al., 2020).

We highlight the last factor to support our argument that a sustainable transition concerning the energy sector depends on a large degree of innovation. In Criekemans (2018) words, this is an ”Energy Technology-Revolution” which is no longer about new techniques to extract fossil fuel from the environment and efficiently manufacture it, with the GHG emissions as tremendous side effects in the current times. So, energy turns into a technology-driven sector. The geopolitics of renewable energies is about the combination of large R&D investments in the energy sector, the observation of opportunities and limitations of certain geographical areas, where the wind rarely blows, or the sun rarely shines for large periods in the year. This will determine ”the new geopolitical context within which countries, regions and territories will be able to operate, create welfare and wellness, and develop a power base – literally but also figuratively” (Criekemans, 2018, p. 7). Those who are investing today in developing RET will consequently have a better and different power situation. This competition includes a large degree of cooperation between units in both senses: collaboration to guarantee the division of labour, and rapid increase of the RE knowledge pool followed by diffusion or KTT, and; coordination to guarantee that the units at least have some similar politics to do not barrier the system development and actually boost it. Thus, this energy transition is about to move to a green economy, increasing the share of RET in the energy consumption mix, reducing the total energy consumption and reducing the GHG emissions, in the sense that one can emit fewer gases and grow the economy. Nevertheless, this has to be done considering the goals toward environmental discussions firmly discussed within the international regime on climate change (IPCC, UNFCCC, IEA and other organizations and actors), with a strict focus on the diffusion of green innovations (O'Sullivan et al., 2017; Scholten et al., 2020).

According to Mayer 2014 ”Innovation, creativity and fast commercialization of inventions are highly valued by governments” [p. 10], and this points out to a new rivalry in international politics. There is a complex interplay between those systems of innovation, states and spaces (Binz & Truffer, 2017; Etzkowitz & Leydesdorff, 2000). Unfortunately, the dominant tradition of IR insists on separating environmental from technology in political analysis when they actually have to be dealt with together. The notion of Anthropocene already recognizes the potential of humanity to explore and destroy the environment using their technology. Nevertheless, it shows the extension of benefits that innovations have on environments. By diffusing low-carbon innovations, politics understands its 'dirty' policies from the past and searching for an international and coordinated effort (Drezner, 2019; Mayer et al., 2014).

Finally, our effort here is very similar to what Herrera (2012) did by identifying the interrelated connections of IR and innovation. Besides, also offer contributions to Innovation Studies by taking the perspective set by Carlsson (2006); Binz & Truffer (2017) to analyse innovation at a global level. To achieve this, we follow the assumptions early developed by Bijker et al. (1987); Rip & Kemp (1998); Hekkert et al. (2007) about socio-technical systems, where innovations play a significant role in the development of society. How knowledge is created and diffused impacts drastically the capacities that a country has to deal with the energy security trade-off. The existence of a socio-technical system made of different institutions and public and private entities located in different countries has to be analyzed by the IR discipline and taken as a serious element of world politics and change processes. In the next section, we try to drop more theoretical insights on how to deal with innovation/technological change and International Relations by acknowledging the presence of two scales of analysis. On the lower scale, there is an international collaboration for innovation diffusion. On the upper scale, there is the development of an international transition policy coordination. The idea of scales, rather than levels, seems to be more feasible because it perhaps avoids misunderstanding on how to concentrate some elements in the analytical process.

1.4.1 International collaboration and coordination for the energy transition

Policymakers are dealing nowadays with social problems that are deeply embedded in scientific discussions. Since the end of the Cold War, there was a growth of uncertainties and complexities of problems for global politics. In turn, this made international coordination more difficult. Dealing with environmental problems that constantly suffer from degradation, aside from the fact that they have global effects, made them be conceived different from a type zero-sum bargaining for world politics. The political project from policymakers can no longer be attached to themselves, but it requires understanding technical issues. To take a good decision, it must require high scientific advising (Haas, 1992b).

By recognizing that the possibility to project a sustainable transition requires an intersection between systemic conditions, knowledge and political actions, this requires an approach that acknowledges the role that a network of knowledge-based experts plays in gathering information, providing scientific answers and helping innovation and State to frame the issue of collective debate (Haas, 1992a; Souza et al., 2014). The idea that information and knowledge are also related to power contribute to our understanding of power in socio-technical change. But this power, in the end, must be canalized to provide answers collectively because climate change effects affect all countries as well. Since threats like climate change can travel across geographical proximity (Buzan et al., 2003), this would open up opportunities for innovation creation and diffusion (Boschma, 2005). On the road of innovation to provide answers for social problems, the exchange of information is fundamental and can certainly create a space to make the process more efficient. The level of proximity is important, and the extremes of closeness or distance are both detrimental to learning and innovation.

We proposed that the incorporation of innovation and sustainable transitions in IR can be done by understanding two scales of analysis: a) Lower scale or Public science dimension: it is related to a collaboration between transnational actors; b) Upper scale or Politics dimension: it is related to the coordination of international policies toward sustainable transitions. The formulation of these scales deeply considers the idea of a shared scientific topic under discussion by experts. So, they create and diffuse knowledge and technology via different channels (Haas, 1992a; Souza et al., 2014; Graf & Kalthaus, 2018; Binz & Truffer, 2017). Table 1.5 illustrates the analytical framework.

Table 1.5: The two scales/dimension and their elements framework

Scale / Dimension	**Elements**
Upper scale Politics dimension	Related to the coordination of international policies toward sustainable transitions. Presence of epistemic communities (Haas, 1992a; Souza et al., 2014). Presence of advocacy coalition (Jenkins-Smith & Sabatier, 1999; Zito, 2001). International politics/power struggle against energy dependence and fossil fuels (Avelino, 2017). Geopolitics of renewable energies (Criekemans, 2018; Scholten et al., 2020). All functions of TIS can be observed here, differing in degree (Bento & Fontes, 2015; Hekkert et al., 2011).
Lower scale Public science dimension	Related to a collaboration between transnational actors. Actors proximity to collaborate vary according to “cognitivity”, “organization”, “social”, “institution”, “geography” (Boschma, 2005). International-EU policy mix for green-innovation (Rogge & Reichardt, 2015). All functions of TIS can be observed here, differing on degree (Bento & Fontes, 2015; Hekkert et al., 2011).

Source: Author’s creation

On the lower scale, lays the collaboration between transnational actors to generate renewable technologies. What actors do is cooperate but in a scientific way. Since knowledge creation is cumulative and interactive, forward, it has to be exchanged and diffused. There is a spatial complexity in the innovation processes where international actors increasingly influence national ones between different industries. This creates an international interdependence to advance in the creation and diffusion of knowledge (Binz & Truffer, 2017), if one considers that the collaboration among experts located in different countries became more often. Boschma (2005) argues that the ”geographical proximity is neither a necessary nor a sufficient condition for learning to take place” (p. 62) but that along with other factors of ’distance/proximity’, it interacts in the process. He argues that exists some distinct forms of proximity:

- Cognitive proximity: since actors are governed by bounded rationality, the access to knowledge is restricted, which requires broad communication and absorptive capacity. But it requires some cognitive common ground to be sufficiently understood.

- Organizational proximity: the organizational arrangements provide coordination on the transaction. They are networks or research groups with formal and material aspects or for analytical purposes. They enable the transfer and exchange of knowledge and information due to the set of interdependencies created by the units.

- Social proximity: economic relations and their innovation process are embedded in a social context, involving the close exchange of informal experiences, friendship or social preferences to relate.

- Institutional proximity: the institutional framework, such as habits, routines, norms and rules that govern the pattern of interaction between units.

- Geographical proximity: is the restriction of space or physical distance in which the interaction of innovation actors happens.

In the innovation process, the factors of proximity enable the cooperation between different partners. On the one hand, closeness is typically preferred, but to some extent, they could tend to replicate or increment some solid assumptions without providing new combinations of knowledge (Boschma, 2005). On the other hand, the distance between collaborators accesses diverse thoughts that often have positive effects (Graf & Kalthaus, 2018). Our first focus is on geographical proximity by identifying an international cluster of countries embedded in a similar development of knowledge and technology. Due to communication technologies, The share of international co-publications has increased from 5% in 1980 to 21% in 2009 (Waltman et al., 2011). The numbers for each science field vary, but in any case, they have been risen. Co-publications represent just a percentage of what we call a network of knowledge. There are also an increase in the number of meetings (seminars or workshops or webinars, for example) and the number of innovations, exclusively co-authored patents.

The actors in this transnational context are not homogeneous, and they interact based on their scientific background, in other words, on their similarities in cognitive proximity. By assuming this network of actors, the distinction between regional, national or international levels becomes complicated because, depending on the position of an actor in the network, it can certainly impact the creation of knowledge on different scales (Musiolik et al., 2012; Markard et al., 2012; Bergek et al., 2008a). The collaboration eventually materializes as a composition of those five factors under a precise topic (renewable technologies) or research field (environmental or energy studies) to exchange information. Thus, they can vary from a high hierarchical integration to a loosely coupled virtual group (Binz & Truffer, 2017; Bento & Fontes, 2015). The objective of this scale into our analysis is the creation and diffusion of knowledge based on a given international context. There is a full government of policies that enable the advance of innovation. They are from different origins, pretty much as the policy mix assumption(Rogge et al., 2015) and related to organizational proximity. In respect to the TIS approach, it is possible to observe all functions only differing in terms of degree (Bento & Fontes, 2015). This scale provides the fundamental assets for the upper one, that constantly deals with the struggle of politics.

On the upper scale, there is the coordination of international policies toward sustainable transitions. Since the growth of technical problems in world politics, decision-makers demand particular information considered scientific or technical. Because the control over knowledge creation and diffusion may lead to new forms of relations among countries and will be decisive on the international policy coordination. This can be analysed as an epistemic community-building process. By definition, ”An epistemic community is a network of professionals with recognized expertise and competence in a particular domain and an authoritative claim to policy-relevant knowledge within that domain or issue-area” (Haas, 1992a, p. 3). Related to the lower scale, the epistemic community, as we defined it, promotes more than just gathering scientists because it has a political behaviour by influencing the political decisions based on scientific and technical knowledge. Traditionally, this approach has been largely used in the analysis of environmental topics (Souza et al., 2014; Toke, 1999; Haas, 1992b).

Some believe that an epistemic community can be seen as a soft form of scientific interaction (Boschma, 2005; Binz & Truffer, 2017), other understand as a more formal organization (Haas, 1992a; Toke, 1999). We lose the current definition provided by Haas, by acknowledging, as Zito (2001) argues, the difficulty to find examples and large evidence on the international level. Our assumption is a network of experts that commonly collaborate to influence political decisions, thus, these decisions may impact international policy coordination. Experts come from a variety of research fields, but a common topic connects them. They share common ground in respect to their world-views, and there is a common belief about the cause-and-effect relationship in a particular area. Their principles include agreed methods and models to inquire, based on the jargon (and its variations) and political values. In the end, they understand the implications of their knowledge development and pointing out preferable policy choices and methods to implement (Haas, 1992a).

Epistemic communities persuade actors in the political dimension to couple with their knowledge by offering 'logical' and clear answers for technical uncertainties. If the struggle on the political dimension is even more complex (crisis, failed policies, unanticipated events or similar contexts), there is a correlation on the high receptivity of policy-makers on the knowledge provided. Since epistemic communities collect diverse experts before providing a solution, they already have a 'laboratorial' inquiry. In turn, it develops knowledge that seems to provide new directions (Haas, 1992a). Potentially, epistemic communities can influence some aspects of politics by "formulating policies and framing issues, diffusing and promoting new ideas and policy innovations, defining the policy solutions that decision-makers select, and working to ensure that the community ideas remain on the agenda" (Zito, 2001, p. 466). The collection of experts in the epistemic communities often are more efficient in guarantee policy coordination if the issue area is a tough one, where the transaction costs are high, and information is still difficult to obtain.

This network of experts is spread across different countries, but they manage to link those which actually have common objectives or those who share some international institutions' principles (Haas, 1992a). This is based, somehow, on an intersection between national and international agendas, for example, climate change is a multi-level threat and something has to be done if not adaptation, mitigation plays the role. Their effects are still not clear, there are some more probable and less probable (IPCC, 2019) and then, experts can comprehend which areas must be tackle and others that can wait by offering knowledge and technologies. This often delineates the goals of a State and the level of embeddedness of its policies on the international level. Because the network provides some consensus about the nature and scope of the problem, reducing the difficulties to mirror States and international institutions behaviour in a cooperative process.

The effort to successfully capture policymakers and coordinate politics is not always achieved. This may happen because there is a lack of relevant shared interest between experts and national or international institutions. Even if the knowledge offered stands for a globalized benefit, the political context might drop it because it does not meet the requirements of the political orientation. Also, policy-makers might be aware all the time about their surroundings and promoting constants follow-ups about their political process (Haas, 1992a). Zito (2001) pointed out that there might be competitive networks that provide different answers for the same topic, and the institution may be confused under which categories one or other project should be picked up. As well as there might be different potential actors to contribute to the formulation of policy. Those actors can have a relationship with the network of experts or just be relevant for the topic, they could be described as non-governmental organizations, economic producers, stakeholders, firms or other more politically oriented coalitions.

This coalition stands to what Jenkins and collaborators named as advocacy coalitions, which is a ”network organised around a common set of normative and causal beliefs and attempting to create policy change” (Jenkins-Smith & Sabatier (1999) cited by (Zito, 2001, p. 468). It is a broad definition that even epistemic communities would fit. But it brings the presence of private organizations and other governmental levels into the formulation of politics. For our purposes, the only networks that interests are those related to the promotion of knowledge and technology for our main issue area, notably energy/environment. The actors in this network can also establish communication with the epistemic communities, decision-makers and society, and easily enable the legitimisation process (Jenkins-Smith & Sabatier, 1999).

Finally, this upper scale seems to embody all the functions of a TIS as well (Bergek et al., 2008b; Hekkert et al., 2011). After the processes happened on the lower scale, the upper absorbs the outputs, knowledge and technology, to generate power. A power that obtains different meanings on the technological change process (Avelino, 2017). The mobilization of these resources contributes to advancing a sustainability transition of a country or international region by replacing fossil fuels political and economic dependencies with efficient renewable energy technologies. Therefore, innovation seems to play an important role in the coordination of international politics. Moreover, the geopolitics of renewable energies points to the differences among the Members of the European Union to mobilize resources and reach energy transition (Criekemans, 2018; Scholten et al., 2020; O'Sullivan et al., 2017).

In the next Chapters 2.2 3 and 4, we propose a serious application of these approaches by identifying the boundaries of the TIS, their units, linkages and difficulties in promoting economically and politically a sustainable transition within the European Union geopolitics of energy transition.

Chapter 2

THE NEXUS BETWEEN CLIMATE CHANGE, ENERGY SECURITY AND EUROPEAN UNION

The chapter has two main objectives. The first one is to present, from a historical perspective, how energy technologies evolved paired with the environmental discussions. To achieve this goal, we start with a contextual discussion about the trade-off between climate change and energy security, highlighting the progressive introduction of innovation as a key factor to address political and practical answers. Then, we conduct a document analysis of some past international conferences (mainly COPs) that warn the world about climate change, focusing on the trajectory of the penetration of the technological discussion as ways to cope with climate consequences. Since climate changes effects will be suffered across the world, we believe that the trade-off between climate change and energy security can be better solved under the mission-oriented policy approach, focusing on societal challenges and managing resources to solve them structurally.

The second objective is to analyse the renewable energy technological innovation systems (RETIS) in the European Union within this trade-off context. As an efficient method to conduct a social network analysis, one first step requires the description of the structure of the RETIS by identifying the specific renewable energy technologies (RET) under scrutiny, describing the market, identifying actors, and understanding the role of institutional bodies. This is necessary to limit the network under analysis in size and level of analysis. The full methodology description is contemplated in the Appendix A.

2.1 Climate change vs energy security

Mitigate the negative impacts of climate change is one of the main objectives of the XXI century because the consequences will affect all countries (Bonnet et al., 2018). In the last years, the amount of GHG emissions has been growing, contrary to what has been expected, acknowledging the international efforts and environmental agreements made. The Figure 2.1 presents the current data from the top emitters of GHG and emissions by sectors. The distribution among the top emitters is quite uneven in respect to economic performance. However, considering the principle of Common but Differentiated Responsibilities, there is a high demand for international cooperation supported by scientific findings and serious political support.

In order to reduce GHG emissions, long before experts identified the energy sector as the greatest share of emissions, which would require a change in the way society interacts with energy. Considering the sectors listed in the figure, those related to energy are Electricity/Heat, Transport, Manufacturing/Construction, Building, Fugitive Emissions and Other Fuel Combustion, and in 2016 they account for more than 70% of total emissions. Therefore, we can affirm that climate change strongly connects with the energy sector and energy policies/security. However, the energy transition policies will vary according to the economic performance of each part but also on the availability of low-carbon technologies. Nevertheless, the knowledge about the probable future effects of climate change is known. One possible form to address efficient answers is based on the creation and diffusion of renewable energy technologies.

The relationship between low-carbon innovations and climate politics is a cycle that starts with two main points: the society seeks better conditions to live in the world, and; the scientific community knowledge in respect to the negative effects of the current way in which humanity is living. Then we move to a political pressure to advance the discussion and create a comprehensive answer to climate change that considers the constraints on the international level. Related to the last point, the tautology between climate change innovation and international politics is related to adopting climate agreements, which are intrinsically linked with the advance of technologies (Bonnet et al., 2018; Criekemans, 2018).

Renewable energy technologies have a great potential to contribute to the fight against climate change effects because they present some answers to the trade-off between energy security and climate change. Energy security has many definitions[1], but to avoid too much confusion, let us take the IEA definition: ”the uninterrupted availability of energy resources

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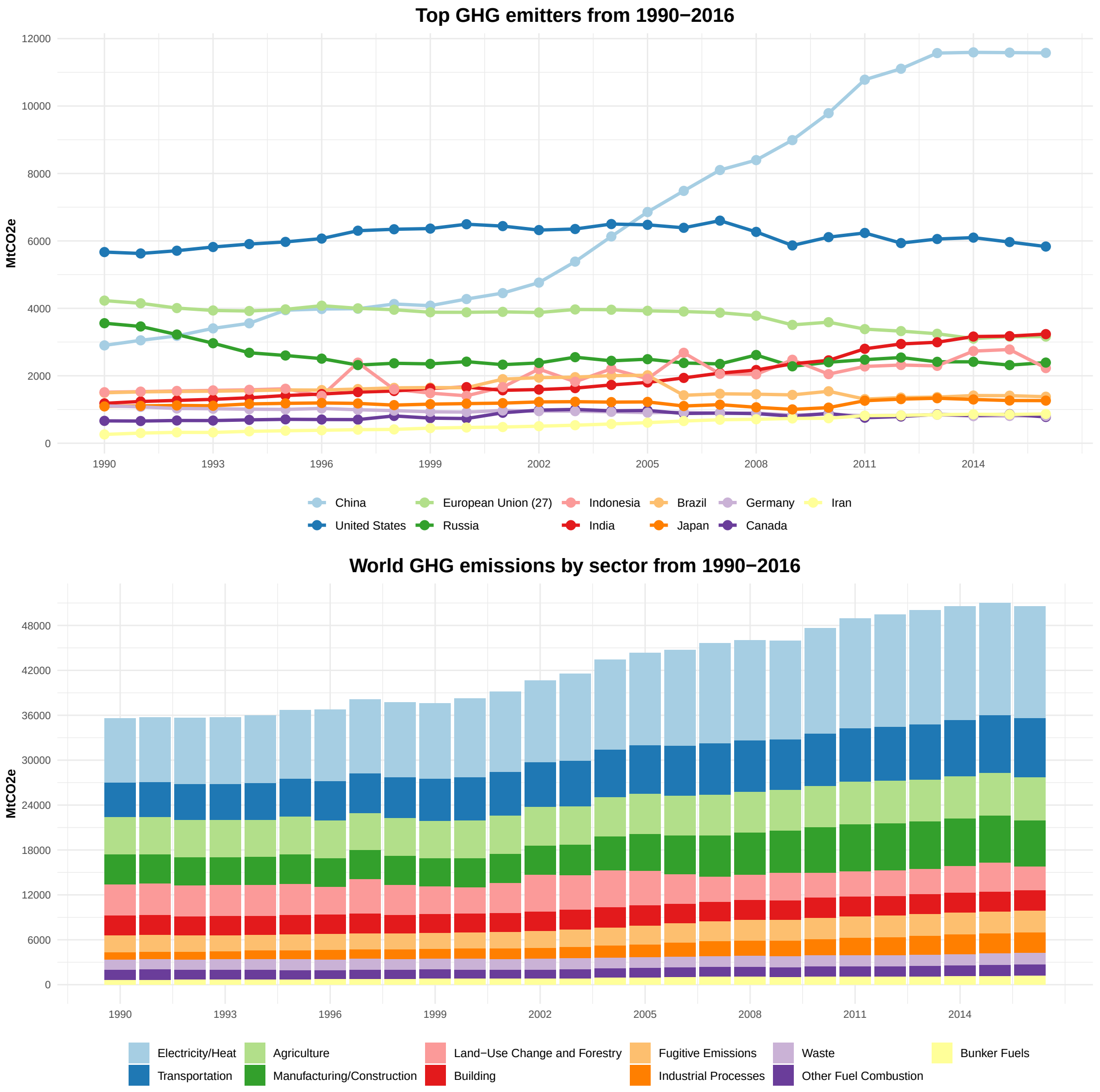
[1] According to Sovacool (2011) there are at least 47 definitions of energy security. This variation exists because each State, institution or scholar can define it based on whichever elements are important for their own reality.

Figure 2.1: Historical emissions



Source: (Climate Watch, 2018)

at affordable prices" (IEA, 2015). A possible answer is to produce more energy, and the price of it will drop through time due to the large offer, but this would require traditional and stable sources to be used, such as fossil fuel. Contrary, climate change policies claim for a reduction in the environmental sources stress. They are opposite forces that counterbalance how humanity thinks about the energy paradigm[2]. In our perspective, innovations are a possible way to enhance the generation of energy in sustainable ways. This process somehow is called sustainable transition, or more specifically, energy transition.

Empirically, the nexus climate policies and energy security can be identified in many ways (Lefèvre, 2007), but we highlight some aspects. On a political aspect, the nexus can be observed as a priority area because it can be an important driver for economic growth, which in turn leads somehow to dependency relations between countries such as the imports of oil from the United States from hostile regions or the exportation of the Russian gas for the European Union (Toke & Vezirgiannidou, 2013). On an environmental aspect, energy is responsible for more than 70% of world emissions (Climate Watch, 2018) and tackling the sector with an environmental approach is necessary to reduce this level. On an economic aspect, the energy sector requires more innovations. Therefore, it is a true opportunity for new entrants to gain market share based on low carbon technologies (Rogge et al., 2015) and return to society the profit of a public investment that will make people's lives easier (Mazzucato, 2015).

In any aspect that one can cover, the trade-off or complementarity between energy and climate change is based almost entirely on the energy mix based on available forms to generate energy[3]. The complementarity arises when there is a will to incorporate environmental principles and sources in its design. Even though this seems to be a simple decision, policymakers are commonly confronted with the trade-off (Brown & Huntington, 2008).

On the climate change mitigation side, reducing GHG concentration in the atmosphere is the historical main goal. The scientific evidence around the anthropogenic climate change can be better observed since the 1970 decade. Still, it also has many factors that are progressively understood by the scientific community (Lefèvre, 2007). Figure 2.2 describes

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[2] The energy sector comprises the whole set of activities involved in the production, transformation, storage, transport, distribution and commercialization of energy. The isolated use of each source and the processing technologies will yield different incomes. These incomes will vary from technology to technology, from source to source and, over time, due to technological development and advancement. In this sense, the level of efficiency that a society produces, transforms, transports and uses energy is strongly conditioned by the set of sources and energy technologies available at each historical moment that will change over time and by the evolution of these technologies (Junior et al., 2011).

[3] Energy mix is a relatively simple concept, which calculates the share of each source of energy. However, there is a variation depending on the moment of the production cycle. It is possible to set an energy mix for on-shore or off-shore production (the first means those sources used on the country's land, the second incorporate those on the country's cost or high sea); for export and import; taking into account the dependency rate; consumption; or even specifying the use of certain sources.

some risks associated. Overall, the greatest problem is the concentration of CO2 about ∼407 ± 0.1 ppm in 2018 (Friedlingstein et al., 2019) that is constantly rising and close to the threshold projected by experts of 450 ppm. The limit is approaching because, in the last ten years (2010-2020), the anthropogenic activities emitted about ± 2.7 ppm/year (Friedlingstein et al., 2019). Beyond the currently observed consequences in the world, such as hotter summers and rapid ice stones erosion, IPCC experts periodically project scenarios with some high or very high confidence level[4]. We summary some robust risks projections below:

These projections have different impacts, and somehow they will occur even with different consequences for the world. In the last IPCC Assessment Report (2019), it became clear that fossil fuels and the current consumption habit of society play a decisive role in global climate change. This is because fossil fuels are responsible for 60% of emissions sources (Jackson et al., 2019) caused by the burning of coal, oil and gas, and on the fact that they are not renewable, which means that they cannot be reused on a scale of time and quantity that is sustainable in respect to the consume. So, improving energy efficiency by switching for more renewable technologies and progressively reducing carbon-intensive fuels combined with the capture or trade of carbon can offer good contributions (Lefèvre, 2007; Brown & Huntington, 2008).

On the energy security side, it increases when a nation reduces the risks associated with its vulnerability regarding the energy supply, avoiding any momentary or prolonged disruptions and blackouts. Let us recap the definition of energy security provided by IEA (2015) ”as the uninterrupted availability of energy sources at an affordable price”. This definition is intentionally broad, but it also draws attention to two main issues: availability and affordability. In the short term, any disruption will cause impacts on the price due to the reduction of energy supplies in the market, and maybe people will suffer from the interruption of the supply. Consequently, consumers are unwilling or just unable to pay the higher price, reducing their consumption. This can happen by several factors, but basically, they are located on the design of the energy mix and the resources available (Lefèvre, 2007). The energy policies can improve security by designing a more stable mix, with sources that have more technological reliability and are established for a long time on the market, which its problems and troubleshooting are well known. Also, it can create economic mechanisms

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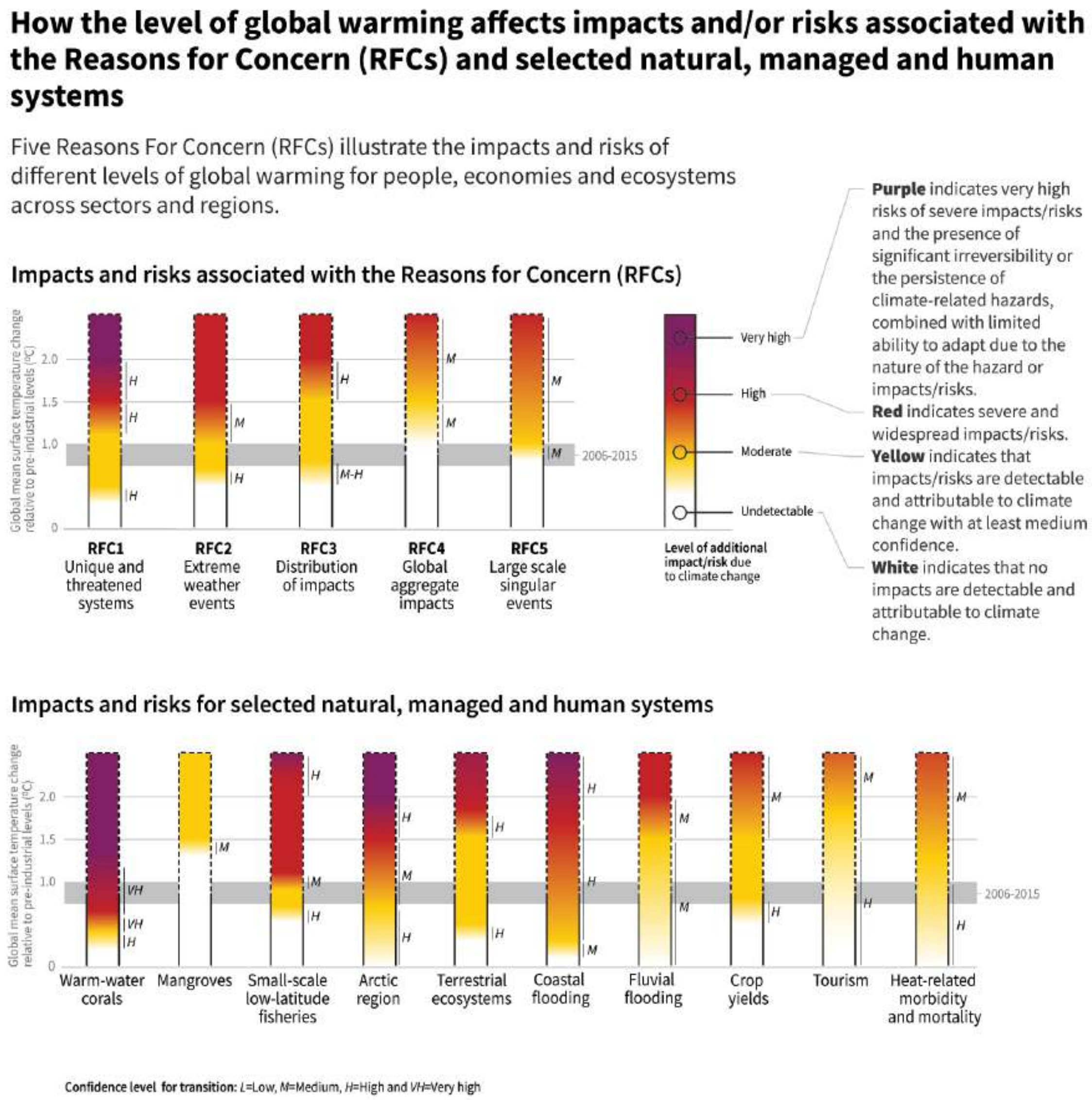
[4] IPCC assessment categorizes the consequences of climate change on five confidence level. ”Each finding is grounded in an evaluation of underlying evidence and agreement. A confidence level is expressed using five qualifiers: very low, low, medium, high and very high [...]. The following terms have been used to indicate the assessed likelihood of an outcome or a result: virtually certain 99–100% probability, very likely 90–100%, likely 66–100%, about as likely as not 33–66%, unlikely 0–33%, very unlikely 0–10%, exceptionally unlikely 0–1%. Additional terms (extremely likely 95–100%, more likely than not ¿50–100%, more unlikely than likely 0–¡50%, extremely unlikely 0–5%) may also be used when appropriate. (Edenhofer et al., 2011)

Figure 2.2: Risks associated with global warming



How the level of global warming affects impacts and/or risks associated with the Reasons for Concern (RFCs) and selected natural, managed and human systems

Five Reasons For Concern (RFCs) illustrate the impacts and risks of different levels of global warming for people, economies and ecosystems across sectors and regions.

Impacts and risks associated with the Reasons for Concern (RFCs)

Purple indicates very high risks of severe impacts/risks and the presence of significant irreversibility or the persistence of climate-related hazards, combined with limited ability to adapt due to the nature of the hazard or impacts/risks.

Red indicates severe and widespread impacts/risks.

Yellow indicates that impacts/risks are detectable and attributable to climate change with at least medium confidence.

White indicates that no impacts are detectable and attributable to climate change.

Impacts and risks for selected natural, managed and human systems

Confidence level for transition: *L*=Low, *M*=Medium, *H*=High and *VH*=Very high

Source: (IPCC, 2019)

for eventual price shocks, and nothing compared to the 1970's shocks[5], but mechanisms for eventual blackouts that may occur in the life-cycle are necessary (Brown & Huntington, 2008).

In the long term, the continuous supply of energy deals with investments and projects for economic development. This is also related to the availability and affordability of consumers, but in the last decades, maybe the discussions moved to the incorporation of environmental and climate change aspects as important drivers for energy security. To fulfil economic growth, countries are required to be more environmental friendly, and this implies, among other issues, a good performance considering two indicators: the progressive reduction in the level of CO2 emissions to generate GDP (CO2/GDP(PPP)) (Mikayilov et al., 2018) and also on the efficient use of energy to generate GDP (Junior et al., 2011). For both indicators, the larger the number, the lesser efficient the economy is. Also, they are measured at an aggregated level. On a global level, the CO2 emissions per GDP (CO2/GDP(PPP)) have decreased from 0.4 in 1990 to 0.3 in 2017, and the energy intensity in the same period from 0.190 to 0.123 (MW/GDP(PPP)) (IEA, 2020). However, contrary to international environmental efforts, the emissions are growing, as shown in the Figure 2.1. Because of such essential and relevant indicators, countries should invest more in low-carbon technologies to increase energy security and reinforce sustainable consumption in society. As Martin (1992) and Hansen et al. (2010) apud Junior et al. (2011) explain, the variation in the consumption of energy depends on three factors: economic growth; the changes (may) occurred in the GDP and; the evolution of the energy mix in each GDP. The last factor is linked to the environmental driver in the sense that, from 1990 until 2017, there have been several efforts around the world to shift from a fossil fuel-intensive economy to a green one. The penetration of more RET in an economy can indicate to users that they can actively contribute to the fight against climate change, which eventually can change consumers' behaviour (Szulecki et al., 2016).

From this overview, climate change mitigation policies can have significant implications for energy security and the other way around. To achieve complementarity, one way would be the increase of investments in renewable energy technologies (Iyer et al., 2015). Away from the political discussion about policies formulation and negotiation, the achievement might mean something quite complicated because this requires a background of technological advance. Or by making fossil fuel generation more efficient and less polluter, or by increasing the share of renewable energy technologies (RET) in the energy mix or combining

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[5] In 1973 and 1979, two important oil shocks occurred. In the first year, the oil price increased nearly 400% after the Arab members of the Organization of Petroleum Exporting Countries (OPEC) proclaimed an oil embargo targeting nations supporting Israel in the Yom Kippur War. The second one was caused by a drop in oil production because of the Iranian Revolution, raising the price by 100% until 1980

both in a dynamic and progressive plan. Although this at a first moment seems to rest solely on a national decision, the availability of RET and the allocation of R&D resources in this sector will drastically vary according to numerous factors, such as geography, economic performance, civil pressure or political priorities (Junior et al., 2011). This somehow explains the different paths of energy mix evolution among countries in respect to RET. Also, different from ideas and (somehow) knowledge, innovation is a private good protected by different mechanisms that allow innovators to profit from that for a certain period (Reinganum, 1989).

On an international level, the defence of such an innovation is, beyond an economic perspective, a manifestation of States' strategies and a demonstration of different types of power to mobilize resources (Avelino, 2017) associated with social purposes or mission-oriented policies State-driven (Mazzucato, 2015). Besides the fact that Intellectual Property Rights (IPR) has existed since 1883, environmental international meetings became more aware of the technological transfer implications for the trade-off climate change and energy security in the last decades. Overall, the political implications for coordinating the creation and distribution of such technology has become clear in XXI Century with a discussion involving the World Health Organization. A brief description of the case is made by Bonnet et al. (2018) as follow:

> The Organisation has concluded that research projects carried out by major pharmaceutical companies, guided by profit-seeking, strive to meet the needs identified in Western countries where the willingness to pay will be stronger. Other diseases that affect a significant proportion of the population in poorer countries are not well researched and are therefore neglected. To address this requirement, the WHO report recommended the creation of a global R&D convention on neglected diseases. Many disputes arose during the negotiations, and the draft comprehensive convention was abandoned, despite the enthusiasm of countries affected by neglected diseases. The delegations of the European Union and the US were the most recalcitrant to the idea of a comprehensive convention.13 While the US delegation refused to comment on its refusal formally, various sources confirmed that their main fear was that the convention would promote technology transfer and access to medicines. (Bonnet et al., 2018, p. 13).

The example with the health system constitutes an issue for the climate because intellectual property and technology transfer can also represent a threshold for climate negotiations. The advances of the renewable energies industry and the future benefits that human society can collect based on energy efficiency have to be considered globally distributed. Otherwise, if few countries have RET and climate technologies, they will be sensitive to climate consequences anyway. To overcome the lack of coordination in the area and promote international diffusion and transfer (KTT), an alternative is via international forums and agreements. The Conference of the Parties (COP) is the most traditional space for this discussion and maybe one of the most influential. COPs now consider energy technology transfer a core issue for climate changes, but recognising this entangled relation was not easy and took some time for science to advance and policymakers to make sense of it. This last section was responsible for identifying the implications of the nexus between climate change and energy security, highlighting the necessity of an international coordinated movement toward a larger diffusion and share of RET. The next section will review the penetration of energy security inside climate change discussion within the COPs and its relation with the RET diffusion and transfer via the formulation of its decisions and advice.

2.1.1 A brief history of energy and technology transfer in climate negotiations

Long before the end of the Cold War, in 1972 happened the first major environmental conference. States gathered in the UN Conference on the Human Environment (Stockholm Conference) to discuss the relationship between human beings and the environment. This raised some important discussions such as air pollution, environmental degradation and efficient infrastructure. One of the main topics was the urgent economic development that respects the environment, originating a well-known term, Sustainable Development (UN, 1972; Benedick, 1999). But related to energy use and similar, few mentions were made, and a low level of discussion seemed to be implemented at that time. Nevertheless, there are precisely three Recommendations that touches upon it, as summarised by Najam & Cleveland (2005):

- Recommendation 57 called upon the UN Secretary-General to ”take steps to ensure proper collection, measurement and analysis of data relating to the environmental effects of energy use and production”.

- Recommendation 58 called for better exchange of information on energy. The recommendation is motivated by the need for ”the rationalization and integration of resource management for energy” and seeks mechanisms (such as exchange of national experiences, studies, seminars, meetings, and a ”continually updated register of research”) for accessing existing information and data, particularly on ”the environmental consequences of different energy systems”.

- Recommendation 59 called for a ”comprehensive study to be promptly under-taken with the aim of submitting a first report, at the latest in 1975, on available energy sources, new technology, and consumption trends, in order to assist in providing a basis for

> the most effective development of the world's energy resources, with due regard to the environmental effects of energy production and use" (Najam & Cleveland, 2005, p. 126).

The idea of embrace the generation of renewable energy technologies seems to be there, as well as the urgent necessity for technological transfer and cooperation among States. But those were small in quantity and importance, partially because of the avoidance to discuss a core issue, due to the Cold War context and the nuclear threat, and partially by the lack of prospect scenarios that put energy as a central discussion, energy was relatively stable on that time (Najam & Cleveland, 2005). However, in the following years, the Oil Crisis revealed a bigger need to seek alternative forms to produce energy. They were marked by two Crises, in 1973 and other in 1979, which, in both cases, raised drastically the price of oil, around 400% and 100% respectively. As a result, the discussion about energy technologies was less related to Sustainable Development and more focused on the availability and accessibility of oil and its products. Innovations worldwide favoured turning extraction more efficient and transport safer than on generation of energy by alternative sources (Nesta et al., 2018).

The promised agenda of Stockholm was to keep on track international political meetings about the environment more often, a goal that was not fulfilled. But in the meanwhile of the 1979 Oil Crisis, the first World Climate Conference (WCC) took place. This was a scientific event that brought together scholars and experts from different areas to contribute to environmental issues. Global warming was one of the concerns, but the science about climate was premature, and, one more time, the prospecting of future consequences and how to mitigate the negative effects were not yet known (UNFCCC, 1992). Therefore, the WCC was an important opportunity for experts to share knowledge from their own country and propose more research agendas. Consequently, almost ten years later, in 1988, the Intergovernmental Panel on Climate Change (IPCC) was set up by the World Meteorological Organization (WMO), the same organization that sponsored the WCC. Nowadays, it is known as one of the most important scientific bodies that release reports and assessments at local and global levels about climate, keeping the topic on track and demanding decision-makers to mitigate and adapt society according to the terrible future effects of climate change (IPCC, 2011).

But it was only after twenty years from Stockholm Conference in 1992 that Rio de Janeiro held the UN Conference on Environment and Development. The Cold War context has gone, and the public interest in the environmental discussions was increasing again. After two energy crises, this topic became determinant for the economy and politics. Unfortunately, similarly to what happened in Stockholm, Rio did not work directly on the energy topic. But they advanced in the discussion, as Najam & Cleveland (2005) affirm, they took the next step relating energy to economic and environmental dimensions. So, one of the most important political mechanisms to fight climate change was adopted in this meeting, the United Nations Framework Convention on Climate Change (UNFCCC - short Convention), a treaty whose main objective was to stabilize the GHG emissions in the atmosphere if compared with the pre-industrial times. Only in 1994, after a certain number of ratifications, the treaty actually entered into force. Unintentionally, UNFCCC in the following years brought energy resources and energy technology access as a central negotiation among countries (UNFCCC, 1992).

After the insertion of UNFCCC and IPCC, negotiations around climate policy definitely evolved at high speed. Monitoring the temperature *vis-a-vis* the natural and human systems provided for the scientific community and world policymakers important possible consequences if GHG emissions do not reduce. But a major concern is about mitigating the rise of the temperature below 1.5 degrees if compared to pre-industrial times. Since 1992, a long journey to understand the climate change impacts in the world society has been made. In the original text from the Convention, the parties dedicated specific provisions for technology and innovation as follow:

> Art. 4, Paragraph 1 - All parties [...] shall: (c) Promote and cooperate in the development, application and diffusion, including transfer, of technologies… that control, reduce or prevent anthropogenic emissions of greenhouse gases not controlled by the Montreal Protocol in all relevant sectors, including the energy, transport, industry, agriculture, forestry and waste management sectors [p. 05].
>
> Art.4 Paragraph 5 - The developed country Parties and other developed Parties included in Annex II shall take all practicable steps to promote, facilitate and finance, as appropriate, the transfer of, or access to, environmentally sound technologies and know-how to other Parties, particularly developing country Parties, to enable them to implement the provisions of the Convention. In this process, the developed country Parties shall support the development and enhancement of endogenous capacities and technologies of developing country Parties. Other Parties and organizations in a position to do so may also assist in facilitating the transfer of such technologies (UNFCCC, 1992, p. 08).

Although they were undermined due to the immature conception and knowledge related to climate and possible climate technologies, this first step can be settled down as the beginning of the international guidance of the research related to renewable technologies. In turn, the constant evolution of these discussions on the international level can be considered an element that performs one of the fundamental TIS functions, guidance or influence on the research (Hekkert & Negro, 2009). The history of the COPs reveals the seek for common ground between countries to start and evolve the renewable energy innovations. The lack of available information motivated experts around the issue area to speed up research that would touch upon it. Only after a clear understanding of the problem, one could advise international policy accurately. However, the robustness of the guidance for political decisions regarding renewable energy innovations took some time. Its first phase is commonly known as "Consultative process" and had two steps. The first happened from 1995 until 1997, when parties made a common effort to gather existing knowledge about environmental problems worldwide, understanding common but peculiar dilemmas from each country. On this baseline, they coined the term climate technologies to understand which type of existing technologies could support the reduction of GHG and future adaptation to climate change. The second step started in COP 4 in Kyoto in 1997 and ran until COP 7 in Marrakesh in 2001. Through that, the Convention promoted Regional Workshops worldwide to explore, debate and broaden the accordance between countries about the climate problems. As well as to robust the issues related to climate technologies and their possible application on national, regional and international levels (UNFCCC, 2020). In addition, the meeting in 1997 eventually came out with the Kyoto Protocol, an important threshold for international climate policies, and provisions for technology were included under Article 10.

The understanding of the trade-off between climate change and energy security starts to become clearer. Different from what happened in the past meetings, the Convention already provided under Article 4 guidance for technologies to seek "energy efficiency" and "energy-intensive products" as important issues on the track to tackle climate problems (UNFCCC, 1992). But still, in 1995 in the COP 1, parties pointed out that energy remained a sideline for the multilateral discussion. Therefore, more development of the Convention's agenda with this goal would be in high demand (UNFCCC, 1995). Also, even if nuclear power has emissions close to zero and largely considered a clean form of electricity generation, the historical events of military use in Hiroshima and Nagasaki and the accident in Chernobyl and Three Mile Island turn the public opinion more critical against it. Greenpeace and other green social movements (Coglianese, 2001) already mentioned these effects as negative points for nuclear power. They constantly pressure governments around the world for the nuclear phase-out and the implementation of renewable energies. At that time, the environmentalist movements were more focused on species protection and environmental conservation, but the pressure to increase the share of renewable energies was not a big issue. Even though international politics experienced an uprising of discussions about energy and climate technologies, which seems both evolved together by an international collaboration of scientists caused by the first phase, the rise of more information to serve cooperation between countries, and the social opinion about the necessity of more environmental concerns.

Moreover, in the third phase from 2001 until 2010, parties agreed to adopt and implement the Technology Transfer Framework and the Expert Group on Technology Transfer (EGTT) right in the first year. The decision was necessary due to implementing the already mentioned Article 4, paragraph 5 of the UNFCCC. The Framework covered five key technology themes: 1) Technology needs and needs assessments - publishing of reports to identify and assess technological needs to reduce GHG emissions; 2) Technology information - the creation of a platform to facilitate the exchange of information; 3) Enabling environments for technology transfer - coordination of public policies around the world to fulfil KTT; 4) Capacity-building for technology transfer - the reduction of technical barriers for future collaborations, and; 5) Mechanisms for technology transfer - innovative financing support for the world depletion of technologies and implementation of the agreement (UNFCCC, 2020; Bonnet et al., 2018). Through the third phase, the robustness of the Convention to deal with climate technologies and energy became more serious. Close to the entry into force of the Kyoto Protocol, parties once again pointed out and discussed the level of emissions concerning energy generation. Unfortunately, on the final report, there were few provisions for energy specifically. They were mainly representing wishes of energy efficiency on the preamble section than providing recommendations via decisions (UNFCCC, 2004).

COP 13 in Bali in 2007 was an important pinpoint on the discussion of energy and technology. Besides strengthening the Framework and the Expert Group by adding more funding for innovation and the development of endogenous innovation and collaborative R&D projects. New partnerships for funding and speeding up renewable energy depletion were established between Global Energy Efficiency, Renewable Energy Fund and the European Union Energy Initiative (UNFCCC, 2007). By the end of the third phase in COP 16 in Cancun 2010, the Expert Group was decommissioned and replaced by the new “Technology Mechanism”, which contains two entities, the Technology Executive Committee (TEC - Policy Arm) and the Climate Technology Centre and Network (CTCN - Implementation Arm). The TEC was formed by 20 technology experts from developed and developing countries. It is responsible for analysing issues and providing policy recommendations that would support countries’ efforts toward climate technologies development and transfer. CTCN performs three services on the KTT activities: 1) Providing technical assistance at the request of developing countries on technology issues; 2) Creating access to information and knowledge on climate technologies and; 3) Fostering collaboration among climate technology stakeholders via its network of regional and sectoral experts (UNFCCC, 2020).

After more than twenty years of progressive knowledge around energy and climate change issues, the parties experienced a downgrade in their expectations due to the difficulties of advancing toward strong climate protection and RET transfer agreements. Finally, in 2015 during the COP 21 in Paris and since Kyoto in 1997, the Paris Agreement was a refreshing moment. The greatest point of the Paris Agreement was the National Determined Contributions (NDCs) pledged by States. One of the objectives was to keep the global temperature rise this century well below 2 degrees Celsius considering pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius (UNFCCC, 2015). The agreement was a reasonable restart, considering the IPCC projections. However, at the same time, some other risks came up and still can compromise the achievements of COP 21, are those: a) the low level of emission reduction commitments made so far; b) the low deployment rate of low-carbon technologies, and; c) the centrality of the so-called negative emission technologies, which are crucial in most scenarios but remain largely hypothetical at the moment (Bonnet et al., 2018, p. 4-5). Summing up, the risks are related to the absence of a massive diffusion of low-carbon technologies because the Technological Mechanism, even though discursively reinforced, remained the same. Partially because of different economic performances and the difficulty of transferring technologies once protected by regulations (such as the IPR discussed later). Pursuing these types of technologies can contribute to a considerable reduction of mitigation costs (Iyer et al., 2015), as well as provide answers to the trade-off between energy security and climate change (Sovacool, 2011; Junior et al., 2011). The role of technologies became serious because of their pragmatic contributions, and since then, the COPs started to give more attention to renewable energy technologies than before.

The most recent decision is the Technology Framework adopted at COP 24 in Katowice in 2018. The measure plays a decisive role in "improving effectiveness and efficiency of the work of the Technology Mechanism by addressing the transformational changes envisioned in the Paris Agreement and the long-term vision for technology development and transfer" (UNFCCC, 2020). Among other decisions, it became clear that the energy sector represents a key factor. Reports by countries and the share of information about the actions from the sector are repeatedly more than twice as well as the encouragement to innovate via financial support from the Technological Mechanism and collaborate with different actors settled in different parties.

The evolution of the international meetings moving from biodiversity conservation in 1972 to more technological driven decisions toward emissions and energy paradigms to fight the negative future climate effects can be seen as a constant influence on how renewable energy knowledge is created and transferred. The more countries accord about the 'times up' moment for the reality as we currently know, the more they become interested in funding R&D activities for renewable energies. As pointed out, Bonnet et al. (2018) low-carbon technologies are fully determined by climate policies. Therefore, to accelerate the creation and diffusion of renewable energy technologies, the intensity and credibility of climate researches and policies implemented by parties involved with the Convention have to be high. The economic value of such innovation depends on the national level of governance and the level of coordination among countries (Bonnet et al., 2018; Haščič & Migotto, 2015).

The call for more international mechanisms to fund and support low-carbon innovations has been grown in the last years for the reasons already discussed. But with this societal challenge concern, considering the trade-off between climate change and energy security, arose lots of complications in the innovation process. RET are considered promissory and fundamental tools to robust the political and material answers against climate change at this point in history. Although the appraisal, the increasing demand for low-carbon technologies pressures the innovation cycle of research, creation, development, diffusion and final consumption. Those steps suffered from different complications that deserve policymakers attention and more technical advice. The next sections intend to discuss those.

2.1.2 Societal challenges and RET

One could mind that there is a run for low-carbon technologies development around the world. From the innovation cycle to international political commitments, these technologies are distinct from the traditional ones and can contribute to climate change efforts. Across the international, countries seek to achieve a high economic performance that is smart, inclusive and sustainable. But according to mission-oriented policies, (Mazzucato, 2013) this ambition can only be achieved if decision-makers rethink the role of the State in the economy. Considering some more conservative approaches, reach economic growth is only possible when the State shrinks itself into a "fixing market failures" strategy. The market-driven mechanisms are praised as the only neoliberal approach to create growth. Because the private sector is considered more efficient on innovation by its vigorous ability to invest strategically in key areas and guarantee and maximise rewards (Kattel & Mazzucato, 2018). This might be a reality for established base technologies or general purpose technologies (Bresnahan & Trajtenberg, 1995). In the Schumpeterian way of thought, they can be applied in the economy based on different combinations. In turn, they are also able to identify economic inefficiencies and some social problems.

But if one considers big challenges for the society, whether travelling to the moon, building an iPhone, connecting people via virtual connections or fighting climate change, it requires a lot of State driven mechanisms. Global challenges have been expressed as the 17 Sustainable Development Goals (SDGs), and they provide an excellent opportunity to set mission-oriented innovation policies around the globe. Disregarding each of the 17 SDGs' specificities, all of them can impact society, support industrial development, and create better living conditions (Mazzucato, 2013).

Governments aiming to shape future market structures via innovation policy must move away from fixing failures and moving to a more mission-oriented approach. By doing this, the key transformational mechanisms are set in the hands of those who are more interested in solving societal problems and achieving economic growth (Mazzucato, 2013). There are uncountable experiences in which the public sector mutually and efficiently act with the private sector[6] to create technology by socializing the risk in the innovation process, but also socializing the rewards (Mazzucato, 2013). In this sense, the direction of the innovation research suffers a "normative turn". Instead, it is based on more decentralized actions, where the triple-helix (governments, academia and business sector) are influenced by international organizations (European Commission, UNFCCC, G77, IEA), philanthropies (Bloomberg, Global Environmental Facility, European Energy Fund) and social movements (Fridays for Future and Greenpeace) and therefore shape the innovation policy agenda (Kattel & Mazzucato, 2018).

This "normative turn" can be called mission-oriented innovation policy. Simply defined as policies toward societal problems (Mazzucato, 2013). Moreover, one Hekkert et al. (2020) call out that these types of innovation policies can be considered a societal challenge-based mission, which can be defined as "an urgent strategic goal that requires transformative systems change directed towards overcoming a wicked societal problem" (pg. 76). Thus, rather than pushing innovation and achieving economic growth, this systemic and decentralized innovation policy approach aims to coordinate different actors to formulate and support missions.

The last two sections briefly described an empirical example in which a mission-oriented policy approach was used. Based on identifying a common and international problem -climate change- and the probable answer -improving energy security via RET- there has been a conjunction of actors to accelerate the path in which alternative technologies can support the answer to solve some problems. Support RET is a decisive step that States can do, but sometimes they are controversial and recall lots of public criticism, (Mazzucato, 2015). Maybe because the process of innovation, as mentioned in the chapter 1, that sometimes is slow and can take decades to provoke social change (Breschi et al., 2000), or maybe the debate around its politics happen on a protected space (Rogge et al., 2015) and the competing narratives limit the evolution (Avelino, 2017). In any case, the State's mission has to be followed by some funding mechanisms where banks for development, philanthropy institutions, and investors can understand its long duration and the probable global benefits in the upcoming years. Despite a big push in the 1970s, green energy industries are still in the early stage, they are largely uncertain, and the market by itself cannot push them forward. Partially because of

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[6] We acknowledge that some distortions of this relation can be corruption or money laundry. However, in our sense and as a goal to be pursued in this model, it is about a creation of policies that avoid the traditional way of public sector financing private sector projects -socializing the risks-, but in the end, the society does not being rewarded -privatizing rewards- with depletion of such technology at affordable prices, for example.

the energy infrastructure that does not consider alternative sources, partially because the business sector is unwilling to enter until the riskiest and most capital-intensive investment happens (Mazzucato, 2015). The State can be more proactive and ”aggressive” by defining the strategies that will call on more investors and keeping the private and civil society as actors constantly aware of the next steps, failures and successes (Mazzucato, 2013). The engagement of other sectors along with the public and private should be more encouraged.

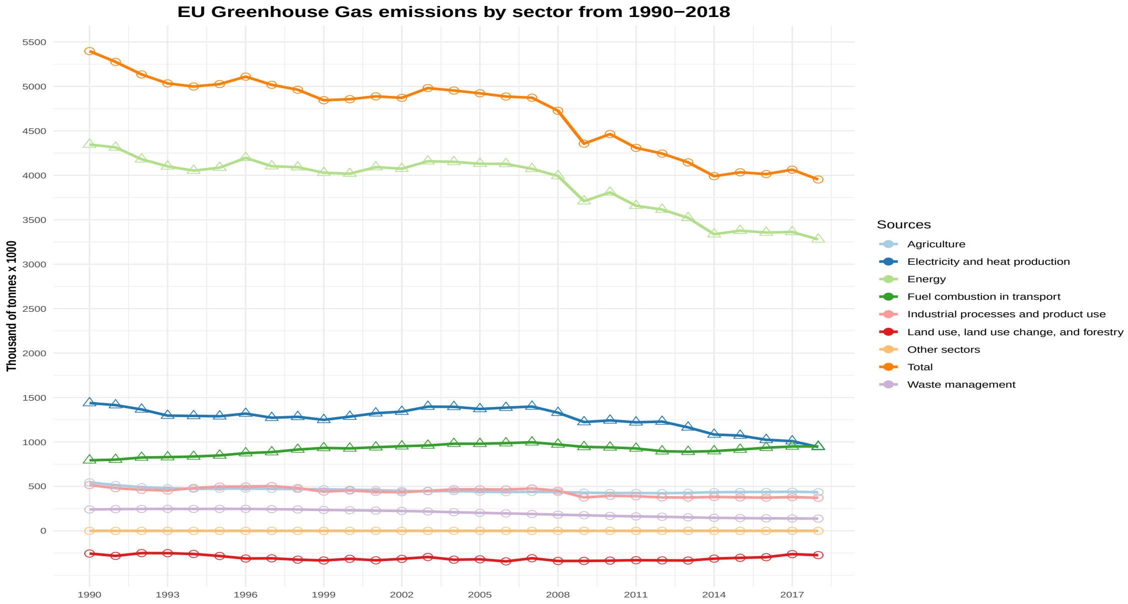
These last three sections discussed the foundations of energy security and climate change nexus. It was identified the complementarities and trade-offs between them and the evolution of international concerning under these trade-offs. Low-carbon innovations became a central point in the international environmental efforts, and the coordination of policies toward RD&D can certainly play a decisive strike in world politics. One of the most important actors in this manner is the European Union. The Union has a comprehensive institutional framework to stimulate the generation of RET and fight climate change. They are the main pillars for the European Commission and the last ten years discussions (European Comission, 2020). The next section cast light on how the EU makes sense of our main problem. As an analytical movement, we define some of the Renewable Energy Technological Innovation System (RETIS) structures in the European Union. Then, we try to analyse some of the main structural aspects and possible complications within this system, creating a background for further analyses.

2.2 European Union in the climate-energy innovation context

Although States traditionally addresses societal challenges initially because it rests on national decision-makers, some upcoming discussion identifies analogous examples on an international level (Mazzucato, 2018). The European Union (EU) in interaction with its Member States would be one of those examples. Since Rio Summit in 1992, the EU is notably one of the parties more interested in the progressive reduction of emissions. It has been creating political initiatives that could tackle climate change problems. EU has developed in the last years a comprehensive framework for policies and practices related to climate change mitigation and energy security, for instance, the Emission Trading System

(ETS)[7], the Energy Union[8] and the Effort Sharing[9] among others. However, the energy sector still shares more than 60% of total emissions, as shown in Figure 2.3.

Figure 2.3: EU Greenhouse Gas emissions by sector from 1990-2018



Source: (Eurostat, 2020c)

EU is still high energy intense even with a short availability of natural resources, which requires more efficient technologies to shift the indicator. Maltby (2013) affirms that because of the unavailability of resources since the European Community for Coal and Still, EU stands under a deep dependency on fossil fuels from external providers, which eventually designed the European electrical sector with difficulty to absorb renewable innovations. This requires some institutional modifications as a whole. The greatest challenge here is reducing energy use and emissions, highlighting the advance in infrastructure and industries and keeping the economy at full operation (Energy Union, 2019; Málek et al., 2018). However, not all State Members can afford the impacts that a transition has on other sectors within the European Union (von Hippel et al., 2011). To promote a shift in the energy sector (mainly in the electric one) with renewables as top priorities has some risks: intermittence of the energy

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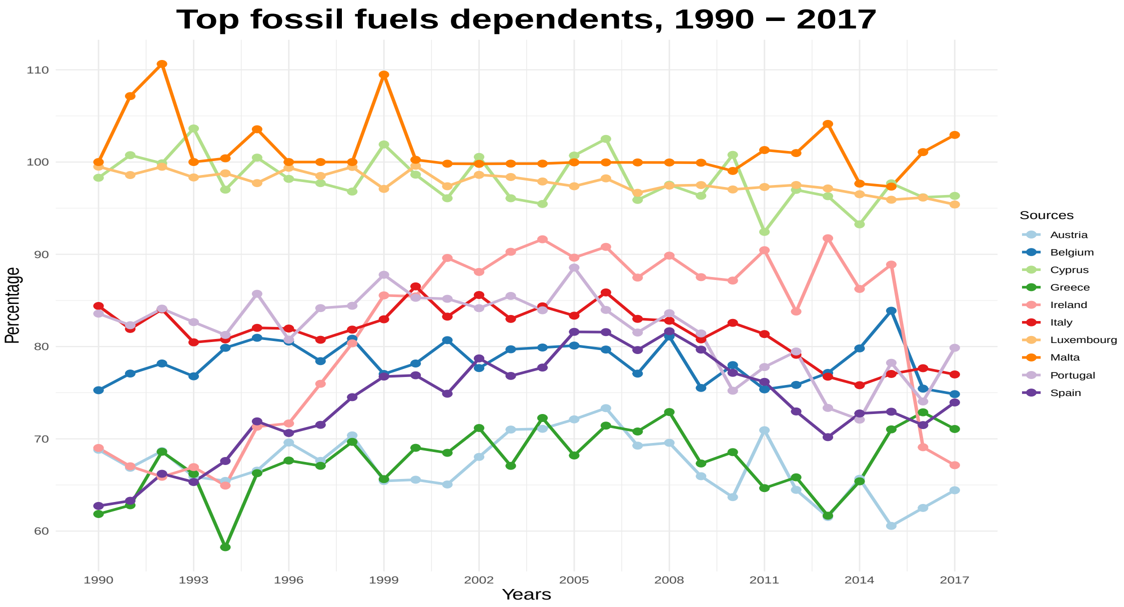
[7] "The EU emissions trading system (EU ETS) is a cornerstone of the EU's policy to combat climate change and its key tool for reducing greenhouse gas emissions cost-effectively. It is the world's first major carbon market and remains the biggest one." (European Comission, 2020)

[8] The Energy Union "aims at building an energy union that gives EU consumers - households and businesses - secure, sustainable, competitive and affordable energy." (Energy Union, 2019)

[9] The Effort Sharing legislation establishes binding annual greenhouse gas emission targets for Member States for the periods 2013–2020 and 2021–2030. These targets concern emissions from most sectors not included in the EU Emissions Trading System (EU ETS), such as transport, buildings, agriculture and waste. (European Comission, 2020)

and the unpredictable reaction on the demand and supply sides (Junior et al., 2011). It is possible to have a glance by the Figure 2.4[10] about how different are energy needs for some top dependents, which also provides some estimates about how hard they have to push on energy policies and RD&D investments to overcome the current situation.

Figure 2.4: Top fossil fuel dependents, 1990-2017



Source: (Eurostat, 2019a)

Dependency is a type of indicator that reveals how deeply connected two nations are based on the natural resource that they trade. On the one hand, it highlights the inefficiency of the energy sector and the average necessity to develop policies that overcome the situation. The funding for RET to raise its share is more than advised in these cases. On the other hand, it catches our attention that finishing a structural trade relation can bring some undesirable effects, such as international threats or compromise economic performance (Junior et al., 2011). The dependency is a complicated element that brings some international political conflicts and economic issues. In 2017, the dependency rate was equal to 55%, which means that more than half of the EU's energy needs were met by net imports. This rate ranges from over 95% in Malta, Luxembourg and Cyprus to below 15% in Estonia and Denmark. Dependency is a type of indicator that correlates But the problem is that the EU needs to import energy resources from third countries, as possible to see by the Figure 2.5. Certainly, the EU has a great dependency rate on Russian products.

The situation becomes even more complex when analysing Russian products' dependency based on historical and political relations. The EU is currently the second largest

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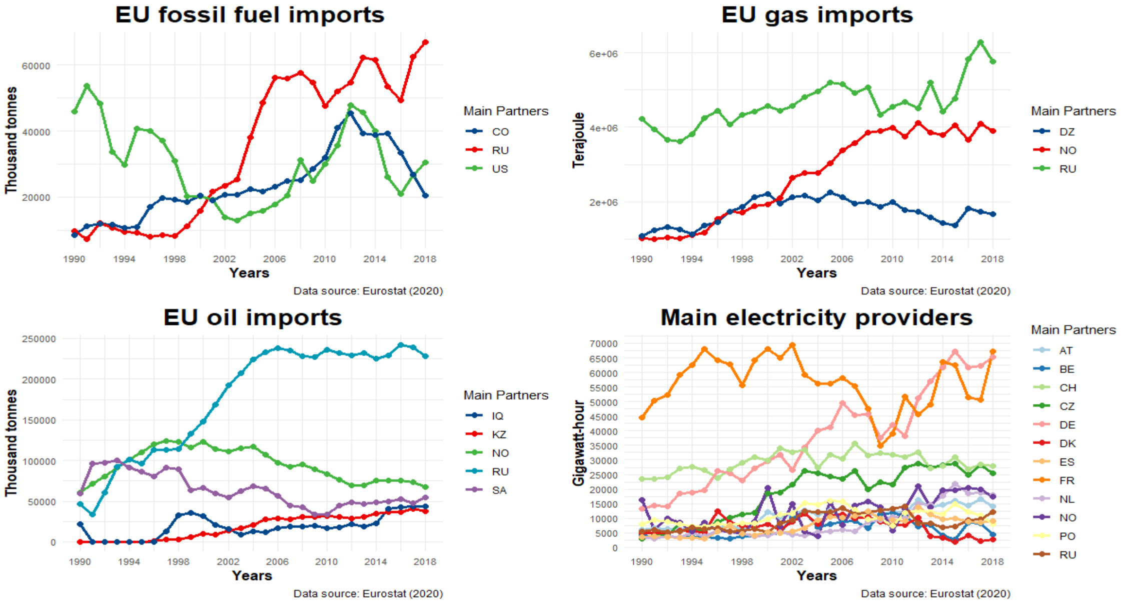
[10] Some countries surpass 100%, this indicates that the installed capacity is not fully used, it is inefficient.

Figure 2.5: Main energy provider partners, 1990-2017


EU fossil fuel imports

EU gas imports

EU oil imports

Main electricity providers

Data source: Eurostat (2020)

Data source: Eurostat (2020)

Data source: Eurostat (2020)

Data source: Eurostat (2020)

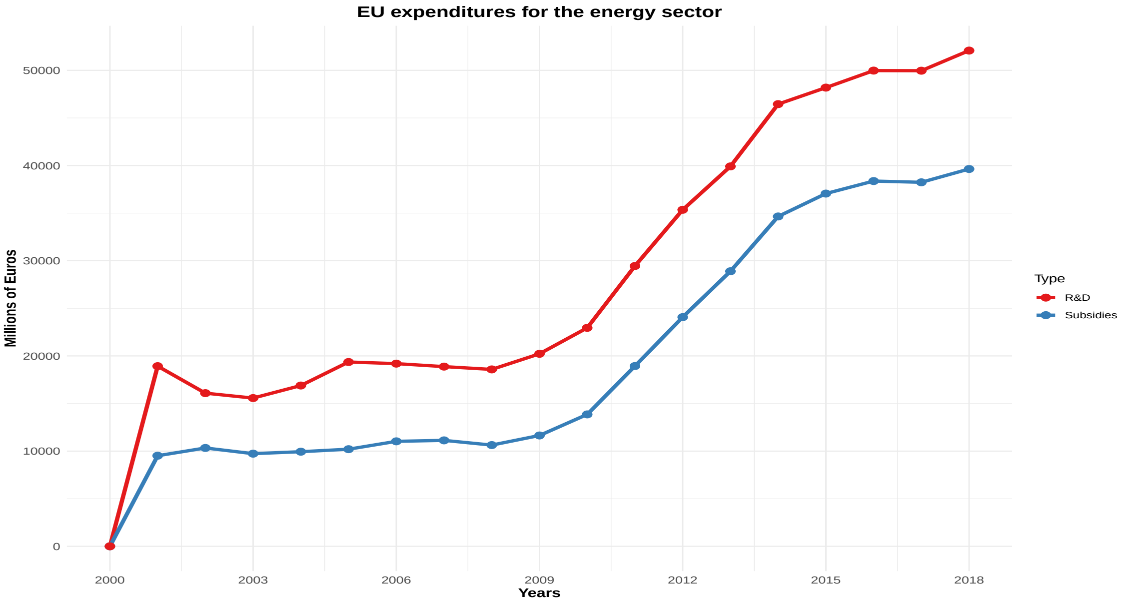
Source: (Eurostat, 2019c)

energy market globally, and the development of a network of climate technologies. If it really wants to produce effects, it has to take into account this event. Since the 1960s, the Soviet Union and the countries in central and eastern Europe have struggled with the natural gas trade because more than 25% of gas reserves are located in the USSR. In the last 30 years, the situation became even more complex after increasing demand due to economic and political circumstances. This means more people, more services and, necessarily, more energy supply. Also, the Crimea crisis revival in 2014 brought State Members some concerns about the future of energy provisions and raised the discussion about energy security. On the one hand, the Russian elite might use gas as an ”energy weapon” in the international geopolitical game. On the other hand, there could be an insufficient supply flow due to a lack of upstream sector investments and inefficient final energy use (Söderbergh et al., 2010).

Even with those appointments regarding energy security, as possible to see in the Figure 2.5, Russia still is one of the main providers of energy resources to the EU. This is a main international trade agreement between both for more than forty years. Russia had made average profits in the last ten years around 14,5 billion euros, with the largest amount in 2013 with more than 19 billion euros and smallest in 2016 around 8 billion euros. Considering that the total profit for Russian imports to the EU in 2013 and 2016 is 207 and 118 billion euros, the gas imports correspond to 7% and 6% (Eurostat, 2019c). Although the percentage seems small, it is the necessary amount to meet the EU energy demands. Without this, more than 1/4 of the EU population will be sentenced to live without electricity, and economic activities would not keep going on (Söderbergh et al., 2010).

The dependency is a problem, and to overcome it, there are some government initiatives to invest more in renewable technologies via RD&D for scientific development and enhancement of the performance, and subsidies to the private sector to accelerate the steps toward a sustainable transition. Investments in the RET come from different sources: The governmental sector, the business enterprise sector, the abroad private non-profit sector, and the high educational sector. Overall, the gross domestic expenditure on R&D is a reliable indicator that shows the pattern of investments in a sector with STI goals. Figure 2.6 provides an overview of the EU expenditures pattern for the energy sector based on this indicator. From 2009 until 2015, there was a boost in both forms of funding. It may have happened due to some innovation policies such as the Framework Programmes 6 and 7 (this will be discussed shortly) that allocates over 1 trillion euros during this time.

Figure 2.6: EU expenditures for the energy sector, 2000-2018

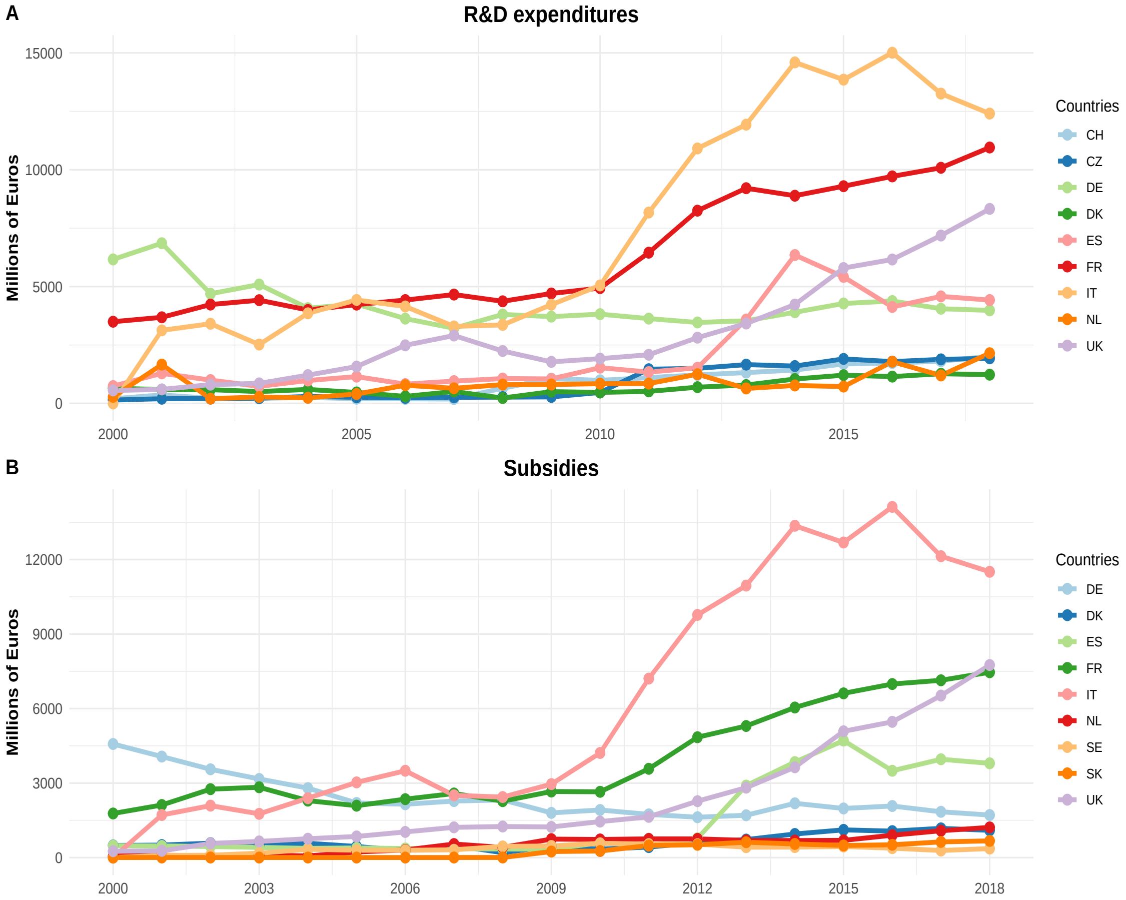


Source: (Eurostat, 2019b)

Graphs A and B on the Figure 2.7 show the Member States' allocation on the energy sector. On the road to scale up the energy sector, Italy, France, and the United Kingdom appear, since 2010, as the top investors in Europe. Italy experienced a boost in wind energy and solar power with plans to double their installed capacity of RET and reducing the dependency by half around 2030, following the strategy 2030 from the European Commission (Solar Power Europe, 2019; Wind Europe, 2020). Even though Germany and Denmark may have the most successful trajectory on the implementation of RET, their investments in the sector are lower if compared to the top ones. Those investments are mainly related to energy generation via sustainable means emphasizing renewable energies, CO2 capture and energy efficiency.

From the perspective of a sustainable transition, innovations play an important role in order to feed the tools to overcome the present situation. At the same time, since European Union is an integration among different States, on the one hand, it requires more coordination at the international level, with the EU and the Member States working closely to negotiate better conditions for the energy market. On the other hand, by the collaboration between national actors to provide innovative endeavours regarding energy technologies. The last point is one we would like to consider firmly.

Figure 2.7: Member States expenditures for the energy sector, 2000-2018



Source: (Eurostat, 2019b)

Creation and diffusion of knowledge are social phenomena, more precisely, a collective process that happens globally. Communication and collaboration between experts around the world have become a reality to improve innovation. At the international level, the knowledge collaboration allows joining into a global knowledge network (Graf & Kalthaus, 2018). Some authors call it embeddedness which ”refers to the process by which social relations shape economic action" (Uzzi, 1996, p.674). Therefore, being embedded in an international network of knowledge provides positive results for creating and further diffusion of knowledge (Powell et al., 1999), and also contribute to more advances in such research area (Graf & Kalthaus, 2018) (This discussion was better developed in Chapter 1). The international collaboration between inventors/innovators has an important influence on the form and how technologies advance. As discussed by Graf & Kalthaus (2018), the collaboration for renewable technologies around the world exists, and some policies adopted to influence the direction of progress.

The European Union, perceiving its huge dependency rate on the Russian energy resources, had decided to implement some important initiatives to accelerate the innovations for a more efficient and sustainable energy sector. By 2015, the European Commission[11] worked on a comprehensive strategy already mentioned, Energy Union, which "aims at building an energy union that gives EU consumers (households and non-households) a sustainable, secure, competitive and affordable energy" (Energy Union, 2019). The Energy Union has a more political bias as it contributes to creating capacities on the federal government from the Member States to develop plans that can ensure, among other dimensions, the efficiency of the energy use, climate protection and mitigation, and integrate the EU energy market (Energy Union, 2019).

Within the Energy Union strategy, research and innovation also received attention from the European Commission. In 2016, It was presented a Communication for a "comprehensive research, innovation and competitiveness strategy, which supports the objectives of the energy union" (European Commission, 2016). The Communication includes 20 measures focusing on what the EU can do to correct the market failure via regulations, giving policy signals and mobilising private investment. It also shows how the EU can set the direction with European public funding. Also, which touches upon the generation of clean electricity, on the year before the Strategic Energy Transition Plan (SET-Plan) was designed to "boost the transition towards a climate-neutral energy system through the development of low-carbon technologies in a fast and cost-competitive way" (European Commission, 2015). The Plan focused on promoting cooperation among scholars, inventors and research centres in the EU for Photovoltaic (PV) and Wind energy technologies to enable the fast transition.

Of course that the European Union has an important role in the green economic transition by funding RD&D and connect actors across the region. In addition to its efforts, some Member States have presented important political contributions to boost renewable energy technologies at a national level and cooperate with their neighbours. The well-known

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[11] European Commission is a decisive driver in the formulation and coordination of missions. It promotes the general interest of the EU by proposing and enforcing legislation as well as by implementing policies and the EU budget. It is fully responsible for gathering Members into political discussions

Energiewende from Germany is one of the most important programmes in this manner. As Cantner et al. (2016) argues, Energiewende and other policies had some positive impacts since 1990 on developing PV technologies and connecting inventors inside the country.

In addition Lipp (2007) compares the three main important cases by the begging of the XXI century for the energy transition in Germany, Denmark and United Kingdom (UK). Despite some differences in how they conduct the implementation of the energy policies, Germany and Denmark achieved some positive outcomes. For example, Germany is a world leader in renewable generation, Denmark is a country with more installed capacity for RE, and UK with a small RE sector. But the effects on the knowledge spillovers are by far the most important, in a sense that German and Danish innovators started to collaborate with different countries, as well as their policies became foundations for policies in other countries such as Portugal, Italy, Spain and France (Ferreira, 2017).

Although all of these packages, the most fundamental part on this behalf are the investments in the development of innovations and technologies to answer societal challenges. Since 1984, the EU promotes Framework Programmes (FP) as political tools to boost RD&D. The FP6 and FP7 sealed the period from 2002 to 2013, accounting for 66 billion euros and many enhancements for renewable energy knowledge and technology (European Commission, 2020b). The eighth edition, Horizon 2020, was the latest successful programme in this manner. By coupling with research and innovation in a broad sense and in every science area, the package could help to improve industrial leadership and tackle societal challenges, with world-class science and expanding the horizon to innovation in the public and private sector. Among the societal challenges, it is possible to find proposals that touch upon 'Secure, Clean and Efficient Energy' (European Commission, 2020b). This is in line with what we mentioned before regarding incentives to innovate in the energy sector.

The programme has been going from 2014 until 2020, fully seven years, with almost 77 billion euros of funding to the private and national public sectors. The 28 EU countries could have applied. A second 12 countries group named Associated Countries (non-EU but European countries) and another 10 countries group from the rest of the world (non-European countries). After fully six years of the project, the 'Horizon 2020 First Results' report showed that a total number of eligible applications in full proposals was 123 334 under the first 100 calls, and the United Kingdom, Germany and Italy are in the first, second and third positions respectively (European Commission, 2020c). In addition, the brochure 'Horizon 2020 In Full Swing -Three Years On – Key facts and figures 2014-2016' provides a follow up with the main achievements, noticing that from the total EU financial contribution allocated through Horizon 2020, more than 22 billion euros were received for sustainable development and climate change (European Commission, 2020d). Under the Horizon 2020 the "A European Green Deal" call is the last and biggest one, counting with more than 1 billion euros. Among other areas, it stresses the commitments toward "Climate Action" and "Clean Energy" endeavours (European Comission, 2020). Based on the data of the applicants (European Commission, 2020b) that during these seven years and with a high investment in research and innovation, lots of collaborations between actors from different countries were made.

The Horizon 2020 ended up in 2020, succeeded by Horizon Europe. Based on the Sustainable Development Goals, the Horizon Europe is the new package signed in 2019. More explicit than before, it is oriented toward "Mission Areas" in the XXI Century such as: Adaptation to climate change, including societal transformation; Cancer; Climate-neutral and smart cities; Healthy oceans, seas, coastal and inland waters, and; Soil health and food. The new package will provide more than 100 billion euros in research and innovation from 2021 until 2027. It follows the idea of societal missions (Mazzucato, 2018) that prioritise citizens by boosting innovations with sustainable means and eventually generating economic growth (European Commission, 2020e). Therefore, it is possible to affirm that, even if the trade-off between climate change and energy security remains in Europe along with its high level of energy dependency since 1992, many political tools were developed to overcome it. Overall, considering the mix of innovation policies, by investing over 190 trillion euros from 1984 until 2020 and using instruments to arrange medium and large sized collaboration groups among different countries (European Comission, 2020), this contributed to form a network of experts that created knowledge to fight climate change and energy security.

Finally, the trade-off between climate change and energy security seems to be addressed thoughtfully in the European Union. This constitutes our technological factors under scrutiny. RET are the core technologies that enable collaboration among experts in our network. Solar power and wind energy technologies are the main drivers in this process because of their clean, renewable and low environmental impact characteristics. The share of these sources increased from 8% to 17% from 2004 until 2018, while fossil fuels decreased from 79% to 73% in the same period[12] (Eurostat, 2020a). Therefore, the trajectory of RET in the European Union is a fundamental data that allow us to track the dynamic relation between the R&D funding RET and the feedback in terms of technological advancement. In the next chapter, we cover the renewable energies technological trajectory.

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[12] The data available on Eurostat for the share of renewable energy start in 2004. For fossil fuels, it starts in 1990 and accounts for about 84% of the total energy mix for available energy, which corresponds to a decrease of about 10% if considered in this period

2.2.1 RET trajectory in the European Union

Technological trajectory is a set of innovations that systematically and consistently evolved in time with some goals. For RET, this happens partially because of the international commitment to climate change, as shown in the last section. But also partially because of the amount of EU funding for these technologies shown in Figure **??**. The trajectory only happens within a complex of policies, political efforts and economic context that facilitate the generation of artefacts and institutions (Hekkert et al., 2011).

Dosi (1982) affirms that technological change traditionally was characterised by two broad categories: demand-pull (praise attention over the market forces) or technology-push (describes the technology as a "quasi-autonomous" factor). They are self-explanatory and related to the degree of activities around a technology that boosts future enhancements. Thus, the technological change in our means is in line with the proposition of Dosi (1982), following the classical explanation about paradigm provided by Thomas Kuhn. He moves forward by acknowledging a "Technological Paradigm" or a Technological Research Programme[13]. By and large, this enables a discussion about shifts in the trajectory of technology in a broad sense, like the technologies to generate energy.

The shifts in energy technology are followed by the complex RD&D dynamics and the close relation with societal challenges in the XXI Century. The changes can be largely be represented by patent count and academic publications. The former tracks the number of applications for RET in the last years by a patent office, in our case, the European Patent Office - EPO. The latter tracks the number of papers published in journals that take into account RETs. To accomplish the task for patents, we searched on OECD REGPAT Database. REGPAT is a traditional database that links patents to its inventors and applicants (Maraut et al., 2008). The database concentrates on OECD countries and a few Non-OECD. It contemplates the European Union (28) countries before 2020, considering the process of UK disclosure from the EU. The total number of patents is 231.605 distribute among the CPC classes (Cooperative Patent Classification). The CPC classes are an extension of the IPC classes[14] divided into nine sections A-H and the special Y. For each group of similar technology, a CPC code is attributed, which can be used to track specific energy technologies. Then, we divided into two groups: Renewable Energy Technologies - RET with 218.617 patents and; Fossil Fuel Technologies - FFT with 12.988 patents. In both cases, we considered data from

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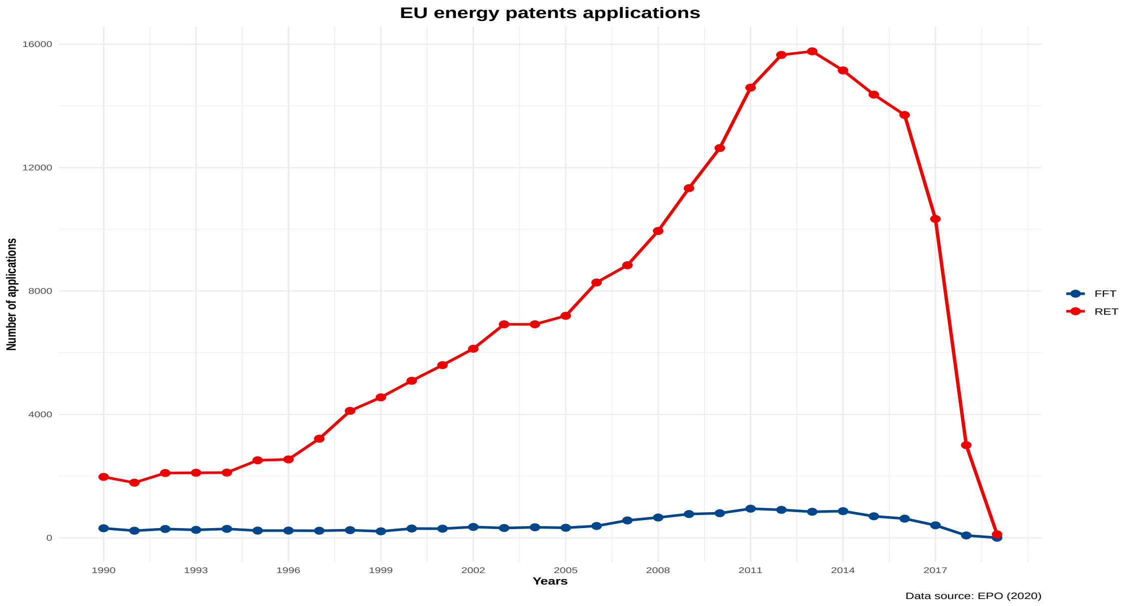
[13] For a deep discussion about the theoretical foundations and emergence of a technological change and technological paradigms, please read Dosi 1982

[14] The International Patent Classification - IPC provides a hierarchical system of language independent symbols for the classification of patents and utility models according to the different areas of technology to which they pertain. It was designed by the World Intellectual Property Organization in 1971. For more information, please check at: https://www.wipo.int/portal/en/

1990 until 2019. Even though our data ends in 2018, since the version used for the analysis is from 2020, we have a lag of 4-5 years to consider our data accurately. In general, patents take 4-5 years to be granted and counted as part of the inventory (Graf & Kalthaus, 2018).

We retrieved data from SCOPUS Elsevier for publications, using title, abstracts, and keywords (TITLE-ABS-KEY) as our default search field. After some selection and treatment, we found a total of 13.338 publications from 1989 until 2020. For a detailed description of the methodology, please check the Appendix A.2.3.

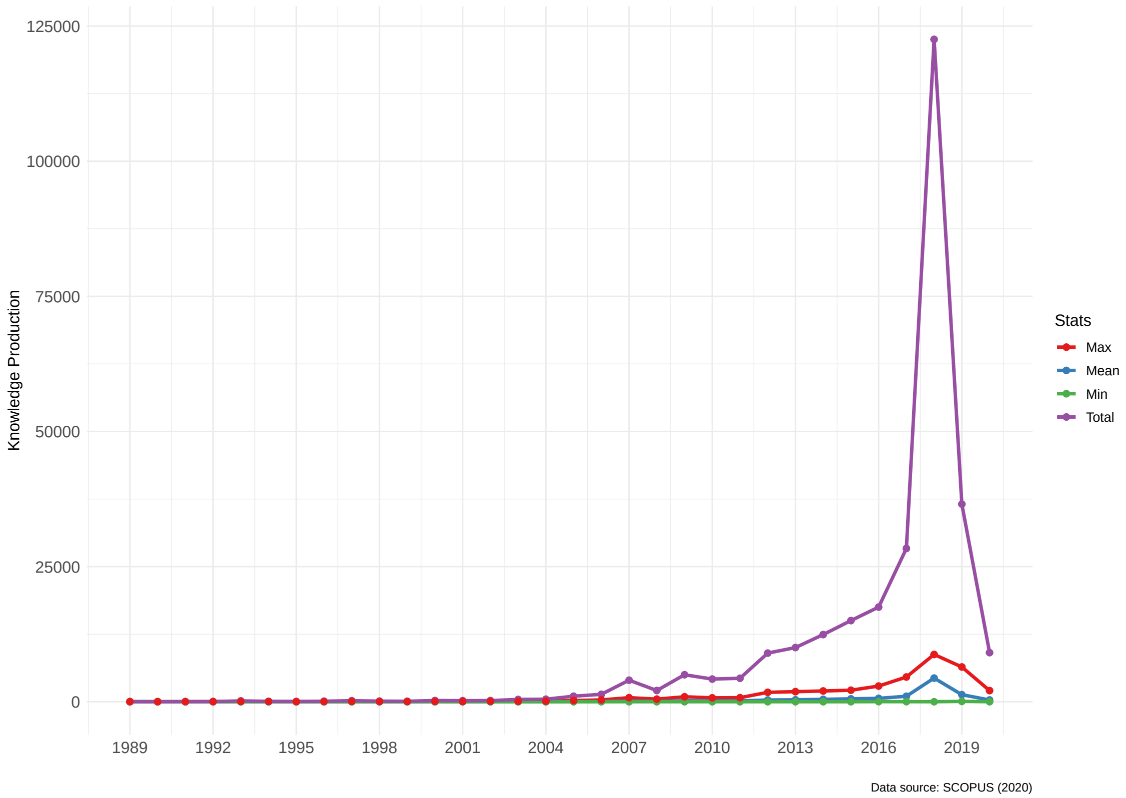
Figure 2.8: EU energy patent applications, 1990-2018



Source: (Maraut et al., 2008)

Figure 2.8 and 2.9 presents the evolution of energy technology patents application based on our data. The first huge difference between both groups is the number of applications. RET experienced a large increase compared to the FFT, and this is partially explained for some reasons. First, the OECD REGPAT database provides FFT data that improves efficiency in production rather than the overall number of fossil fuel technologies (Maraut et al., 2008). Those can be understood as technologies that incorporate sustainability indicators on FFT. Second, the critic is partially solved by some arguments raised by Nesta et al. (2018) regarding the maturity of FFT compared to RET. Fossil innovations are quantitatively fewer than renewables innovation because of the maturity of the industry. The World made its history based on the Industrial Revolutions and the large depletion of fossil fuel resources on the basics of energy economics, which maturated the FFT, and now they require more incremental innovations. Third, continuing to follow Nesta, RET are more likely to require intellectual property rights because they still suffer a moment of expansion and full private

Figure 2.9: EU renewable energy publications, 1989-2020



Source: SCOPUS Elsevir (2020)

and public investments because they are characterised as radical innovations (Nesta et al., 2018).

Fourth, RET are under World observation and hesitation because of climate change and the current awkward events, such as unexpected floods, hot weather and unexpected burn in forests. International organizations and social movements have been pressuring decision-makers to accelerate climate change mitigation measurements (which (Haščič & Migotto, 2015; Bonnet et al., 2018). Fifth, the funding for RET are larger considering the demand for more efficient forms to generate energy and the natural patent run that speed up the R&D activities exponentially. Sixth, the market structure for RET has been consistently growing (section 2.2.2 will provide a better discussion) (IRENA, 2020b).

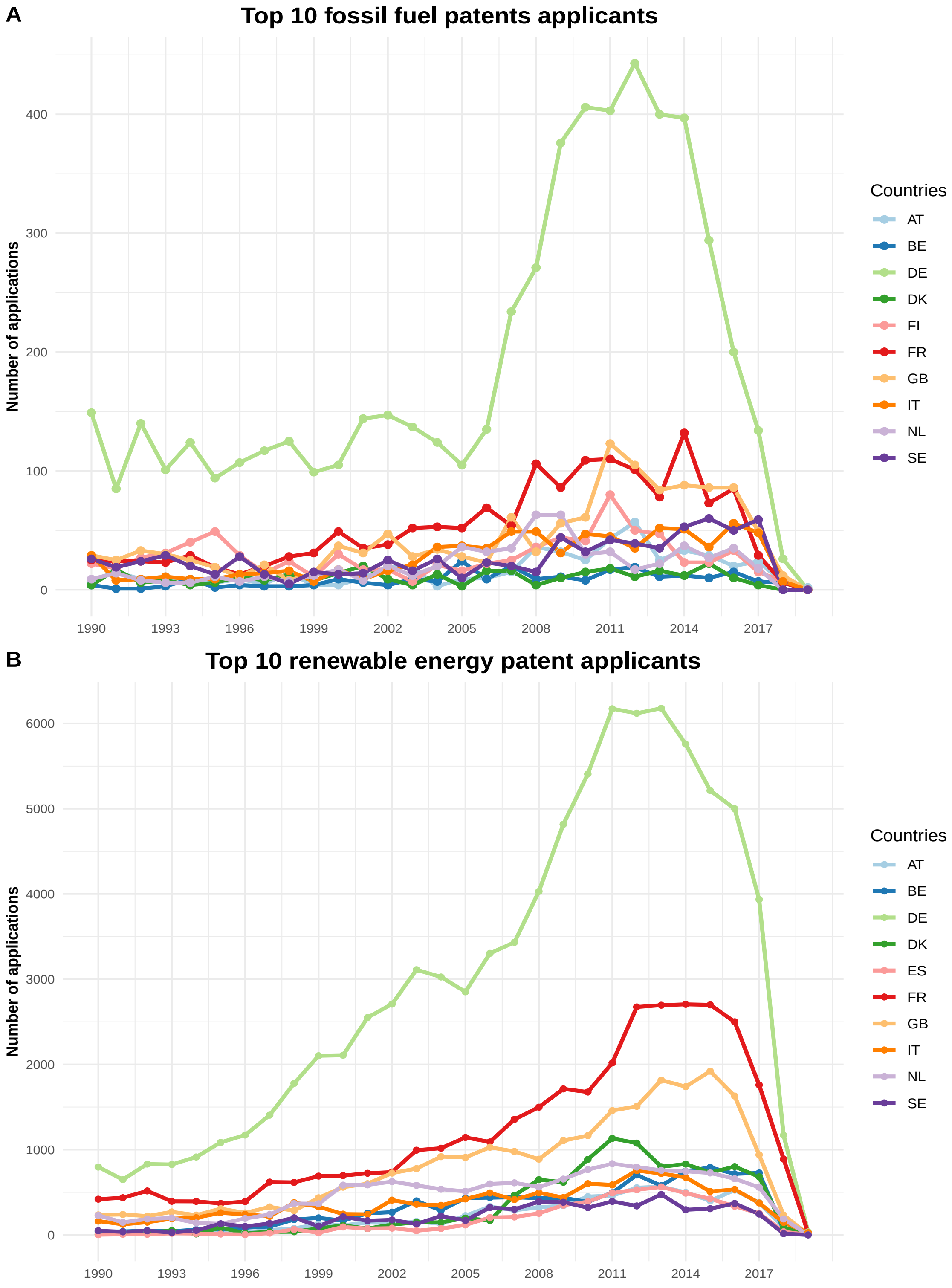
Also, it is possible to observe two moments where the curve of RET incline: around 1996-98 and 2004-06. Considering the 4-5 years gap, the first moment can be explained by considering the Rio Summit in 1992. This was the first time the world discussed global warming effects, even though climate change concerns were in their infancy (UNFCCC, 1992; Najam & Cleveland, 2005). At the EU level, following the international trends, the European Wind Energy Association - EWEA, publishes in 1992 its first action plan for European wind energy development, showing potential for an installed capacity of 4,000 MW by 2000; 11,500 MW by 2005; 25,000 MW by 2010, and; 100,000 MW by 2030 (Wind Europe, 2020). Thus, the beginning of researches about climate change also can explain the small inclination and its messy but challenging diffusion.

Considering the second period, The COP in Kyoto 1997 and Marrakesh 2001 developed the previously mentioned ”Consultative process” that eventually formed the Technology Transfer Framework and the Expert Group on Technology Transfer. Close to the entry into force of the Kyoto Protocol, the collaboration among experts and international hesitation to get ready for the environmental negotiations benchmark may have contributed to the increase (UNFCCC, 2004). At the EU level, European Commission published the White Paper for a Community Strategy and Action Plan, upgrading its predecessor Green Paper from 1995 to double the share of renewable energy sources by 2010. It was expected some smaller contributions from PV (3000 MW), geothermal (2500 MW) and heat pumps (2500 MW) (European Comission, 2020). EWEA publishes in 2001 the next action plan for installed capacity in Europe: 8,000 MW by 2000; 40,000 MW by 2010, and; 100,000 MW by 2030 (Wind Europe, 2020).

Figure 2.10 provides an overview of the patent race for renewable energy technologies among selected Member States, while Figure 2.11 provides an overview of the top publisher countries. Germany runs far from its neighbours in the EU in the patent count. The German case is known as a successful one, and since the 1970’s the country experience important investments in RET (Cantner et al., 2016). The 1000 Roof Program from 1992 for solar power, the 100/250 MW Wind Program in 1989 and the Electricity Feed-in Law increased the private and public interest for RET and FFT to turn energy technologies more efficient and viable for diffusion. Also, the Renewable Energy Sources Act since 2004 increased RD&D activities (Cantner et al., 2016). Although Germany has more research centres than the UK, it stays in the second position when looking at the publications. The country counts with important well-known research institutes, the Fraunhofer Institute, Max-Plack and Helmholtz, and all of them have specific research lines for energy transition and sustainable development (European Commission, 2021b, 2000). In time, the share of renewable sources for electricity generation increased to about 30% in 2019, an important amount when considered 2010 before Energiewende, where the share was about 10% (IEA, 2020). Publications have the UK with the first position. This might happens because of SPRU, one of the most traditional centres to research things related to innovation. But also, there are at least 7 institutes that are fully dedicated to research renewable energies (European Commission, 2000, 2021b).

France is the second in the patent race. Although the country introduced researches on renewable energy policies in 1985, this is late considering the European context (John-

Figure 2.10: Top 10 energy technology patent applicants, 1990-2018

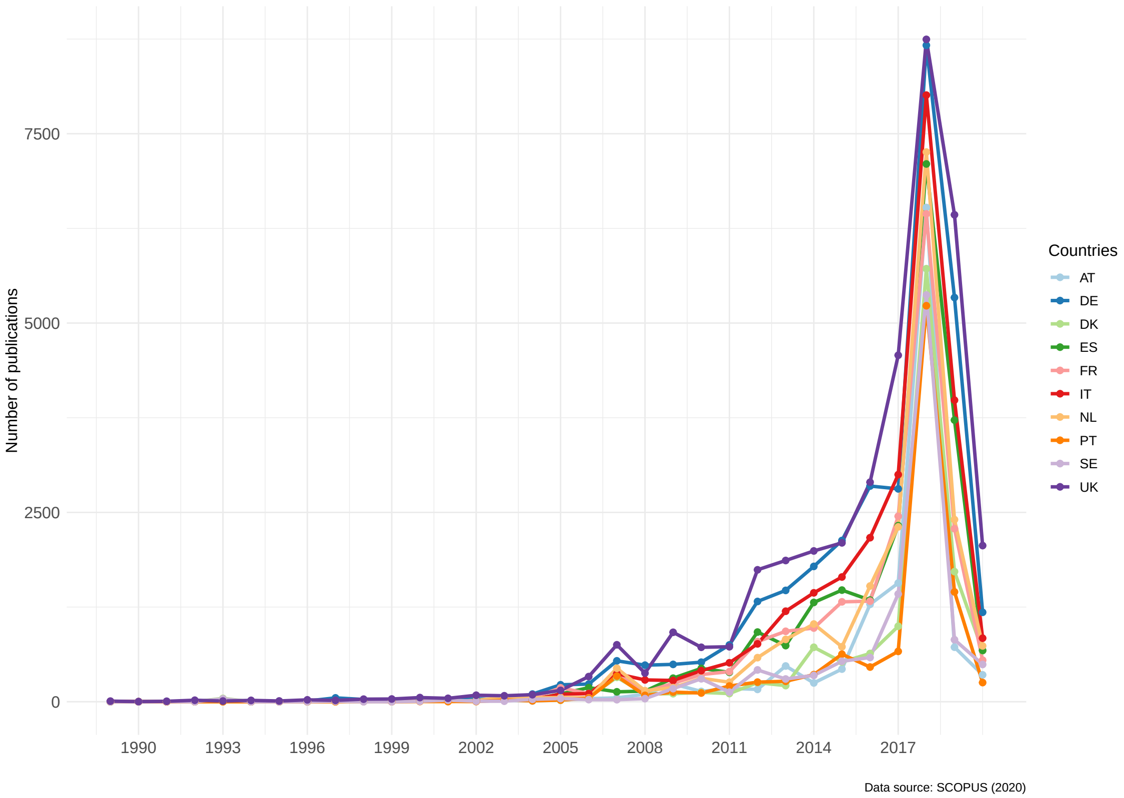


A Top 10 fossil fuel patents applicants

B Top 10 renewable energy patent applicants

Source: (Maraut et al., 2008)

Figure 2.11: Top 10 publisher in renewable energy, 1989-2020



stone et al., 2010). Even though RD investments have been growing (Eurostat, 2019b), the willingness to move from nuclear (which represents over 75% of the electricity generation) to renewable sources seems not to be shining. So the patent count suggests that France followed the international tendencies but did not fill the energy plans with a structural transition. Further information would be necessary to address a better explanation of the French case.

Although the graphs do not show some comparable relevant improvements, Denmark and Netherlands had remarkable trajectories. The Netherlands have one of the most important research institutes for RET. The Copernicus Institute of Sustainable Development has contributed to energy policy analysis and theoretical foundations for energy transitions for a long time (Kemp et al., 2007). The Transition Management (Loorbach, 2010) and Technological Innovation System (Hekkert et al., 2007) approaches had partially its foundations and important contributions from there and the studies around sustainable transitions surpassing different disciplines. For example, renewable sources' energy generation increased from about 140GWh in 1990 to about 17GWh billion in 2019, due to the project implementation transition management from 2002, which enabled from 2004-2007 more than 160.2 million euros used as part of the transition project (Kemp et al., 2007).

Denmark is considered the most energy secure and sustainable country among OECD members. The country reduced its dependency on external sources from 100% in the 1970s to 0% in the 2000s (Eurostat, 2019a). In 1985 the danish energy policy took advantage of the country's natural fast wind conditions, and the government agreed with the electricity firms to install 100 MW of wind capacity in five years (Sovacool, 2013). This was followed by the Danish Wind Turbine Guarantee, reducing the risks to support the radical innovations by users and the private sector, which boosted R&D activities. As a result, wind energy generation grew from 3 GWh in 1978 to around 7809 GWh in 2010. The country still depends on fossil sources, but more than 50% is supplied with renewable energy technologies (Sovacool, 2013; IEA, 2020).

Finally, based on EU political efforts following the international tendencies to fight climate change, the Union set RET as a central discussion for the energy sector, increasing public and private investments and promoting rapid growth of the knowledge production for renewable energy. A market maturation followed this since the 1990s to supply the energy transition. In the next section, we continue to scrutinize the main RET within the EU renewable energies market. It is important to note that the recent energy policies put solar power and wind energy as the core drivers for energy transitions, this is why in the next section, the market structure is dedicated to them.

2.2.2 Wind energy and solar power market structure

Over the last decades, the use of wind and solar energies has been growing in the EU. They are key technology alternatives to implement energy policies that are aligned with international commitments. The policy framework to boost renewable energy diffusion in the EU has its roots in 1992. However, it is possible to track the first robust and regional policy in 2001, only nine years later, with the Directive 2001/77/EC of the European Parliament on Electricity from Renewable Sources in the internal market. This was followed by the Directive 2003/30/EC, and together they formed the first energy policy framework in European Union (Wind Europe, 2020). By 2009, a new Directive 2009/28/EC came into force and is still on. It repealed the last two directives from 2001 and 2003 and committed Europe to achieve 20% of its energy from renewable sources by 2020. Furthermore, the Directive established that every Member State had to adopt a National Renewable Energy Action Plan (NREAP) and submit it to the European Commission. Every NREAP must contain a roadmap to achieve the enhancement by 20% by 2020 (Arantegui & Jäger-Waldau, 2018).

In 2015, the European Commission decided by the Energy Union strategy, as already mentioned. With the Paris Agreement, the EU took a new step toward the diffusion of RET by contributing with the 2030 Climate and Energy Policy Framework (Arantegui &

Jäger-Waldau, 2018). This one provides new energy infrastructure goals for the EU, setting energy efficiency as a top priority and affordable prices for customers. The last and most recent regulation regards the (EU)2018/1999, which emphasizes the current 2030 targets and advances on integrating a common energy market in the EU followed by investments in RD&D (Energy Union, 2019). On this behalf, the Energy Union strategy interacts with the Horizon 2020 programme by creating the renewable energies innovation policy framework that could foment the research and achieve the targets. The framework provided to the EU lots of changes by modifying the energy market and increasing the share of RET in the energy market by about 17% in 2018 of the total energy generation in the EU, which corresponds to 2 billion GWh. This follows the trend of investments in alternative technologies experienced by the EU since the beginning of the XXI Century (Eurostat, 2020b).

Create some impact over the electricity industry balances is the top priority because the transport industry continuously develops new models with hybrid technologies by producing automobiles that alternate between electric power and fuel or remain exclusively on electricity (of course, oil products have a larger percentage if compared to the other sources, but our goal here is to understand the RET-solar and wind-, in the EU context). To achieve the increase of 20% in the share of renewable energies by 2030 as part of the 20/20/20 strategy, (European Comission, 2020), some investments in RET projects were accomplished, which impacted the energy market. The Figure 2.12 provides a historical overview of the evolution of the energy market. All three graphs comprehend five main sources, namely: Geothermal; Hydro; Solar; Tide, wave, ocean, and; Wind. Even though Hydro presents larger numbers in the three indicators, according to the Energy Union, the depletion of renewable energies in the EU has solar and wind as top priorities. Graph A suggests an increase in the installed capacity[15], which is a reflection after the RD&D investments in the last years. Along with graphs B and C, they present the current status of the renewable energy market in the EU. From 2010 to 2018, the installed capacity of renewable energy in the European Union grew about 176%, while in the World, it grew about 196%, China 298% and the USA 179% (IRENA, 2020b).

Wind energy is notably one step ahead if compared with the other technologies. Nevertheless, it suffered many improvements in the last years, acquiring the first position in the rank. Wind energy industry diffusion in the EU has its roots right after the 1970's Oil Crises when a group of European agricultural machinery factors fly to California to assess the wind

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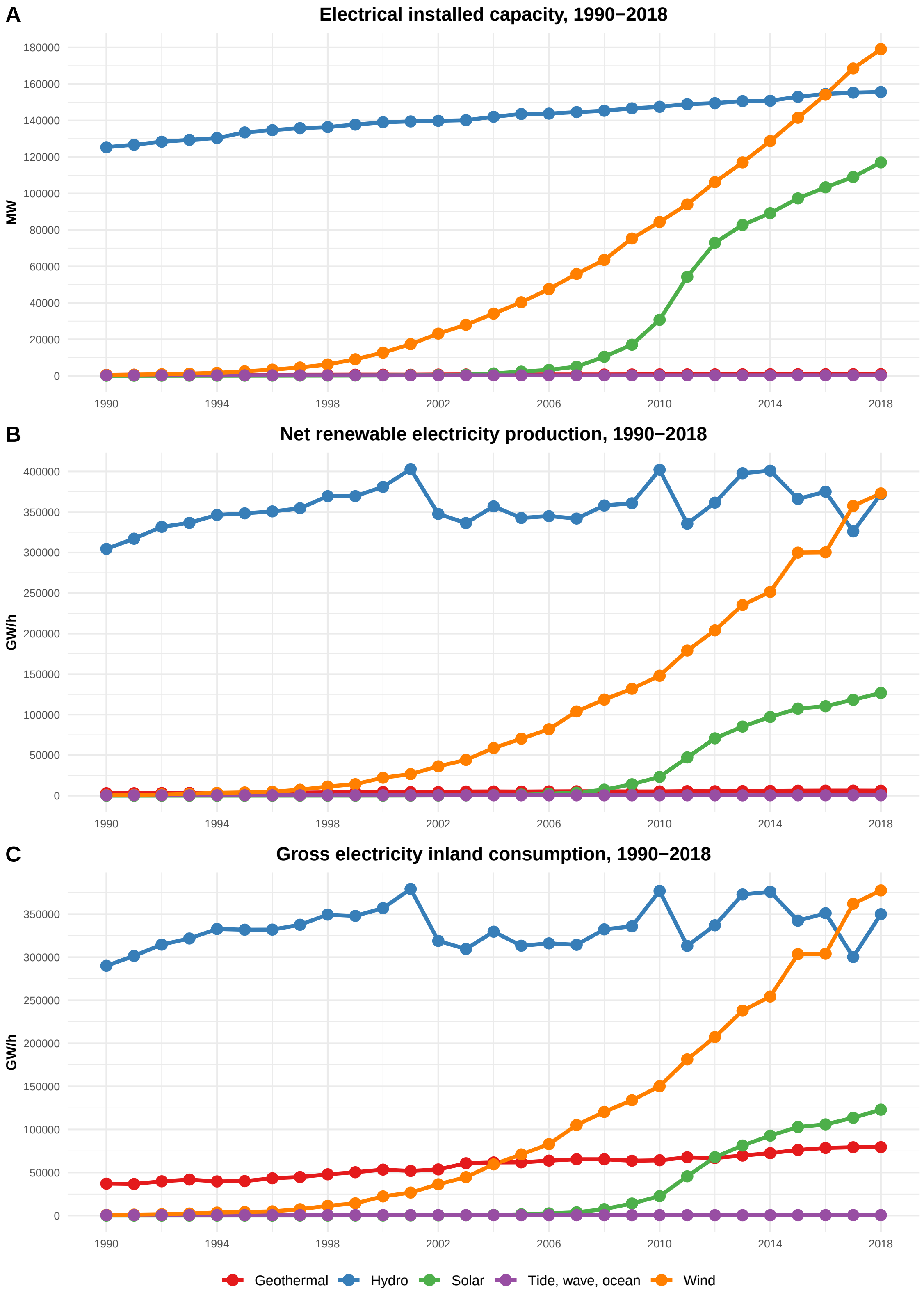
[15] Electrical installed capacity "represents the maximum net generating capacity of power plants and other installations that use renewable energy sources to produce electricity. For most countries and technologies, the data reflects the capacity installed and connected at the end of the calendar year. The data is presented in megawatts (MW) rounded to the nearest one megawatt." (IRENA, 2020b, p. 9). Moreover, energy generation or energy production are different from installed capacity because they comprehend the generation of energy under a certain period of time.

Figure 2.12: EU 28 renewable energy market, 1990-2018



Source: (Eurostat, 2020b)

market in the USA (Wind Europe, 2020). In 1982 the first wind turbine was installed in the first wind farm in Greece and then a further expansion in Europe. The first policy in this manner was in Denmark in 1985, followed by an EU funding project to increase the installed capacity by 97 demonstrations. The development and improvements in the technology happened to build generation capacity and enlarge the duration of the wind farms. It was impacted by the policies mentioned before and reached high levels of performance in the last years (Wind Europe, 2020).

The growth of the wind energy market in the EU went from about 84.398 MW in 2010 to 179.105 MW in 2018, a growth of 213% (IRENA, 2020b). In 2018 the greatest shares in the market for wind energy were Germany (58.843 MW), Spain (23.405 MW), United Kingdom (21.770 MW) and France (14.900 MW) (IRENA, 2020b). Those countries are historically ahead on the RET diffusion, highlighting Germany and France and their capacity to supply the EU with electricity, as shown in graph D in Figure 2.5. Those Member States in which the wind market is still small and have not experienced and expansion in the last years are Malta (0 MW), Slovakia (3 MW) and Slovenia (5 MW) (IRENA, 2020b). However, while the penetration of wind energy in the market will progressively reduce the prices in the spot market, oil and gas are still dominating due to their established technology status. Also, the cost of installation is still high, 12%, if compared to fossil fuels (Bórawski et al., 2019). The most recent technology is the repowering of old turbines, which takes down the over 25 years old turbines and the installation of new and more efficient ones. The benefit is the reduction of the number of turbines per wind farm. The last case study in Spain shows a decommission of 69 turbines with 33 GW/h of generation, replaced by 7 turbines with 66 GW/h of generation (Wind Europe, 2020).

Solar power in the EU receives the second spot of RET under large investments. Solar power can be divided according to its two destinations. Those used to heat are called Solar Thermal or Solar Heating (they are the same product). Those used for electricity purposes are called Photovoltaics (PV) or Concentrated Solar Power (CSP). PV is the simple conversion of sunlight to electricity. CSP concentrates sunlight heating, and then it converts to electricity. Solar panels were by Edmond Becquerel invented as we used today in 1839 in France. But it is possible to correlate the beginning of solar power depletion in the EU around 1991 with the Feed-in Tarif (FiT)[16] by Germany as part of the Electricity Feed-in Act, the first legislation to support renewable energies and also solar power in the world. At that time,

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[16] FiT mechanism involves the obligation on the part of a Utility to purchase the electricity generated by RES, paying a tariff determined by Public Authorities and guaranteed for a specific time period. A FiT's value represents the full price received by an independent RES producer for any kWh of electric energy produced, including a premium above or add to the market price, but excluding tax rebates or other production subsidies paid by the Government (Campoccia et al., 2014).

the installed capacity and energy generation in the EU were about 11.000 MW and 15.420 GW/h, respectively, and the generation was totally for electricity purposes, not for heating (Eurostat, 2020b). Specifically for the CSP, its origins are around 1984-91 in the US, but the initiative was decommissioned due to the drop in oil prices. However, it actually restarts by 2006 in Spain along with the FiT as an incentive to diffusion (Islam et al., 2018).

The solar power market grew in the EU from 30.887 MW in 2010 to 117.444 in 2018, and this corresponds to a 38% growth (IRENA, 2020b). The greatest share in the solar market was Germany (45.181 MW), Italy (20.114 MW), United Kingdom (13.118 MW) and France (9.617 MW) (IRENA, 2020b). Excluding Italy, they are the same countries compared to the wind market. Those Member States in which the solar power market is still small are Latvia (2 MW), Ireland (24 MW), Estonia (32 MW) and Croatia (68 MW) (IRENA, 2020b). Certainly, solar power grows faster than wind energy. An explanation can be related to the cost that is really low compared with any other technologies. They can pay back customers because the energy is generated inside a grid and sold via FiT to other customers or the main power plant. Also, it demands shorter space to install if compared to wind turbines, and the installation of the mobility models on top of cars, buses, and trains can be accelerated (Solar Power Europe, 2019).

Solar and wind technologies are the main drivers of the energy transition in the European Union. They have received a lot of attention from civil society and finance from private and public sectors. The number of policies provided for developing the RET in the European Union can be understood as an example of a mix of policies toward innovation. Once again, the evolution of the market is deeply related to the international commitments to fight climate changes, as it was possible to check previously, and the increasing of RD&D rates for it, which boosts the knowledge development. This only would be possible because of actors dedicated to the advance of RET in the world and inside the EU. In the next section, we provide an overview of some relevant actors in this large network.

2.2.3 Relevant actors in renewable energy technological innovation system

Identify the actors involved in the innovation process is a key step to a systemic analysis. Hekkert et al. (2011) pointed out that the actors ”involve organizations contributing to technology, as a developer or adopter, or indirectly as a regulator, financer, etc.[p.5]” The actors can create and diffuse a technology within the system, and identifying them is partially important and partially very difficult because of the variety of actors that a network can have. Since our definition of actors corresponds to many elements (knowledge institutes, educational organizations, industries, market actors and government bodies and supportive organizations), it would be not easy to track every node that compounds the system.

Some methodological strategies to overcome the messy construction of this actors framework were applied. The complete description of our methodology is in the Appendix A.1.1. We aggregated the actors into three categories: Academia, Market and Institutional Bodies. Academia groups the actors involved in the research centres, high education institutes and other educational governments. Market group industries, market actors and entrepreneurs. Institutional bodies groups organizations that may enable and support the technology advance. The actors were divided into two levels: International and Regional. International are those that do not belong exclusively to European Union, contrary to Regional, referring to those exclusively in European Union. Table 2.1 provides an overview of the most relevant actors. It would be impossible to fill a readable and analytical table with all possible actors in a system because actors involved in a system of the size of the European Union are a large number. So we intend to describe under the selected elements in each cell what other type of actors could belong to the category.

Table 2.1: Relevant actors

Type of actor	International level	Regional level
Academia	Erasmus+, DAAD, STRN, NEST	Energy cities association, Fraunhofer Institute, Max Planck Institute, Copernicus Institute, SPRU
Market	Russia and energy dependent partners	Wind Europe, Solar Power Europe, Siemens Gamesa, ENEL, Planète Oui, Bulb, EDP Renovables, and other reneawble energy companies
Institutional bodies	IPCC, OECD, Technology Framework, IEA, IRENA	European Commission, European Parliament, European Research council, European Innovation Council, Ministries for science, energy and environmental

Source: Elaborated by the authors

Beginning with the Academia actors, on the International level, Erasmus+ is a programme in which Master students and PhD students can apply for funding support for their research endeavours. This enables non-European scientists to have prolonged contact with different high educational institutes in European Union. This somehow can diffuse researches and knowledge connected to renewable energy. It is budget with 14.7 billion euros per year and since 2014 attended over 4 million people, by linking over 125.000 high educational institutes and provide international collaboration in key disciplines (European Commission, 2020a). Although Erasmus+ might represent an institutional body, it is specifically for academic and scientific purposes. DAAD is another globally known scientific program to support non-German postgraduate students to receive funding from the German government by joining a high educational institute or research centre in Germany. It links ca 2.6 million academics inside and outside Germany, supporting housing, funding and the learning of German as a foreign language. In 2019 the budget was around 594 million euros (DAAD, 2020).

The Network for Early career researchers in Sustainability Transitions (NEST) is part of the Sustainability Technology Research Network (STRN). The STRN came first as a network able to connect academics research sustainability transitions worldwide by setting workshops and international meetings to exchange experiences. In 2020 it counted over 2000 scholars who are constantly joining web conferences, seminars and workshops. They encourage collaboration between members of different scientific fields under its research agenda for sustainability transitions. A larger part of them is interested in energy transitions varying on the scope and goals (STRN, 2020). The NEST is a community of PhD and researchers interested in sustainability transitions. It is a repository of opportunities and the diffusion of transition innovations (NEST, 2020).

On the Regional level, one can find basically high educational institutes and research centres. For example, the Energy Cities Association developed lots of researcher around societal challenges specifically for RET. Under Horizon 2020, it received over 14 million euros for researches. Fraunhofer Institute is one of the most important research institutes globally. From 2014 until 2020, it received, under the H2020, over 9 million euros. If considered the previous FP7, it received over 40 million euros since 2002, connecting Member States with over 11 thousand projects (European Commission, 2020b). The Copernicus Institute of Sustainability with the Science Policy Research Institute (SPRU) may have provided baselines to discuss energy transitions in the last 20 years. The Copernicus Institute bases its researches on the SDG and have a specific thematic group for the Goal 7 Affordable and Clean Energy, which historically contributed with papers and research projects to develop foundations for the energy transition discussion (Negro & Hekkert, 2008; Markard & Truffer, 2008; Binz & Truffer, 2017). SPRU is a classic research center for science policy, and the department for Innovation studies was once headed by Christopher Freeman. Nowadays they have a specific research activities for energy and sustainability. Also they account important scholars that embodied the energy security/climate change discussion (Sovacool, 2013), sustainable and innovation policies (Rogge et al., 2015), science and technology (Mazzucato, 2018) and the

Multi-level Perspective (MLP) (Geels, 2002).

For the Market category, we consider those actors that might play an important role in the Market structure of the European energy infrastructure. On the International level, we focused on Russia and energy dependent partners for some reasons already discussed. Russia, besides supply central Europe with fossil fuel imports, also has a dependent relationship with them. On the regional level Wind Europe (previously EWEA) and Solar Power Europe are institutes that can set advice policies and regulations to install wind energy and solar power inside the EU. They also provide information about the market trend for RET and future impacts (Wind Europe, 2020; Solar Power Europe, 2019). Siemens Gamesa, ENEL, Planète Oui, Bulb and EDP Renovables are firms that provide installation and generation of energy by RET. Siemens Gamesa is a fusion between the German Siemens and the Spanish Gamesa toward the fabrications and installation of renewable energy. The firm is over 75 countries around the world and over 105 GW of installed capacity (Gamesa, 2020). Also, from 1990 until 2020, they applied for over 2000 patents for RET (Maraut et al., 2008). ENEL Green Power is an Italian company for energy that has evolved in the last years toward a great share in its energy generation portfolio by RET. It has over 83 GW of installed capacity around the world, with over 80% in Europe (ENEL, 2020).

For the Institutional bodies category, we consider those actors that stimulate the research of the topic and enable collaboration among experts. On the international level, IPCC and the Technology Framework were already mentioned as organizations that enable collaboration for climate change and energy and climate technologies, respectively (IPCC, 2011; UNFCCC, 2020). OECD is an international organization where members can have access to renewable energy technology transfer between them. It is a closed space to shared sustainable and development common agreements. The International Energy Agency (IEA) and the International Renewable Energy Agency (IRENA) are international organizations committed to providing energy data and statistics, joining international meetings and advising governments toward their efforts to promote energy policies. They often publish assessments about the energy policies and their economic and infrastructural impacts (IEA, 2020; IRENA, 2020a). IRENA deals only with renewable energy diffusion by serving as an international platform for international cooperation and a repository of practices and political tools to encourage and enable the adoption of RET (IRENA, 2020a).

On the Regional level, the EU has a complex institutional structure in which all of them somehow contribute to the large adoption of RET. The European Commission is the most important actor because it can decide over new common policies for Member States toward RET (European Comission, 2020). As we already mentioned many times, it decided about the budget and the direction of new RD&D activities in the European Union. The

European Parliament would be the body where civil society can express their wills by vote. The Parliament have several Committees for a different topic, and one dedicated to Industry, Research and Energy. They commonly submit advice to the Commission, which can be transformed into regulation on the EU level (on Industry Research & Energy, 2020). The European Research Council (ERC) is the public body for funding scientific and technological research activities in the EU. It was formed in 2007 during the FP7, the predecessor of H2020. The ERC received 13 billion euros from 2014 until 2020 within the H2020, working directly for researching activities (Council, 2020). The European Innovation Council (EIC) does a similar activity as the ERC, but it stays on the commercialization side by financially supporting small-medium entrepreneurs (SME) and start-ups. In 2019-20 EIC budget was over 2 billion euros covering the innovation chain (pilot, 2020). Finally, each Member State in the EU has a Ministry that could deal with RET by legislating or just encouraging the infrastructure development. In turn, they can decide over important cooperation among countries for RET transfer or energy trade. The degree to which a Member can influence the system depends on the degree to which they encourage the diffusion and enhance installed capacity in the country.

Identifying those actors is important to analyse the evolution of the RETIS and understand its political implications. It is important to affirm that those elements in each cell correspond to examples of many actors that were filtered according to our methodology in the Appendix A.1.1. Some of these actors are actual nodes in the network. Some of them form the framework in which the RETIS is.

Finally, this chapter was responsible for achieving some goals. One of them was to discuss the evolution of the climate negotiations moving to a deep discussion of energy security and renewable energy technology diffusion. We pointed out the trade-off or complementarity relation of the energy security and climate change relation considering the CO2 emissions, which poses a societal challenge for governments. We argue that to offer some answers for it, a mission-oriented approach is necessary, in a sense that the EU, as a supranational institution, has enough political force to induce the creation and maturation of a renewable energy market. This is necessary because of the panorama of the EU energy sector. The Union decided to bold climate targets until 2030 by reducing 20% of emissions and increase in 20% the share of RET. The targets are set under a historical energy dependency from Russia fossil fuel exportations. Around this panorama, we start the analysis of the renewable energy technology innovation system (RETIS).

We defined the structures of the RETIS, identified the technology trajectories for RET, the market structure, institutions and actors. Our approach to analysing the trajectory was the patent count using data from OECD REGPAT Database and retrieving CPC classes related to it. We identified that wind energy and solar power are the core technologies around the energy transition process in the EU. We move forward with the market structure mapping and analysing the countries with the greatest share of RET and, on an aggregated level, the advances of the EU electrical market. We found out that there is an upcoming tendency to invest more in RET and that they actually contribute with environmental targets on a time frame. Last but not least, we identify some actors. Since this can be a messy step, we categorized three types of actors: Academia, Market, and Institutional. For each category, we provided examples of some relevant actors at an International and Regional level.

Concluding, the structure and boundaries of the RETIS are set. We found out that the EU invest and encourage Member States the adopt renewable energies at the first moment during this whole time, but after the Kyoto Protocol and COP 16 in Cancun in 2010, the knowledge and technology production experienced a large increase. Therefore, the EU created a structure to enable collaborations between scholars, industries, government and civil society. Our next step is to identify the network and discuss the evolution and functions of the RETIS. This is going to be done in the next Chapter.

Chapter 3

THE EUROPEAN UNION RETIS

The chapter is responsible for providing the social network analysis based on the TIS approach at the national level. We discuss the development of the European collaboration between experts by using knowledge production. This is the fundamental knowledge and technology flow in the network, notably new techniques and materials in terms of patents and scientific publication in terms of bibliography.

The chapter is structured in the following order. First, we introduce how our RETIS would look like, providing graphs and network statistics to help understand the network's evolution through the nine selected periods. Second, we discuss the mix of policies that accelerate or hold back the development of the RETIS. Here we highlight important actors and institutions. Third, we discuss some of the functions of a TIS that have shown importance in the Lower Scale.

3.1 Introducing the Renewable Energy Technological Innovation System - RETIS

The collaboration among scholars in every field of science has been growing exponentially in the last few years (Graf & Kalthaus, 2018). Also, evidence confirms that the more international the members are in the collaboration, the best the research will be (Wagner et al., 2017). The cognitive proximity between actors from correlated science fields nowadays does not often face geographic distances as a barrier. On the contrary, it is compensated with communication technologies that allow experts to perform KTT from long distances (Boschma, 2005). In turn, this speed up the number of collaborators for projects, and experts can rest over other types of proximity to collaborate.

Knowledge production became a central concern in European Union policies, firms and alike. Since the boundaries between the States are not high limitations for mobility and communication, the collaboration among experts to produce knowledge via patents and academic publishing is very often. According to Boschma (2005) the geographical proximity would be a traditional factor to enable collaboration among experts, but this is no longer a problem in the EU case. Figure 3.1 presents the configuration of the Schengen Area[1] in 2020, which is the passport-free travel area since 1995 provisioned by the Schengen Treaty. Schengen includes 26 EU countries, excluding Ireland, that maintains the opt-out[2] and operates its own common travel area with the UK, and four from outside: Iceland, Norway, Switzerland and Liechtenstein. Also, Bulgaria, Croatia, Cyprus and Romania are willing to join Schengen at some point in the future (European Parliament, 2020). Under the Schengen, over 3.5 million people cross borders between Member States without passport control every day. People can live in another Member State to work and study with a valid passport or identity card[3]. Even with the opt-out of Great Britain from the EU after 2020, there have been decades with lots of collaboration between them.

The Schengen enormously contributes to the dynamic contact with different people from different geographical locations, but precisely for experts' collaboration, through the XXI Century, it does not pay too much. On the one hand, if a PhD student decides to travel or move to another Member State, the bureaucracy remains steady because taxes are still applied. The study *in loco*, in contact with the "Foreign" supervisor, or a double-degree modality, has lots of contributions and is really valuable to experience different research methods. Of course, one can claim the fact that from Italy to Germany, the language pays back, and the misunderstanding can be really high. This might be a reality in small towns, but cities with an international University might not apply. The language of science, for better or worse, is English. And is more common that staff and members from Graduations, Doctoral Programs and Research Centers communicate with themselves in English, even at an average level. Researchers within this reality can do a pretty good job and work really fine on their projects.

On the other hand, collaboration among firms to produce patents can occur locally to see the artefact's development closely. But the designing of it can occur via virtual meeting respecting the distance or any other reasons that do not allow someone to be in the same location. Precisely, with the COVID-19 pandemic context in 2020, workers, who can work

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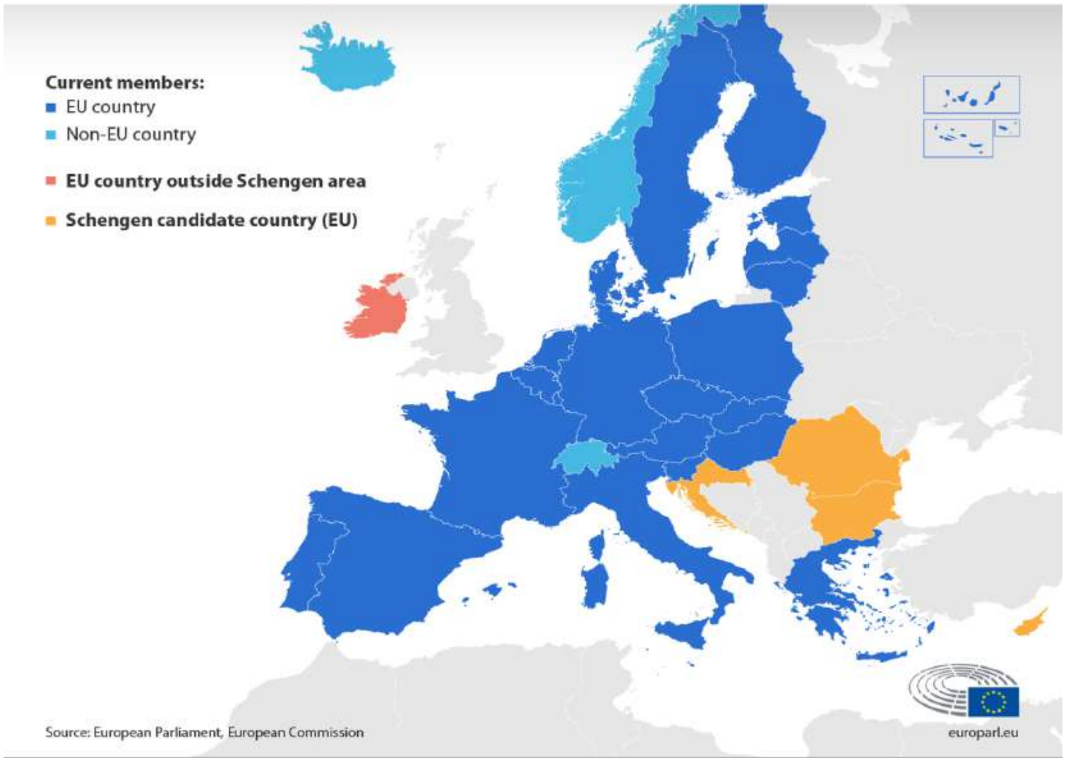
[1] As noticed before, Brexit reconfigured the European Union geographically and institutionally by exiting Great Britain out of the EU. We acknowledge this, but to assess the impacts on the collaboration among experts still requires more studies.

[2] Opt-out are decisions that a member of an integration can make in terms of some policies related to the integration. In the EU, the Schengen and the Euro are examples of procedures that one can opt-out

[3] The particularities for the security and migration brought by Schengen are also important (European Parliament, 2020; Ceccorulli, 2019), but they are not our objective here.

Figure 3.1: Schengen area configuration in 2020



Source: European Parliament (2020)

from home, had to continue their activities respecting social distancing. Of course, a home is not the perfect and infrastructural place to work, but by mobilizing applications to enable virtual meetings, geographical proximity is not a problem.

The RETIS is located inside the European Union, which makes the problems regarding institutional proximity (Boschma, 2005), considering the institutional frameworks of rules and norms, something that is partially solved. The European Commission (European Comission, 2020) partially solved. Several Framework Programmes, as already mentioned in Chapter 2, stimulated and supported the collaboration among experts via investments in R&D (European Commission, 2020e). But more than this, since mission-oriented initiatives or plans that intend to increase the share of renewable energies are decided inside the EU institutions, it is easier to accomplish some of these marks established in the plans. Summing up, until now, it is possible to affirm that our RETIS has institutional and geographical limitations that enable proximity among actors. The Schengen Space, where people, information, finances, and so on, have a relatively low level of restrictions to travel, can be understood as our institutional boundaries. At the same time, it allows the exchange of resources and research between actors. As a supranational institution formed by 28 Member States, the European Union constitutes our geographical boundary because our analysis restricts itself to the formulation of policies via the spillover of information generated inside these States.

3.2 Structure of the RETIS

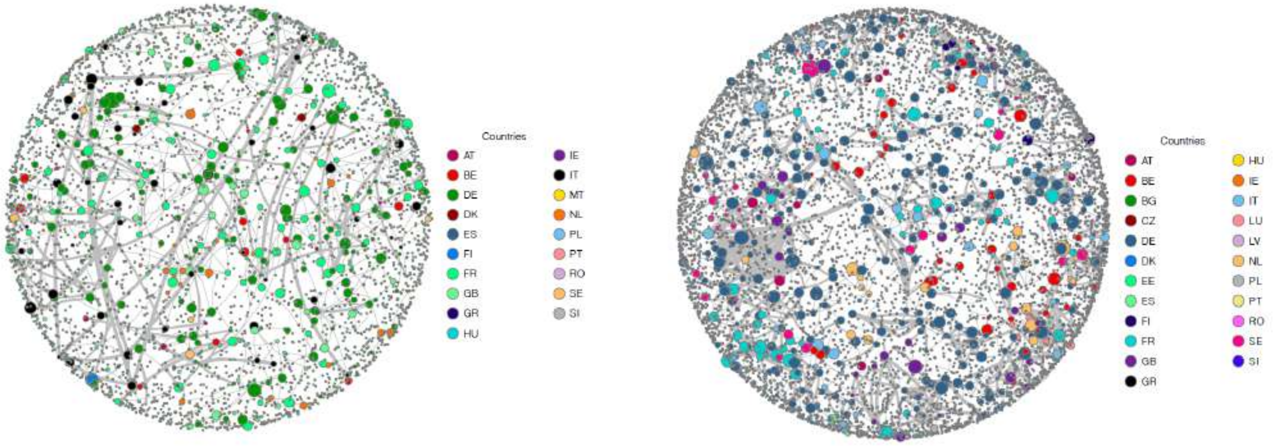
So we move to the presentation and description of our network. According to Wasserman et al. (1994); Scott (2013) it is necessary to understand the structure and dynamics of this collaborative knowledge production. Also, we employ methods of social network analysis (SNA) provided by the authors to identify the patterns of collaboration. Our complete methodology to apply the method is fully described in the Appendix A.2.4. In general terms, our main objective was to track knowledge production collaboration and its evolution through the years. The knowledge production was separated into two categories: Patents, Publications. We adopted this strategy because we understand the TIS approach with a possibility to grab the production of knowledge related to the development of such technologies, and this last one is not restricted to material artefacts but also as ideational, institutional and all possible biases that it can apply in the process of sustainable transition. We understand that our demonstration of the network may not catch all possible connections and missing some of them, but it is possible to observe the evolution and tendency.

We reconstructed the networks for patents from 1990 until 2014 (discarding 2015-2019 because of the 4-5 years lag) and publications from 1989 until 2020. Thus, we identified 9 periods that comprehends 3-4 years. Figure 3.2 displays 4 international networks for patents. Figure 3.3 displays four international networks for publication.

Figure 3.2: International co-patenting network for 4 periods

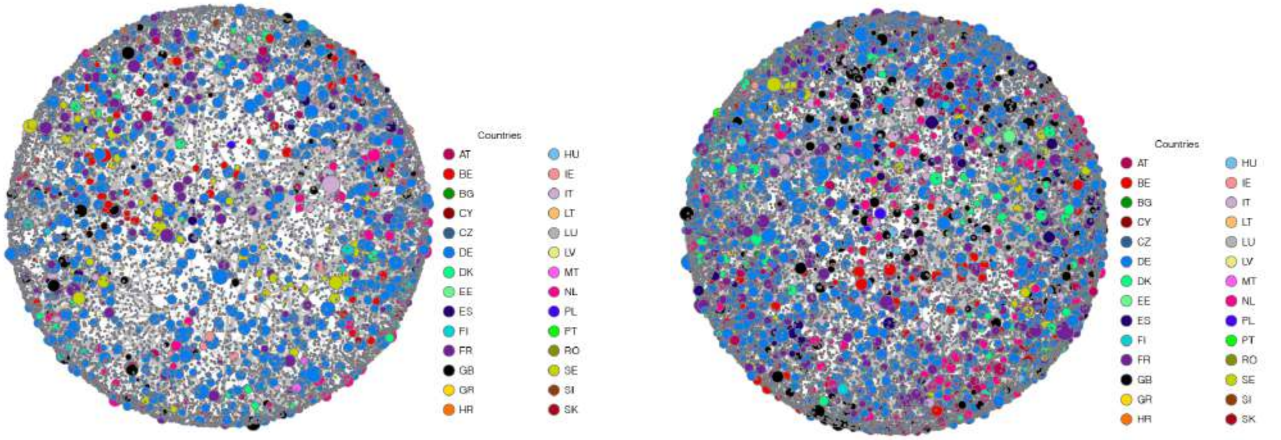
(a) P1 90-92

(b) P3 97-99



(c) P6 06-08

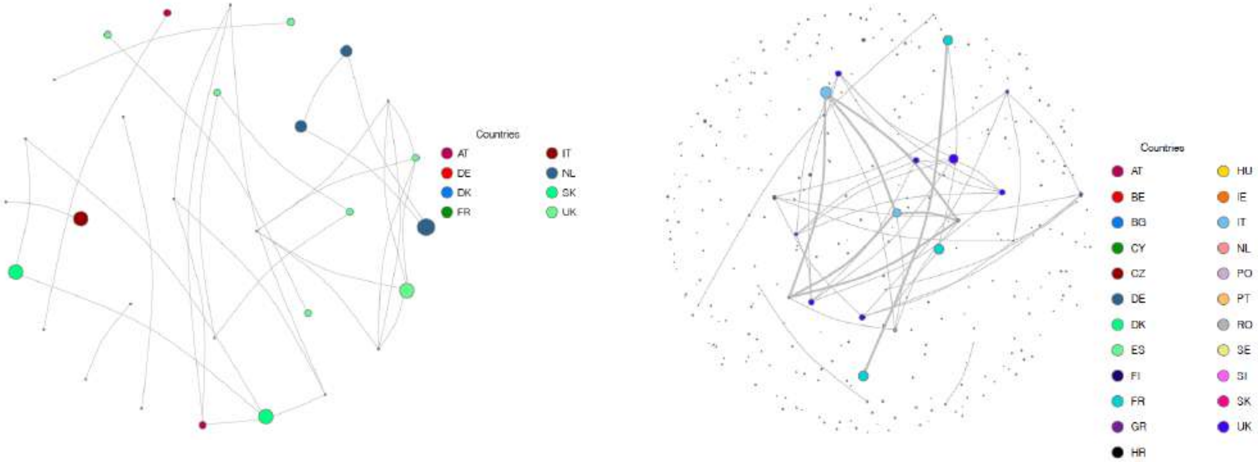
(d) P8 12-14



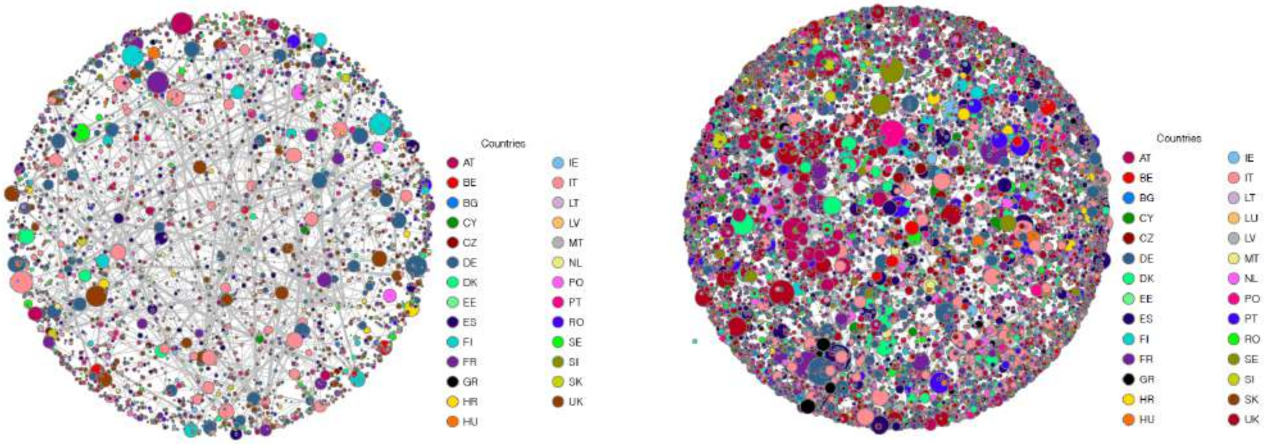
Note: Node size is a function of node's degree. Due to some computational problems, the colour of nodes in relation to their countries was not able to remain the same, and for each period, the countries legend should be observed for comparison.

Figure 3.3: International co-publication network for 4 periods

(a) P1 89-92 **(b)** P3 97-00



(c) P6 09-11 **(d)** P9 18-20



Note: Node size is a function of node's degree. Due to some computational problems, the colour of nodes in relation to their countries was not able to remain the same, and for each period, the countries legend should be observed for comparison.

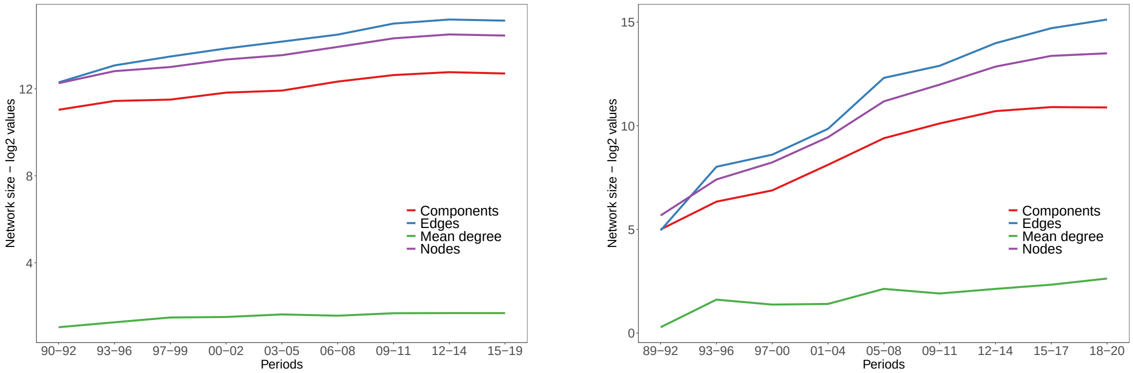
The sociograms on Figures 3.2 and 3.3 serve as initial insights to track if there were some visual modifications in the network through the years. We made several data manipulation and modification to avoid a dense mass of nodes without any correlation or meaning to showcase such graphs. It was distributed to the inventors and authors among the European Union Member States with the following colour on the legend for every period, but also hide nodes and edges that have short values that do not have huge relevance for the display (Of course, those values appear in the network statistics analysis, but right now they are irrelevant). With a visual analysis of the sociograms, the figures illustrate how these networks change in size and general structure. By size, on both Figures, it is possible to track the increasing number of coloured dots that indicate the increasing number of nodes through time. The pace of development between both networks is something interesting here to be noted. While Figure 3.2 shows an evolution of the co-patenting network with some controlled progressions, revealing non really drastic modifications in the number of countries participating from graphs (a) to (d), P1 90-92 and P8 12-14 respectively. Figure 3.3 may indicate a profound insertion of such topics in the research agendas from the countries. P1 and P3 express the drastic modification in terms of enlargement of participation, but P9 indicates a process of maturation of such research agenda by contemplating all Member States, followed by more nodes and edges.

By general structure, Figure 3.2 reveals some core inventors located in Germany (DE), France (FR), Belgium (BE), Denmark (DK) and the United Kingdom (GB), and the increase of more relevant ones from these countries through time. It also indicates a centrality of DE as a main patenting country for this technology type. The results might be rooted in a relevant level of investments in public R&D but also from the private sector that applies for patents with the EPO. Also, it indicates a dominance of the five countries over the renewable energy technologies market.

In its turn, Figure 3.3 reveals the influence of the last years of Belgium (BE) and Italy (IT) on the research agenda of renewable energy technologies. Notably, Italy has the highest public expenditure for the energy sector according to our Figure 2.7. Belgium does not have large investments, but it locates The Association of European Renewable Energy Research Centers in Brussels - EUREC. The EUREC brings together 36 relevant research institutes for RET, launching periodically policy papers supporting and guiding governments around Europe to develop climate and energy policies. We will further discuss the political advisory activities. For now, it is important to notice that EUREC is a network connecting many research institutes, consequently authors and researchers, for the RET topic (EUREC, 2020).

We do not rely only on visual inferences when applying SNA method but rather on statistical analysis and measurement tools from and beyond SNA to assess the structural network characteristics (Wasserman et al., 1994; Graf, 2017). Also, with only the sociograms, it is difficult to identify clusters, strong connections and other characteristics. So we calculate several indicators to describe the development of both international collaboration networks over time. We broken down some of those indicator into two: Network size - Figure 3.4, and Network characteristics - Figure 3.5 (Graf, 2017).

Figure 3.4: Evolution of the size of the international collaboration network



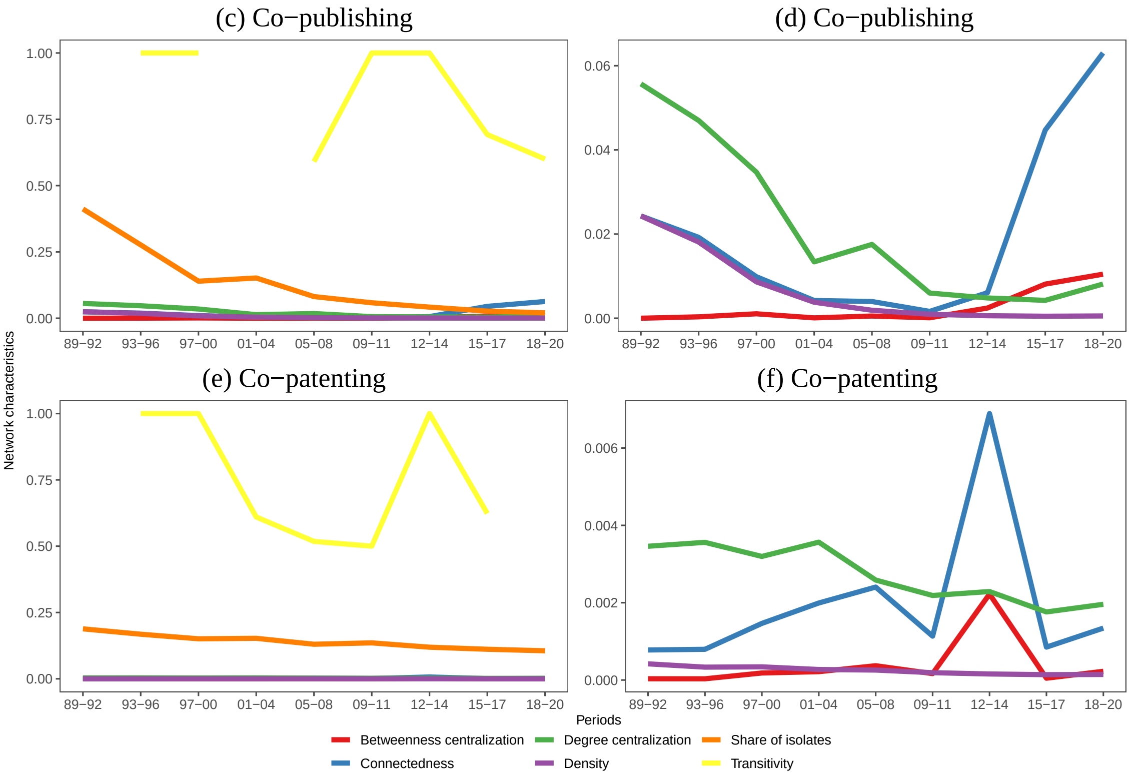
(a) Co-patenting **(b)** Co-authoring

The Appendix A.2.4 provides a full descriptive table with all indicators mobilized in this study and some other useful indicators that might be helpful for different analyses. Also, we explain every measurement and its application in this study.

To overcome some uneven values distribution among the indicators' in Figure 3.4, we logged on base 2 to plot the graphs (a) and (b). The original values for both graphs on the axis Y are between 0 and 40000. In terms of size, there is a progressive enlargement of both networks. The number of nodes suggests a steadily increasing number of innovators contributing to the spread of RET inside the EU. Co-patenting original values go from 4900 in P1 to 23164 in P8, corresponding to 372%. While Co-authoring goes from 51 in P1 to 11551 in P9, corresponding to 22.549% of ratio. The number of edges also increased, linking more individuals among each other.

For mean degree, which is the average number of connections per node, we see a slight increase, indicating that individuals from different countries collaborate more often and expand the range to more countries. For co-patenting, we see an increase of 70% from P1 to P8, while for co-authoring, we see Original values suggest an increase of 436% from P1 to P9. Surprisingly we see an increase in the number of components. Although individuals are expanding the links between different countries, we also see a formation of different spaces to perform researches. This suggests a steady spread of groups that quite often collaborate with themselves. Graph (a) goes from 2100 in P1 to 6959 in P8, and (b) from 32 in P1 to

Figure 3.5: Evolution of the characteristics of the international collaboration network



1898 in P9. It is important to mention that from P8 to P9 we see a small decreasing 1913 to 1898 respectively. This could indicate the beginning of more bridges between components, making them communicate among each other more often, or simply a variation of 0.7% that may reaper on future periods. In any case, by analysing the size indicators, it is possible to observe that the knowledge production concerning RET, is increasing since P1.

In Figure 3.5, the values go from 0-1 in every graph. But the values for Betweenness centralization, Degree centralization, Density and Connectedness are really closer to zero as it is possible to check on graphs (c) and (d). So, graphs (e) and (f) are zooming graphs for these indicators that are difficult to see variations on the original graphs. Contrary to what we expected after the values for the components indicator, the Share of Isolates is decreasing in both cases. This indicator reveals the percentage of individuals that are not collaborating with anyone else in the network. If the indicator reaches 0, this means that every actor in the network is collaborating. In (c), we see a tremendous decrease, reaching close to zero and varying from 0.41% to 0.02%, respectively, in P1 and P9. In (e), the decreasing is steady, varying from 0.18% to 0.10%, respectively, in P1 and P8. This suggests that the network attracts more individuals to collaborate if they have a common topic. Notwithstanding, it also suggests that they do not integrate an existing component of this network but rather rearrange themselves into a new component because the values in the component indicator increasing over time.

Also, concerned with the evolution of centralization and the joining of countries in the network and their position, we follow the studies from (Graf & Kalthaus, 2018; Freeman, 1989), and measure the degree and betweenness centrality. Degree centralization focuses on the linkage of few nodes and their centrality in the network, or the level of information it spreads and its influence. Betweenness centralization measures the dependence on nodes that connect many other nodes. In a star network, both values are equal to 1, and all nodes are connected with a central node but not among each other. We see different behaviour in both cases. In (d), the degree tremendously drops from P1 to P7 and then stays steady, indicating a pluralization of central nodes/individuals in academia. More people discuss the topic and collaborate among themselves, progressively reducing the dominance of such one scholar as the RET's main source, which is somehow confirmed by the betweenness indicator. Once there is an increasing number of nodes and components over time, the knowledge flow remains closer to zero until P6 (09-11). It is possible to check a boost of more publications within the topic, and more nodes appearing from different countries contribute to this development.

The situation is slightly different in (f). The degree is also decreasing but more steadily, varying from 0.0034% in P1 to 0.0017 in P8. A similar explanation can be provided here. RET are relatively new if compared with others, and since P1, the awareness of international society toward environmental problems became bigger, requiring a modification of the technologies to generate energy. This somehow allowed the entrance of different inventors in this topic, reducing the importance of a specific one and recognizing several artefacts, protected by patents, as contributors. However, the betweenness centrality does not follow the increasing of nodes and components, showing some increase over time. This indicates a difficulty to flow the knowledge between the nodes. Interesting to observe is that in P7, a pike is indicating a different tendency over time. This explanation must be observed 3-4 years before the publication of these patents assuming that something relevant happened to hop the curve in P6 (2009-2011). Further, we provided some possible explanations.

Density measures the share of all present connections in all possible connections. In cases (d) and (f), density decreases, indicating a decrease in the number of edges over the increasing size of the network. Despite the enlargement of the network, few new connections appear over time. This might suggest that scholars tend to co-publish with their traditional companions, and inventors remain with their old but safe collaborations to develop new RETs. Connectedness is equal to 1 when the network is fully connected, but the number is shorter than 1 when it presents components. Since we have an increasing number of components, it is lesser than one, but with some difference between co-publishing and co-patenting. In (d), connectedness presents a similar 'V' shape. Since there was an expansion in size and connections between nodes, the indicator drops close to zero. However, since the number of edges also enhance, it is possible to mention that, even though some units might prefer the traditional collaboration peers, some of these traditional ones can also include new members connected to other components or distant colleges. Thus, the evolution in (d) is beneficial because it indicates a diffusion of the research agenda and a more collaborative profile, even though some would prefer not. In (f), the connectedness varies over time, but interesting follows the same period of pike for betweenness centrality. We would dedicate some space to understand this pike of the flow of information and interconnection between network actors.

Finally, transitivity measures the likelihood of adjacent nodes of a node are connected to each other in respect to the main component. When equals 1, the main component has nodes fully connected. We selected this indicator following the same strategy Graf & Kalthaus (2018) and how to Wasserman et al. (1994) believe it is important to understand structural balances in social networks. We found some intriguing values for some periods. Since there is an increasing number of components and the arrangement of nodes around a central one, the transitivity varies over time. In (c), we see a variation, but some specific periods reaching perfect transitivity. From P2 to P3 (1993 - 2000 duration), the fact that the network is small and new, allowing a high probability that authors might know each other, can serve as a good explanation. This changes a bit in P5, representing the period of the largest expansion of the network, followed by a perfect collaboration and flow of information for every three nodes in the main component. Then it drops over time, followed by increasing nodes, edges, and components created by new nodes that join the network but collaborate in a traditional cluster. While in (e), transitivity also begins in perfection, then drops to half from P3 to P6 (1997 - 2011). This is also followed by the expansion of the market and new entrants, providing some new collaborations even though they might be part of the main component. Intriguingly, we see the same pike in the same moment 2012-2014, then a decreasing path.

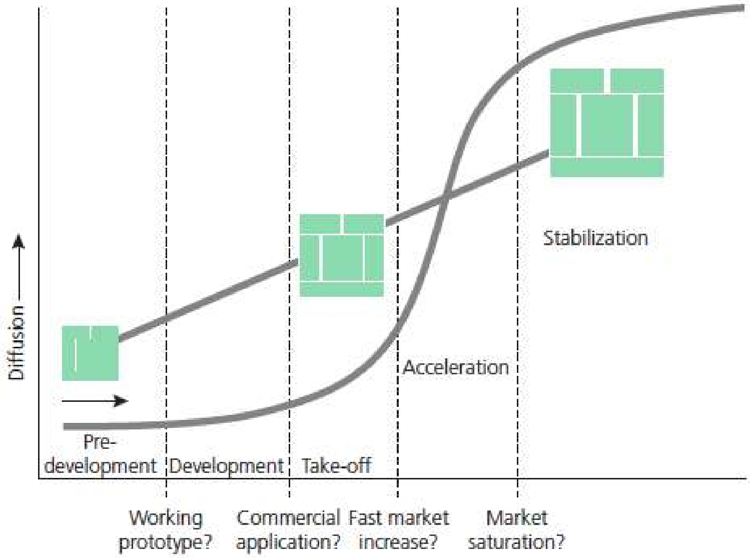
This section introduced the boundaries of our network correlating co-patenting and co-publishing as data for it. Once again, this was done because it would be impossible to aggregate both raw data together. They are extensive data and might have crushed the computational power. However, following some examples of the studies already mentioned, it would be possible to understand the development of the network by observing both data. We highlight the size and characteristics of the network mobilizing some indicators that might be useful in this manner. So far, now we can move to analyse deeper characteristics of the network and understand the political, social and economic events that might support the development.

3.3 The development of the RETIS

In the following, we focus on the multi-level characteristics of the RETIS. We analyse the political decisions in a policy-mix approach (Rogge & Reichardt, 2016). We take into account the participation of other actors rather than individuals and their influence. After presenting the network measures, it is possible to observe an increase in network size, indicating that more organizations emerged and engaged in RET research. This section presents some political and policy contexts that may have supported the development of the RETIS. It is worth noting that to address a close correlation between the knowledge production based for our RETIS and the policies discussed in the following, it would be necessary to identify in every patent or publication in the 'Acknowledgements' section the policies responsible for supporting or funding. So we understand the limitation of the method. This might be a contextual presentation of the collection and continuation of policies at different levels that might have influenced the development of the RETIS.

We follow the development model provided by, Hekkert et al. (2011), which considers some main stages: Pre-Development; Development; Take-off; Acceleration; Stabilization, and Saturation. Every technology has to overcome several barriers, from prototype to maturation. This process follows an S-Curve (see Figure 3.6), with the highest inclination in the Acceleration phase. At the end of the development analysis, we may suggest at which phase the RETIS is.

Figure 3.6: Phases of development



Source: (Hekkert et al., 2011)

Beyond the diffusion evolution, we want to capture also the political influences. We base the methodology to attach policy-mix analysis with functions of TIS analysis proposed by Reichardt et al. (2016); Hekkert & Negro (2009). We allocate labels to the events representing the components of both policy mix and functions of the TIS, as presented in Table 3.1. We do not distinguish among variations of instrument mix, such as demand-pull, technology push or systemic, because the differences do not pay any contributions for our purposes. We take the development of the network analysis in the last section to attach some of the events preset in each period. We already mentioned several of them by this far, but now, we organized them in a timeline to visualize the duration and accumulation.

Table 3.1: Policy mix and functions of TIS components

Type of component	Labels
Policy strategy	[PS]
Instrument mix	[In]
Policy mix characteristics	[PC]
Policy mix processes	[PP]
Knowledge development	[F1]
Influence on the direction of research	[F2]
Entrepreneurial activities	[F3]
Market formation	[F4]
Resources mobilization	[F5]
Legitimation	[F6]

Source: Reichardt et al. (2016); Hekkert & Negro (2009)

For a policy mix analysis, it is important to affirm that we conduct it in three different geographical dimensions: Member States, European Union, and World. The first two are more objective. The latter comprehends all the events outside the European Union that might influence how some energy transition policies are designed, abandoned and rethought (Rogge & Reichardt, 2016). Another dimension clearly defined is time, and it is limited by the periods of the SNA (Wasserman et al., 1994), which were assorted by the phases of the TIS diffusion development (Hekkert et al., 2011). During the analysis, we touch upon which events in this timeline can be identified as part of one of the three building blocks: Elements (instruments and policy strategies); Policy progress (policymaking and implementation), and; Characteristics (consistency of elements, coherence of processes, credibility and comprehensiveness) (Rogge & Reichardt, 2016). As we explained, they are labelled in the analysis.

Finally, there were more elements than we can showcase in this timeline, and during the building of our argument, we sometimes mention some of them. Figure 3.7[4] showcase

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[4] Unfortunately, we can not control every parameter when creating a timeline in RStudio, and some labels

the timeline with the events selected. The RET Diffusion Curve is just an estimation based on the size and number of initiatives to promote RET.

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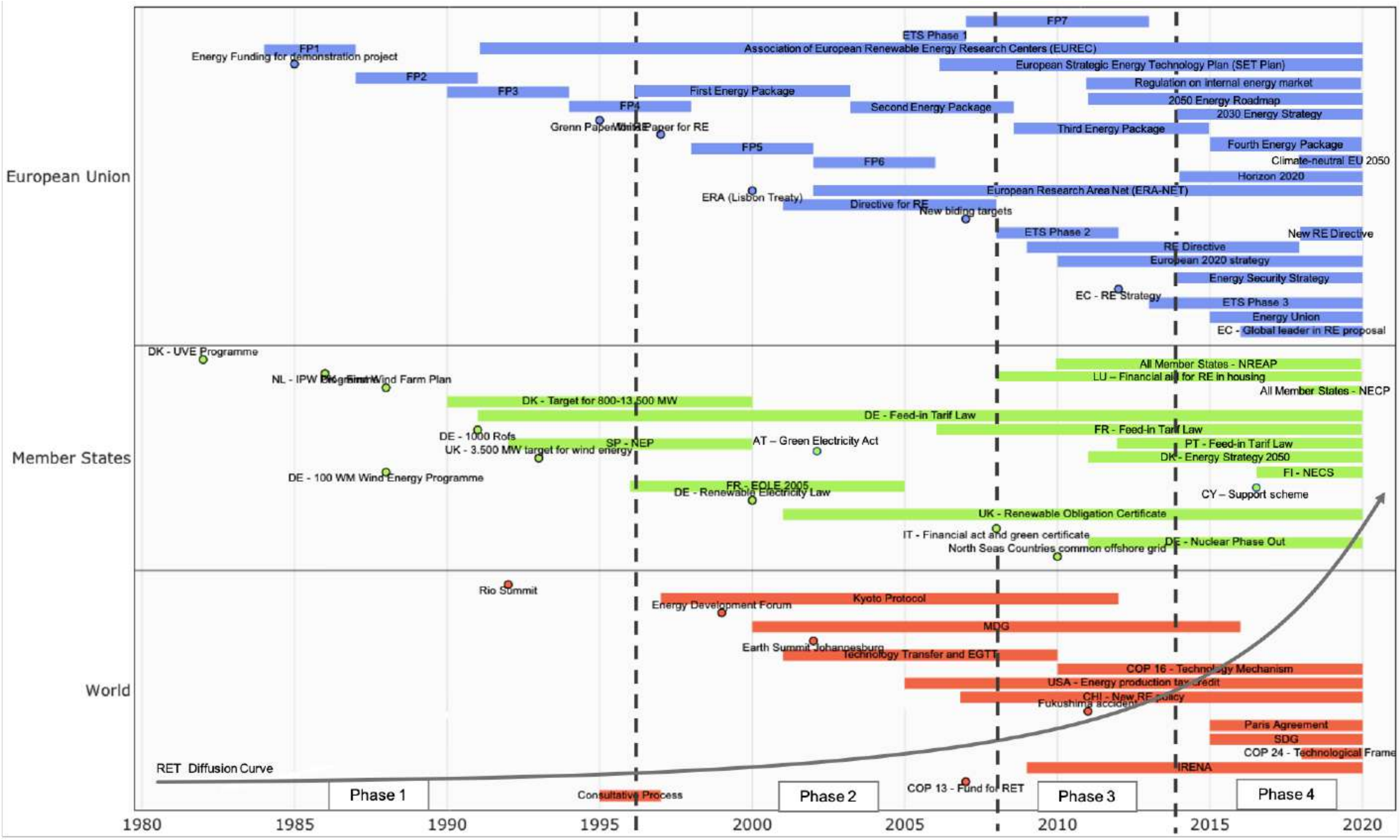
may not be evident to read because they are on top of something else.

Figure 3.7: Phases of development of the RETIS 1984-2020



Source: Own elaboration based on IEA (2021); Wind Europe (2020); European Parliament (2021a); Bonnet et al. (2018)

3.3.1 Phase 1

We attach the P1 and P2 of our network and early years on Phase 1. Although RET were not invented in the 1990s, a long study and prototypes related to it were produced beforehand (Bonnet et al., 2018). Since the foundation of the European Community in 1957, the support for research and innovation on a European scale level has always been part of the Treaty of Rome. Phase 1 is marked by a few applications and experimentations of renewable energy technology in public policies from Member States. In 1981 one of the first wind turbines - the 22 kW Bonus model - was first produced by the Dutch company Bonus and installed in the country [F3]. The beginning of the wind era in Europe had started with a turbine of 10m height followed by a next model with 55 kW capacity. This market breakthrough encourages a group of European agricultural machinery manufacturers to fly to California and assess the market for wind turbines, concluding with the exportation of wind turbines to the US in 1982 [F3] and a boost for the European internal energy and infrastructure market. A few implementations of energy policies in Denmark, Netherlands, Germany and the United Kingdom before P1 [In; F3] internally developed the wind power technology (Wind Europe, 2020).

The ”Energy funding for demonstration project” [F1; F2] was a benchmark to innovators think on different ways to generate energy, including renewable sources. The Framework Programme (FP1 and FP2) are at the very beginning. Although FP1 has political provisions for managing raw materials and energy resources because they were very closed to EURATOM principles of non-proliferation and nuclear energy for civil purposes innovation, it does not touch upon projects aiming to diffuse RET. Differently, the FP2 had a clear drive toward energy [In] of the Single European Act in 1986 [PS], which aims to strengthen the scientific and technical basis of the EU (European Commission, 2020b). This context made the Danish wind company Vestas focus on R&D activities to constantly innovate on wind power technologies (Wind Europe, 2020).

Considering the SNA, P1 begins after 1989, and here, it is possible to observe a new wave of policies. With the end of the Cold War and the lessons learned from the Oil Crisis, it notably became more than clear that the way society interacts with the environment had been detrimental. However, the research agendas or R&D activities, including environment followed by energy sources, are still very few. According to our SNA, firms or research institutes have a small contribution. Although few papers existed, they were mostly written by a single scholar interested in a very effervescent topic in the 1990s. In addition, firms started understanding the application of the ”sustainable” label as something fundamental for efficiency. Even though many patents already exist in this period, they were mostly prototypes and experiences and more connected to solar power, once this technology is older than wind (Solar Power Europe, 2019).

Germany rises its interest in solar power with the historical 1000 rooftops plan from 1991, which increased the energy generation by renewables in this period [F3;In]. It was also followed by political discussions and struggle by reviving an Energiewende [PP] idea, first proposed in 1970 by the Green Party (Ferreira, 2017), but did not have strength enough to politicise the debate. As a result, more wind farms are deployed for the first time in Greek, UK, France and Spain. This last one was the company Gamesa one of the most important companies for wind turbines. Also, in 1991, the first offshore wind farm is installed in Denmark, followed by the 1.5 MW prototype onshore [F3] (Wind Europe, 2020).

On the European level, the beginning of the Association of European Renewable Energy Research Centers (EUREC) engages the EU to promote renewable energy. Since 1991, EUREC had connected 36 research centres from 16 Member States to exchange knowledge and expertise about renewable energies [F4;F5]. Since that time, renowned institutes, such as Fraunhofer, Universidad Zaragoza, CNRS and others, joined the network (EUREC, 2020). In addition, the FP3 had an important influence [F1;F2] to boost the budget available for European collaboration toward the same objectives in FP2, including energy (European Commission, 2020b). Also, The European Forum for Renewable Energy Sources (EUFORES) and the European Energy Forum (EEF) were found in 1995 [PP]. Both organizations enabled meetings with Member States to discuss the trends and opportunities for RET in the European and Mediterranean market and the complex dependency of fossil fuels from foreign sources (Forum, 1995).

Phase 1 might have reached an end after the experiences with the Rio Summit in 1992, the Green Paper in the European Union to address concerns with the environment and economic growth [FP4], and the accumulation of policies for RET from the Member States (Rogge & Reichardt, 2016). Altogether they began to forge some characteristics of R&D plans and energy market trends by politicising RETs as key drivers for further economic growth. In addition, the Consultative Process enhance the knowledge development of RET around the world [F1;F5]. As one may have noticed in Figure 2.12 in Chapter 2, 1996 is the beginning of take-off (Reichardt et al., 2016; Negro et al., 2012) for wind energy in the EU, doubling the installed capacity and generating and consuming this alternative source.

We can suggest that the end of this phase happens in 1996 when there is an accumulation of basic knowledge for RETs and the preparation of the world to enter in one of the most important common decisions in the 1990s, the Kyoto Protocol. P1 and P2 also account for this process with the emerging number of co-patenting activities and co-publications in Europe. On the one side, among Member States, an important decision is taken by Germany with the Feed-in Tarif Law [In]. Feed-in Tarif continues until 2020 with some updates over time, but it still is an instrument that is a benchmark in the infancy of energy plans throughout the EU. The presence of new targets in DK and UK and the entry of SP with a new plan and signalize for the coherence of processes and consistency of elements inside some countries in the EU (Rogge & Reichardt, 2016). On the other side, the experience learned from applying three editions of Framework Programmes [In] induced more collaboration among individuals to produce and diffuse knowledge. Beyond financially supporting the knowledge production, FPs, since their foundation, stimulate the aggregation of different institutions in one project as a pre-requisite for submissions European Commission (2020e).

This phase enabled the development of the first renewable energy policies, entrepreneurial activities, and knowledge development around the EU. However, we still do not see a homogenization of policies or common interests at the EU level. Also, the plurality of firms and institutes gave different directions to what should be researched since the network was new. But we see some movements to achieve common sense in the next phase.

3.3.2 Phase 2

Phase 2 is characterized by the increase in numbers of publications and patents and a depletion of the RET around the EU. The SNA suggests that it starts with the COP 3 in Kyoto in 1997 and goes until 2008, comprehending P3, P4 and P5. The Kyoto Protocol might be seen as the most important international event at this time [F2]. We already mentioned it, and it was significant for the world in terms of diffusing the necessity of a more proactive climate policy. At a European Union level, in 1997, the Commission proposes the White Paper for RE, a comprehensive plan targeting the enhancement of the share of alternative energy generation by 2010 [PS]. We see a development of our network in terms of size. After gathering knowledge with the Consultative Process, understanding sustainability was more or less diffused across the EU. A new age for RE policies and innovations began with an uprising curve in terms of quantity. Also, it is necessary to mention that degree centralization suffers a downgrade in this period, perhaps occasioned by the rapid growth of knowledge, with new entrant firms and new research centres fostering the knowledge pool.

By the end of the XX Century, the Millennium Development Goals (MDG) was launched, an instrument to coordinate national policies worldwide toward 8 objectives [PP]. MDG does not contemplate energy as an objective, but on the seventh objective, it mentioned: ”Between 1990 and 2012, global emissions of carbon dioxide increased by over 50 per cent (United Nations, 2000). The target has its basis in the energy sector, and researchers started understanding the inseparable principle. Non directed linked, but related, the Technology Transfer and the Expert Group [F1; F2; F5; In] were responsible for connecting and reinforcing the necessity to share knowledge between countries and transfer some technologies to speed up the international share of RET in the mix (UNFCCC, 2016, 2004).

Also, in 2000, phase 1 of the European Research Area (ERA) [PS;F1] has been launched to connect different research institutes across the EU, reducing barriers between States and creating a mass of knowledge and a continental-wide competition (European Comission, 2020). The ERA lasts until 2018 (and has been revitalized), and one of the objectives is: ”prioritise investments and reforms in research and innovation, to support the digital and green transition[...]”. Phase one of the ERA ended in 2007, and the greatest achievement was creating a large network of research, which promoted co-publications and co-patents around the EU. They also support the plurality of newcomers to receive investments from the FP5 and FP6 [In] (successfully encouraged more during the FP6) (European Commission, 2000). Furthermore, the ERA-NET scheme came into play in 2002 [In]. The scheme intends to support the coordination and collaboration of research and innovation programmes by connecting, funding and implementing joint activities between public and private sectors within selected topics, such as neuroscience, renewable energies or land use. Basically, the ERA-NET contributes to structuring the ERA plan (European Commission, 2000; ERA LEARN, 2021).

Even though lots of elements supported the development of the RETIS, the Directive for RE in 2001 [F4] is critical to define the next steps. Following the White Paper, this directive was responsible for coordinating States’ energy policies, concluding with the New binding targets in 2008 [In] and the European Trading Scheme in its first phase [In]. These two latter were important instruments to encourage States to innovate with technologies that generate energy with renewable sources, enhance the share in the energy mix, and limit the CO2 emitted in the economy, achieving climate-neutral objectives (European Parliament, 2021a).

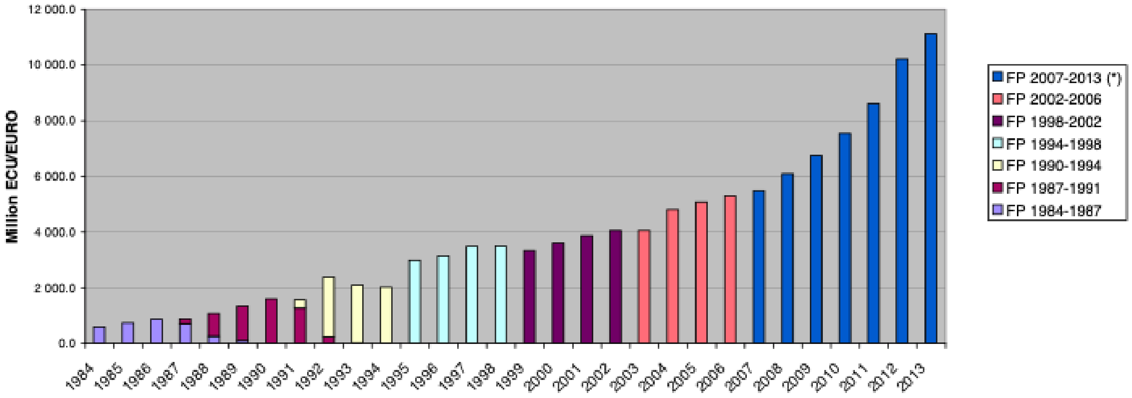
At Member States level, in Copenhagen, the first large-scale offshore wind farm was erected [F3] in 2000. 8,500 shareholders shared the 20 Bonus 2 MW turbines in the Danish cooperative. This cooperation was crucial to set Denmark as a relevant market player in this period. Basically, Vestas and Bonus Energy, the two pioneers of the wind industry, were located there. The companies reached thins market share of 3rd and 5th respectively, because of the subsidies for wind turbines and call for demonstration projects [F2;In] in 1999, and the Wind Energy Cooperative Tax Incentive in 1997 by stimulating users to sign for wind energy wires because they would be taxed 60% according to the normal energy taxes [F6] (Wind Europe, 2020; IEA, 2021). These policies opened the market locally for new entrants by making buyers willing to pay and large companies spreading their wires and making profit.

More Members decided to promote renewable energy plans. The EOLE 2005 from France [PS] basically subsidised the energy industry for renewable technologies depletion

[In], and the Green Electricity Act from Austria [PS;F4] introduced subsidies and a uniform feed-in tariff for all RET. In addition, there was the introduction of certificates to ratify the concerning of the firms with the sustainable development ideas in this period [In]. This promoted some modifications on the installations e the obligation of limiting emissions and waste in the UK and Italy (IEA, 2021). Outside Europe, in 2005, the USA went for the introduction of the tax credit [In] in order to stimulate the firms to turns their R&D activities toward RETs. While China, in 2007, decided for reforms in the energy sector, mainly targeting the increase of the share of renewables and reducing emissions until 2030 [PS] (Peoples Republic of China, 2007). It is important to mention that the EU had trading activities with both countries in the years before. The US can be set as the beginning of the solar power industry, and several countries, including Germany and Denmark, bought the technology at the beginning of the 1990s (IEA, 2021; Wind Europe, 2020) as well as Germany exported ten 30 kW wind turbines to be installed on Sijiao island off the Shanghai coast of China (Wind Europe, 2020).

Phase 2 ends around 2008 with the end of the first Directive in 2008 and the beginning of the FP7 in 2007 [F1;F2;In]. FP7 had over three times the budget compared to its predecessors. The finance was around 55 million euros over 7 years, compared to 19 million euros in season 6. Clearly, the FP7 contemplates energy efficiency and security as areas to be financed (European Commission, 2020e,b). Important to mention that the FPs were responsible for a considerable push in the research, development and innovation in the European Union. Figure 3.8presents the distribution over time according to each FP. The budget was around 68 billion euros if limited the duration before 2008. This contributed enormously to the creation of the excellence in research priority in the ERA.

Figure 3.8: FP budget for the European



Source: European Commission (2020b)

Moreover, COP 13, in Bali, in 2007, created a new fund to invest in RET around the world [PS; In]. The Bali Roadmap defined strategies to finance the development and transfer of RET among countries. Now experts have some relevant evidence to acknowledge the effects of climate change on future generations (Bonnet et al., 2018; UNFCCC, 2007). During the Second Energy Package [PS], in 2006, the first step of the SET-Plan was created [PS;PC]. It progressively promoted an environment to exchange knowledge and technology related to renewable energy. It was a primary and key strategy boosting policy to speed up RET diffusion in a competitive way. The SET-Plan consists of the SET-Plan Steering Group [F2], the European Technology and Innovation Platforms (ETIPs) [F2;F5], the European Energy Research Alliance (EERA) [F1], and the SET-Plan Information System (SETIS) [F4] (European Commission, 2021b). They will be discussed later because its contributions are stronger in Phase 4.

Finally, after 12 years of Phase 2, the mix of policies in the European Union RETIS is reaching a moment of credibility. The combination of SET-Plan and ERA-NET is basically the renewable energy innovation framework [PC]. The diffusion is rising because more countries are supporting RET. As well as EU follows the international conferences and decisions toward energy and climate change. This is a coherent step to maturate the RETIS.

3.3.3 Phase 3

Phase 3 is characterized by the continuous development of network size to stabilise density and increase betweenness centralization. There are more patent applications and publications, and knowledge became better diffused. Phase 3 comprehends P6 and P7. The SNA suggests that this period is one of the most important ones because of some strategies and instruments from the EU. It seems to start aggregating a political framework focused on the autonomy of the European Union regarding sufficient renewable energy generation, reducing the dependency and use of fossil fuels.

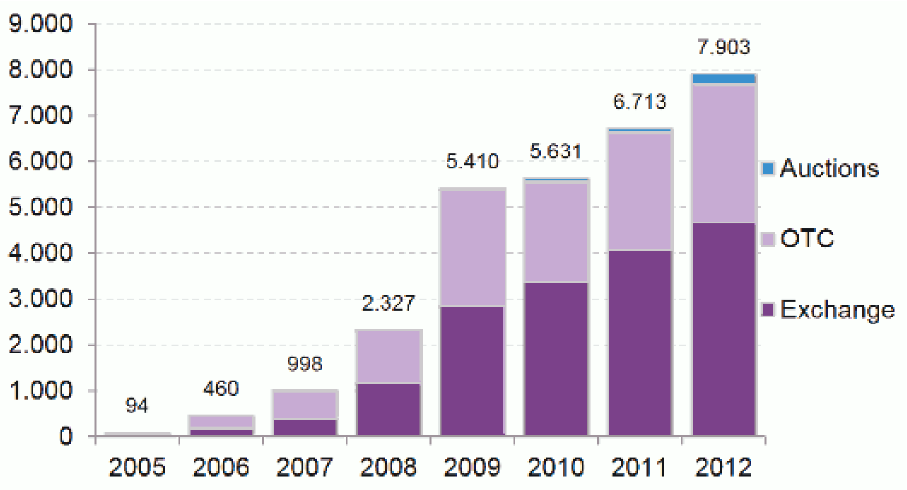
This phase is largely responsible for the number of strategies and regulations at a European Union level. It would not be able to cover all of them, but it is possible to mention some. The RE Directive in 2009/28/EC of the European Parliament and of the Council [F4;In] is part of the Third Energy Package [PS], which aimed to improve functioning in the internal energy market. The Directive is certainly the most important guidance for the future robustness of the energy market through compliance with the Kyoto Protocol. Unlike the previous 2001 Directive mentioned in the last phase, which did not tackle the RET directly, the 2009 Directive is entirely dedicated to developing and enlarging a renewable energy market in the EU (European Parliament, 2021a). It established a mandatory 20% share of energy consumption from RES by 2020, and all Member States are required to obtain 10% of their transport fuels from RES by 2020 (European Comission, 2020). Beyond the targets, it also established joint projects between States for technology transfer, collaborations for future innovations and joint schemes for supported energy policy development. Among other provisions, the Directive is the common ground for future energy strategies.

The Directive opened space for strategic measures toward the future of energy policy, innovation and market. Under this basis, the first comprehensive energy strategy is the European 2020 Strategy [PS; F1], launched in 2010. Also known as the 20-20-20 strategy, it ended in 2020. It focused on reducing greenhouse gas emissions by at least 20%, increasing the share of renewable energy to at least 20% of consumption, and achieving energy savings of 20% or more (European Parliament, 2021a; European Comission, 2020). According to Figure 2.3 the reduction of GHG emissions until 2018 was close to 16%. Also, in Figure 2.12, we see an increase in the contribution of wind and solar on production and consumption over the years. Moreover, from 2010 to 2019, the share in consumption increased by 39% (Eurostat, 2020b). The policy also supports the development of joint projects to increase the achievement of the targets rapidly (European Comission, 2020).

In the next year, 2011, with the '2050 Energy Roadmap' [PS; F2], the EU has set itself a long-term goal of reducing GHG emissions by 80-95% compared to 1990 levels. It calls for a unified policy framework that would synchronise all instruments from research and innovation policies to deployment policies that would support such efforts. This would demand joint investments in the upcoming RET and more coordination between research centres to progressively guarantee the energy revolution in the EU (European Comission, 2020). Moreover, a lot of new regulations on the energy market take place in this phase by taking into consideration the tendencies toward renewable energy. This is represented by the new regulations for the internal market in 2011 [F4; In]; new regulations for energy efficiency in 2012 [F4; In], and; the ETS Phase 2 [F4; In] with a progressive reduction of emissions and increasing in trading volumes of GHG. Figure 3.9 describes the evolution of the trading scheme. EU ETS remained as the main driver of the international carbon market until phase 2. It reached over 7.9 billion of allowances trade in 2012, corresponding to 56 billion euros.

Followed by the legal basis, the number of interest around RET became very clear in our network. Here, the number of publications and patents reach the top of the curve, with a curious pike for some co-patenting network characteristics: transitivity, connectedness and betweenness centrality on P7. The general amount of investment came from the new FP7 [In]. The notorious definition of EU objectives toward better energy efficiency, increasing the installed capacity, generation and share of RET, might explain this. As noticed in Figure 3.8, the budget was never seen before, followed by the Technological Mechanisms that enable more collaborations in R&D activities between firms. In addition, from 2012-2014, there is a transition between framework programmes (FP7 and Horizon 2020). The number

Figure 3.9: Trading volumes in EU emissions allowances (in millions)



Source: European Comission (2020)

of applications corresponds to over 113 applications in this period, considering that every project must be collaborative under the FP (European Commission, 2020b).

The SET-Plan [PS] in partnership with the ERA-NET Plus [In](the new funding scheme for FP7) and the FP7 is another important policy implementation [PP] to enable regional collaboration. The partnership creates several networks of national and regional funding organisations and RTD and innovation programmes. In this phase, the FP7 was able to fund 376 collaborative projects for the energy sector, with a budget of 1.81 billion euros (European Commission, 2020b, 2021b, 2013). The SET-Plan defined the priorities to improve energy transition at the European Union level. The ERA-NET Plus fund the projects under the FP7 that attend the priorities of the SET-Plan and other energy strategies. In addition, the ERA-NET Plus developed specialized funding networks for renewable energy researches during the FP7: ERA-CAPS, BESTF2, NEWA, Smart Grids, and CORE Organic Plus(ERA LEARN, 2021).

Another important contributor was the European Energy Programme for Recovery (EEPR) [PS], launched in 2009. The programme dedicated around 4 billion euros to co-finance renewable energy technologies, mainly offshore wind, electricity infrastructure and carbon capture storage (European Commission, 2013). Other important financing actors were the European Investment Bank - EIB and the European Bank for Reconstruction and Development - EBRD, the former covering 6.2 billion euros in 2010 mainly for wind and solar. The latter contributed over 2 billion in 2009 and 2010 for wind projects and wind farms. The main beneficiaries were Italy, the UK, Germany and Spain, corresponding to 65% (European Commission, 2013). The amount of investments in wind energy reflects a collection of the

Position paper from EWEA [PP] about the necessity to stimulate the development of the technology and infrastructure that integrates it competitively in the energy market. As a result, the support for wind energy has always been superior compared to solar power (Wind Europe, 2020).

During Phase 3, the curve of patent applications reached the top with 16000 publications in 2013, and as mentioned before, the connectedness indicator presents a pike. This might be occasioned by the comprehensive legal framework for RET [PC]. It demanded from Member States the definition of the National Renewable Energy Action Plans - NREAP [PS; F2; F5]. Every Member set its own roadmap until 2020, observing the 2009 Directive, with a revision over the objectives until 2030 (the NECP). The objectives with the NREAP were around the definition of targets for the renewable share in electricity, cooling and heating, cooperation between national authorities to perform technology transfer, joint projects, and others (European Parliament, 2021a). Basically, the Plans defined some instructions for national market development and progressive integration of RET in the European market.

A rapid diffusion of RETs follows the NREAPs and more entrepreneurial initiates [F3] became popular among States In 2008, Iberdrola Renovables and Gamesa signed an agreement to develop and manage some wind projects together and supply 4.5 GW of turbines. Basically, both firms are leaders in Spain and have an important market share in the EU. In 2009, the world's first full-scale floating wind turbine named Hywind (2.3 MW of generation) started its operations in the North Sea. It was followed by the Principle Power's Wind Float prototype on the coast of Portugal in 2011. These offshore turbines were set with some new techniques allowing them to be erected without heavy lift vessels (Wind Europe, 2020). On the solar power technologies side, there is strong support for the CSP new models. There are several demonstration plants with prototypes in Spain, for instance: PS10 in cooperation between Instalaciones Inabensa S.A. from Spain and Fichtner GmbH from Germany among others; ANDASOL with Solar Millennium AG from Germany and Instalaciones Inabensa S.A. from Spain among others, and; Solar Tres with GHERSA from Spain, COMPAGNIE DE SAINT GOBAIN from France and SIEMENS AG from Germany among others (Maraut et al., 2008; European Commission, 2012). The diffusion of RET is responsible for the incresing in installed capacity in this period. Figure 2.12 in Chapter 2 showed an increase around 800% for solar and 107% for wind installed capacity.

On the international level, the International Renewable Energy Agency - IRENA [PC; F2] is created as part of a comprehensive set of institutions to regulate and guide renewable energy policies. One of the first reports in 2012, *The Capacity Building Strategic Framework for IRENA (2012 – 2015)* [PP; F1], touches upon the implementation of solar and wind technologies in coherence with the provisions from COP 15 in 2009 in Bali [PP]. Mainly

IRENA intends to support the coordination of public and private interests in developing the renewable energy market. This initiative comes with the creation of a hub to facilitate the exchange of information identifying barriers and failures on the development of the market (IRENA, 2012). The report was followed by a collection of assessments and policy advising documents for every technology. Since then, the Agency works to advise governments based on the periodic studies about costs, capacities and benefits to increase the share of RET (IRENA, 2020a). Important to note, all Member States collaborates with IRENA to promote a sustainable future, and its publications serve as baselines for the definitions of some EU energy policies.

In addition, The Fukushima accident may have enormously contributed to the acceleration of the energy transition in some countries. Especially in Germany, where the Energiewende restated to happen after over 20 years of a slow pace (Ferreira, 2017). The Energiewende [PS] came with the nuclear phase-out and several other targets for renewable sources and GHG emissions.

The end of Phase 3, according to our network and patent and publication count, would be before the Paris Agreement [PP; F6] and Sustainable Development Goals - SDG [PS] in the international context, and the beginning of the Energy Union and Horizon 2020. Phase 3 might be short, but one can affirm that it was one of the most important phases because of some reason. First, the evolution of the characteristics of our network with the continuous expansion of innovations and application of several new prototypes to turn RET more efficient and affordable. Second, we see the legal basis of the European Union to be strengthened. This short period of 6 years was responsible for setting the major institutional boundaries for the energy market in the EU with new regulations and directives for the energy market, efficiency and progressive diffusion of the technologies. Third, we see coherent financing instruments and institutions supporting the R&D activities of firms and a boost in the number of collaborations. These elements contributed to creating some consistency between Member States [PC], defining how the research for RET should go and more individuals joining the RETIS (Rogge & Reichardt, 2016; Reichardt et al., 2016). Last but not least, although we still have data for P9 because of the 4-5 years gap for the patent application, our analysis of the development ends on P8.

3.3.4 Phase 4

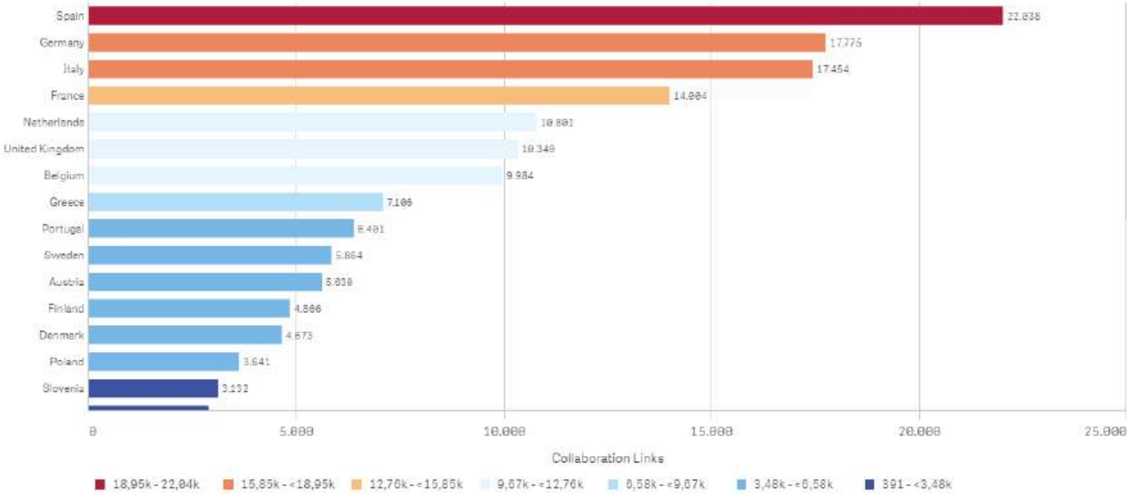
Phase 4 is characterized by a continuous evolution of the network size and a slight downgrade of publications and patents. It comprehends P8 and P9, respecting the 4-5 years gap for patents. We see the robustness of the RETIS with the confirmation of some strategies and the increase of research and innovation on the energy field by both Horizon 2020 and the Energy Union. It goes from 2014 until 2020.

On the International level, the end of MDG and the beginning of the SDG [PS; PP] is an important achievement aside from the Paris Agreement [PP]. With the Agenda 2030, the SDG brought a different perspective for States worldwide on conducting energy policies. Goal 7, Affordable and Clean Energy, is entirely dedicated to encouraging the energy transition (United Nations, 2015). The targets present provisions to increase the share of renewables, energy efficiency, affordability and accessibility. The development of the SET-Plan and Horizon 2020 in this phase have a strong connection with the SDG. The projects accepted to be funded in the 8th Framework Programme must attend one of the goals (European Commission, 2020b). The Paris Agreement, as we already noticed in Chapter 2, would be the most important commitment to the environment in the last years. The limitations of the global temperature by 2°C and the National Determined Contributions - NDC seems to be coherent with an energy transition. And they have to be revised every two years to account for the advances and challenges to reduce emissions and increase energy efficiency with RET (UNFCCC, 2015).

Although both events are benchmarks in terms of provisions to fight climate change and address better policies for society, what touches upon the energy sector is not something new for the EU. As we analyse on Phase 3, the EU already set the framework for energy transition with a long Roadmap of aspirations to be concluded in the future. The investments to increase the share of renewables on final consumption expecting to reduce the energy intensity have targets until 2020 and 2030 as part of the policy measures already mentioned. Since the beginning of the last Phase 3, the EU has drastically reduced the Primary energy consumption as required by target 7.3. In 2019, primary energy consumption was 3% above the 2020 energy target and 19.9% above the 2030 target (Eurostat, 2020b). The consumption of 1350 Mtoe corresponds to 15% of the world primary energy consumption (Eurostat, 2020b), which overall, is not reducing since the SDG entered into force and would require deep commitments of countries around the world (United Nations, 2015).

On the European Union level, the FP8, or Horizon 2020 [F1; In], enabled over 1.3 thousand grants for a 'Secure, clean and efficient energy' thematic area. Since H2020 requests the submission of a collaborative project, the number of grants is divided among 12.843 legal entities. This thematic priority accounts for 7.7%, with an estimated budget of around 5.931 million euros, (European Commission, 2020b). The H2020 was a terrific innovation policy to speed up the knowledge base and diffusion of RET. The collaboration was intense with all Member States applying and granting for the topic. Figure 3.10 highlights the top collaboration links. In 2018, the Commission proposed that Horizon Europe (Framework Programme 9 - FP9) will follow H2020. With a budget of over 100 billion euros, investing more on cross-country projects and oriented by missions (European Commission, 2020e).

Figure 3.10: Top collaboration in 'Secure, clean and efficient energy', 2014-2020



Source: European Commission (2020b)

The establishment of the ERA-NET Cofund scheme [In] was important to foster and fund H2020 projects. The scheme was designed to support public-public (P2P) partnerships on transnational projects by creating the network for a specific project and managing information across the member. The European Joint Programme Cofund (EJP Cofund) [F5; In] is another co-fund action responsible for supporting coordinated national research and innovation programmes. Beyond that, it mobilized the knowledge accumulated locally to diffuse through Horizon 2020 projects, achieving significant advances (European Commission, 2020b). During Phase 4, both schemes created more than 20 networks. Some examples are DemoWind, ENSCC, ERANet SmartGridPlus, Solar Cofund 2, BESTF3 and SOLAR-ERA.NET Cofund. These networks were responsible for managing 16% of all networks, according to thematic areas from Horizon 2020 (ERA LEARN, 2021).

With the Fourth Energy Package [F4; In] comes the Energy Union [PS], which falls on the coordination of the energy transition toward a low-carbon economy in the EU. We already discussed it in Chapter 2.1 its matters. Now we highlight the consistency of the energy policies in this period [PC]. Horizon 2020 feeds the intentions of the Energy Union to increase the share of RET, followed by a new regulation in policy process with the Fourth Energy Package supported by the redefinition of the SET-Plan. The Fourth Energy Package focuses on internal marketing design, liberalising and setting the boundaries in which new entrants can go to the energy market, and the incentives for consumers to contribute with the internal market (European Parliament, 2021b). This set of policy implementation comes as part of the 'Clean Energy for all Europeans package' [PS] from 2015 until 2020. A robust decision after the Paris Agreement, with eight main legislative acts (European Parliament, 2021b). Basically, it is the cornerstone for this phase, giving credibility to the energy transition. Thus, the EU accumulates a coherent, comprehensive and consistent framework to enable and support such transformations in the sector.

Moreover, one of the most interesting and contributing plans is the SET-Plan. Along with the Energy Union, in 2015, the Commission communicates *Towards an Integrated Strategic Energy Technology (SET) Plan: Accelerating the European Energy System Transformation* (European Parliament, 2021a). In addition to the traditional objectives of collaboration and coordination on RET to reach the energy transition, it now involves 154 umbrella organizations representing 16700 entities. The Integrated SET-Plan is a tremendous institutional building block to keep the guidance of the research in the RETIS but overall reducing the miscommunication and innovation difficulties. The Integrated SET-Plan set ambitious R&I priorities through the ten Key Performance Indicators (KPIs) that orient the future actions of the plan. Are they:

1. Integrating renewable technologies in the energy systems
2. Reducing costs of renewable technologies
3. New technologies and services for consumers
4. Resilience and security of energy systems
5. New materials and technologies for buildings
6. Energy efficiency for industry
7. Competitiveness in global battery sector and e-mobility
8. Renewable fuels and bioenergy
9. Carbon capture and storage
10. Increase nuclear safety

This action aims to accelerate the decarbonisation of the energy sector by making technologies cost-effective and better-performing. Also, the SET-Plan works for the continuous integration of the whole innovation chain from research to market up taking, tackling financing and regulatory measurements. In this new version, innovation stays at the heart of the process, and it has to be done collaboratively. SET-Plan now defines organisational support. The SET-Plan Information System (SETIS) [F1; In] provides up-to-date information on its activities covering all research and innovation priorities of the Energy Union. The European Energy Research Alliance (EERA) [F1; In] represents the research community, while the European Technology and Innovation Platforms (ETIPs) [F1; In] represents the industry of renewable technologies. These platforms promote political advice and knowledge exchange for many different topics related to energy, i.e., wind energy, solar power, and energy transition.

Based on the framework that has been built, Member States now should scale up the diffusion of RET. We follow the continuation of some policies and the addition of new ones. For example, Cyprus has its first fully Support Scheme for RET [In], reducing cost and giving incentives such as subsidies for new entrants. We follow the progress of the nuclear phase-out in Germany (Ferreira, 2017), and the development of new financial incentives in Lithuania, Belgium, Portugal and Austria in 2017 (IEA, 2021). Most important, in 2018, two main elements come into play: the revision of the NREAP, now National energy and climate plans (NECPs) to follow the conclusion of the 'Clean Energy for all Europeans package' in 2018; and the revision of the 2009 Directive aiming to make the EU a global leader in RES and to ensure that the target of at least a 27% share of renewables of energy consumed by 2030 is met. The NECPs were submitted to the Commission by 2019, and they cover strategic areas for energy transition, such as energy efficiency, interconnection and R&D activities.

We also follow the constant rise of solar power technologies with the new small-scale PV and solar storage installations to pay back consumers in the long term [F3] (Solar Power Europe, 2019). Since 2015, a bunch of big companies are now investing in wind, solar and climate technologies. IKEA announces a 1 billion euros commitment for the technologies. BMW, General Motors, Nissan, Honda, CEMEX, Heineken, LEGO, IKEA, Facebook, Google, Amazon, Microsoft, and Apple now invest o RET power up the business (Wind Europe, 2020; Solar Power Europe, 2019). In 2016 Germany reached 95% of energy generation by renewable sources for few hours in the morning, and in 2017 Denmark supplied 100% with enough wind to cover the entire power demand. Moreover, the first offshore wind farm without subsidies was built up in the Netherlands [F3]. The Dutch Government granted Vattenfall the deal for Hollandse Kust Zuid (I & II) with 700 MW in total (Wind Europe, 2020).

In conclusion, Phase 4 is populated by new policies, actors and the development of betweenness centrality, indicating an increase in the exchange of information among units. Several organizational bodies joined in the process during this phase. Considering that this one is really near to the development of this study, it is not possible to track and correlate coherently and consistently. Since the COVID-19 crisis, there was a reduction in terms of knowledge sharing because structural and individual habits modification required so. After the Paris Agreement and the 'Clean Energy for all Europeans package', we clearly understand some modifications in the network characteristics regarding connectedness and the continuous enlargement of size. However, the process seems to be stuck in 2019 and still has difficulties related to severe budget and political interest to proceed. This phase began in 2015 but maybe will take a long time to speed up. The running for the RET does not stop, but it was drastically and momentarily braked for pharmaceutical and biological R&D activities.

In conclusion, this chapter was responsible for dealing with the social network analysis, a key method in our research. We observed a continuous development in terms of size with some variations in the characteristics of the RETIS. Then, we developed a qualitative analysis of the development of the network. We observed rapid growth of the energy, overall renewable energy thematic in the European Union. This was only possible because of the constant effort from Member States and the EU to provide research and innovation development conditions. The complexification of the energy market happens due to the progressive amount of investment from public and private sectors on the technologies. The SET-Plan since 2002 evolved to coordinate and collaborate with several actors via their supporting institutional branches for firms, industries, research institutes and so on.

Moreover, in the development analysis, we perceived several networks that connect national governments and innovators to mobilize common knowledge to define national and regional politics. EUREC, EERA and the Innovation platforms under the SET-Plan umbrella: ETIP Wind, ETIP PV, Smart Networks for Energy Transition and ETIP on Renewable Heating and Cooling are just some of the existing networks that diffuse knowledge and are mobilized by the government authorities to define the next step in the geopolitics of energy transition. They can also be addressed as research communities or epistemic communities feeding decision-makers in the EU and national level with valuable information about it. One might affirm that the European Union is so much ahead in the knowledge pool and legal basis to develop renewable energies. It might be not easy to find someone who will not follow this revolution in which the EU is the world leader. However, the characteristics of the European integration, by combining different countries with different histories, economic performances and visions of RET, set difficulties in coordinating the transition.

So far, we have seen the development of the network exclusively based on the country level. This already indicates deep connectivity within European Union to produce knowledge for renewable energies, divided by academic publications and patents applications. Also, we have noticed how the development of the network was followed or induced by the politics and policies in this area, with massive investments in economic and political instruments to regularize and coordinate the knowledge and material application of energy infrastructure in the EU. We mentioned the difficulty of assuming that those policies on the policy mix/TIS analysis have impacted directed the development of more publications and patents. Notwithstanding, we assume that, as a contextual historical frame, the findings revealed with the four periods of the TIS (Pre-development, Development, Take-off and Acceleration) in respect to the number of knowledge production and the number of organizations (research institutes and firms for example), point for a high level of political coordination or multi level governance from international to national decisions to enhance the share of renewable energies in the generation of energy. This showed some cohesion of the mix of policies that points for a speed up process to enhance installed capacity and reinforce the European integration by recapping the original energy generation issue, but in a moment ahead from 1951.

The next chapter deals with the collaboration of knowledge on the country level but applying a different approach to identify preferable partners to produce knowledge. We consider the evolution of the EU treaties as policies to enable the join of new Members. Moreover, we analyse which countries in our network are central (or powerful) and which are not. This is also important to understand the geopolitics of energy transition within the European Union and the differences of timing between Members considering their positions and other factors.

Chapter 4

INTERNATIONAL POLITICS DEALING WITH TRANSITION

The chapter has the objective to continue our analysis now on the Upper Scale. The knowledge flow revealed to be actually improving, as was also expected the market generation and maturation, the robustness of institutions, and acceptance and legitimation of the renewable energy use by the society. However, as our two scales framework approach suggests, we still need to investigate the power dynamic on the Politics dimension and the geopolitics of renewable energy in the EU.

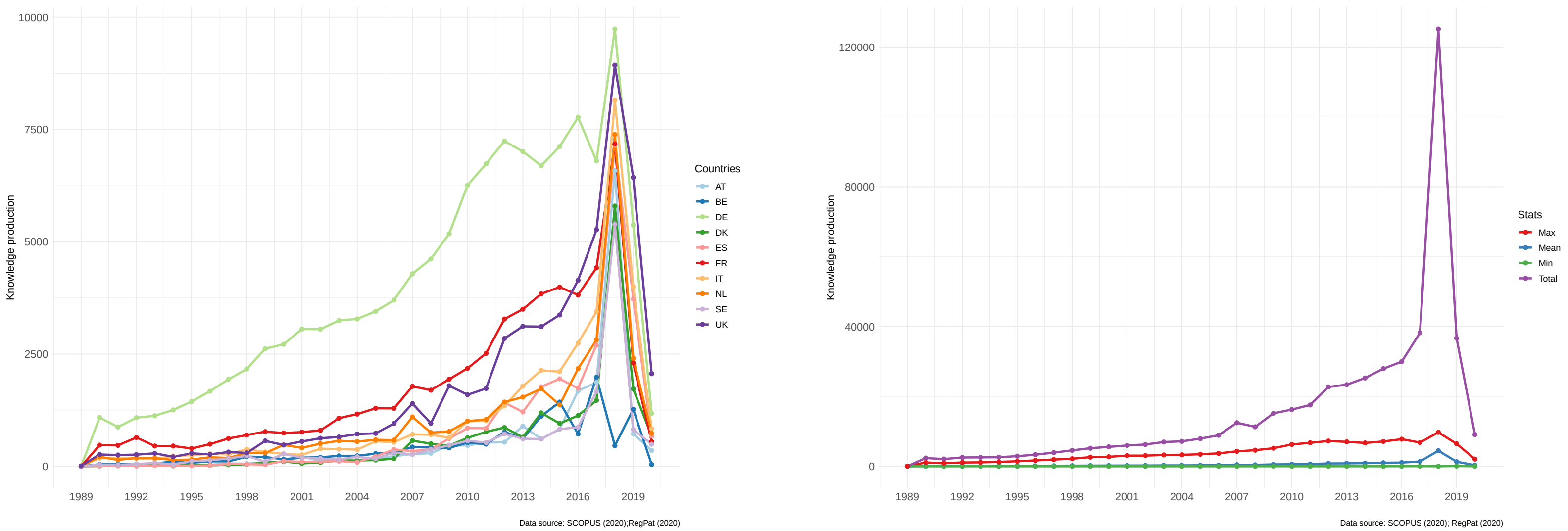
We deal with the international level of the network but focusing on different elements. First, we begin by investigating the collaboration at the country level. Second, we provide a structural and relational embeddedness analysis of the network, focusing on the centrality measurements, community detection and the most intensive relations throughout the periods. Finally, we move to a second part of the chapter, where we mobilize elements, such as the RET potential, installed firms and parks and the issues related to that, to investigate the power dynamic and the geopolitics of energy transition of the European Union.

4.1 Country-level network analysis

The knowledge flow between individuals is important to provide a framework to evaluate the size and inner characteristics of the network. But they do not reveal, on the international level, the embeddedness of some countries or how they related to each other considering the frequency and level of collaboration to enable political decisions. Here we provide an international level analysis of our network. By running the community detection based on edge betweenness, we identified how the 28 EU countries are collaborating more over time until it becomes a universal collaboration of knowledge. An analysis of four centrality measurements follows this. This is necessary to evaluate the most important units in this analysis, or the most influential Member State on the production of knowledge, that latter, on Section 4.2, reveal to be a central political actor in the geopolitics of renewable energy.

In this section, nodes are countries, and the links are the knowledge production collaboration between them. Since we did not run into a lack of computational power in this step, we could assemble both types of knowledge production, patents applied and academic publications together in a single data frame, accounting for 491.942 observations (207.107 from patents and 284.835 from academic publications). Figure 4.1 presents the top 10 knowledge producers and some descriptive statistics in the nine periods. The standard deviation is represented by short numbers in all periods indicating, even in the 2018 pike, a dispersion close to the mean. However, the means fall short due to over 50% of all periods where some countries did not produce any knowledge, indicating that knowledge production is not balanced among Member States. Also, it can indicate a difficulty to apply the same policies to foment renewable energy knowledge diffusion, provisioned by European Commission, in all 28 countries. Further, we can suspect that there is difficulty providing energy transition coherently when considering the coherence of the policies and the actual capacity to rethink internally e peculiarly new energy sector models.

Figure 4.1: Knowledge production



(a) Top 10 knowledge producer

Data source: SCOPUS (2020);RegPat (2020)

(b) Descriptive statistics for Knowledge production

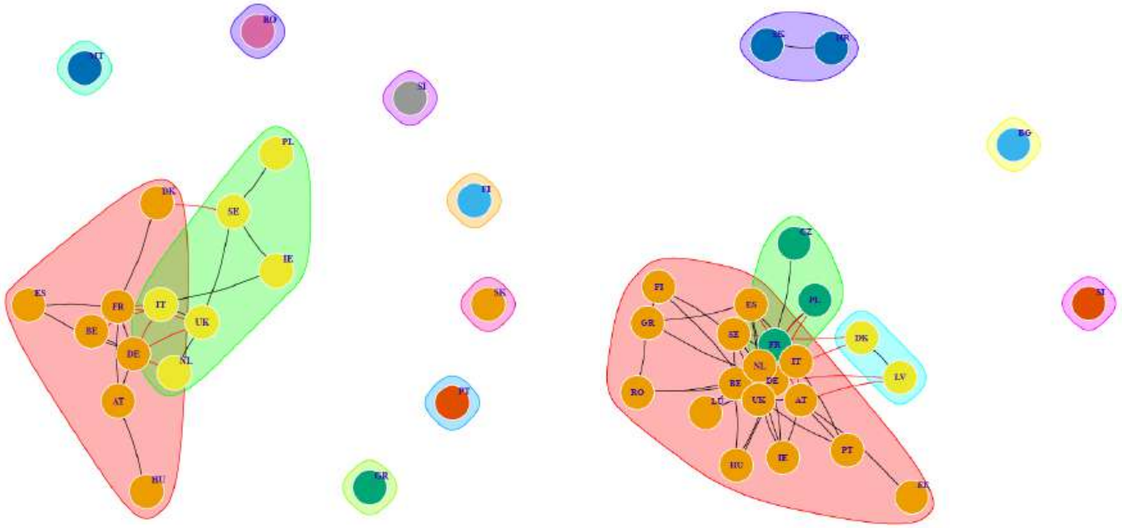
Data source: SCOPUS (2020); RegPat (2020)

We observe that Germany has more publications until 2018, reflecting the financing on renewable energies, as discussed in Chapter 2. France and the UK follow a similar pattern of knowledge production, with the UK surpassing France in 2016 and then Germany in 2019. These three countries (mainly Germany) may be responsible for increasing total numbers of knowledge production over time and responsible for the maximum number of publications that accumulate in total. Although the rest of the countries are included in the top 10, their knowledge contribution is relatively on average. Italy, Spain and the Netherlands are important countries in this manner. Although their production is more restrained, they have important firms, such as Siemens-Gamesa in Spain or the Sustainability Transition graduation Utrecht University that traditionally has dealt with energy transition in the Netherlands. Moreover, Belgium is the only top 10 that during the pike in 2018 does not increase the knowledge production. In the next section, we deal with grouping the 28 countries in our sample based on knowledge production over time.

4.1.1 From multiple clusters to a universal one

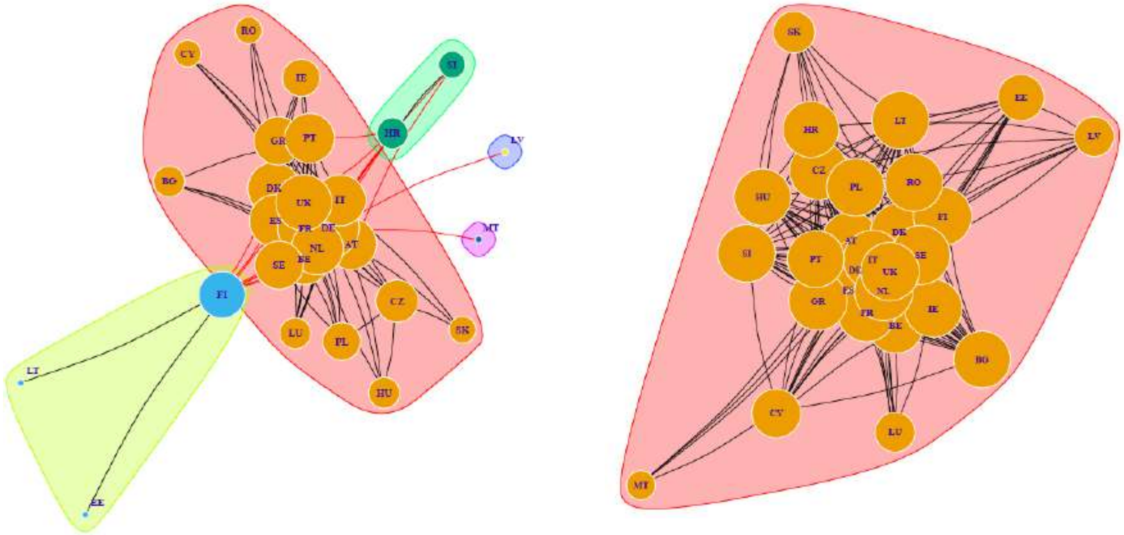
The Newman-Girvan method to detect communities based on edge betweenness was handy. Removing edges does not show centrality, but it focuses on edges that are most likely ”between” groups of nodes. After applying this algorithm, it revealed how often a country is embedded in a cluster or not, if the country collaborates with another outside its own group, and other issues discussed below. The algorithm does not provide a component measurement, which is a traditional SNA indicator, but the final stats can be similar or not. After running the Newman-Girvan method, we noticed that the number of communities in some periods is near to the number of components (P1, P2 and P9) but completely different in others. Since then, the benefits of applying the algorithm and do not follow the traditional indicator lie in the possibility of simplifying, even more, the pattern of links between nodes, calculating a particular edge as the number of times it appears in the shortest path matrix of the graph. As a result, the method provides a network with each edge value as 1 (without weighting the relationship), revealing the links between Member States that detect a scientific community. Figure 4.2 shows the development of the clustering process of the RETIS.

Figure 4.2: Development of communities in RET collaboration



(a) P1 1990-92

(b) P3 1997-99



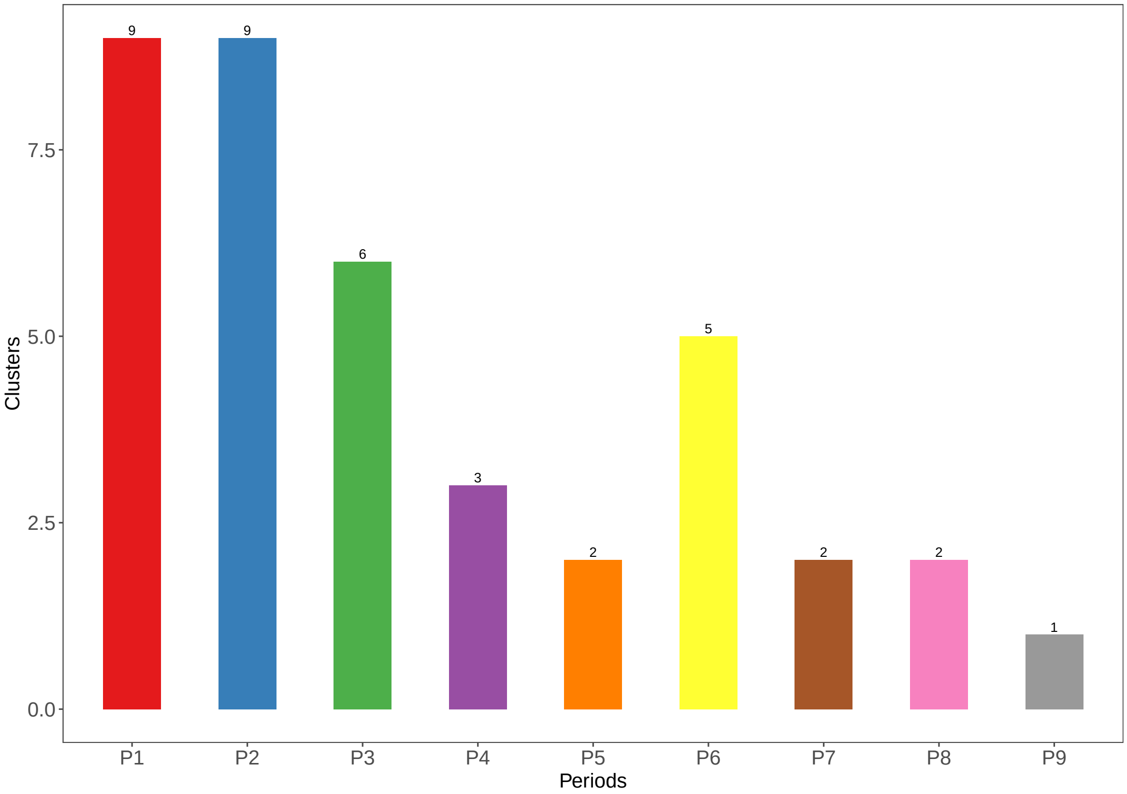
(c) P6 2006-08

(d) P9 2015-20

Note: Node size is a function of node's degree. Due to some computational problems, the colour of nodes in relation to their countries was not able to remain the same, and for each period, the countries legend should be observed for comparison.

Figure 4.3 presents the distribution over the periods concerning the number of clusters. We quickly remind the years corresponding to each period: P1 (1989-1992), P2(1993-1996), P3(1997-1999), P4(2000-2002), P5(2003-2005), P6(2006-2008), P7(2009-2011), P8(2012-2014) and P9(2015-2020).

Figure 4.3: Number of communities in each period



Also, following the assumption from (Bocquillon & Maltby, 2017) about the treaties of the EU and their connection with climate policies, we identify that the widening or deepening process may contribute to understanding the development of the grouping. Table 4.1 presents the evolution toward the integration of more Member States to be used as a temporal orientation in this European level analysis. Paris, Rome, Maastricht, Nice and Lisbon are known as deepening treaties. The others are widening (or enlargement) treaties, and instead of using the title of the treaties, the States are presented. Also, we highlight the treaties that actually brought modification in terms of the EU membership or institutional reinforcement, putting aside those that exist for the integration's diplomatic purposes but add few contributions to the development of the RET.

Comparing P1 and P9, far positions from each other, we observe that the States moved from a structure of multiple clusters to a massive collaboration. In P1, the European integration was not named yet European Union, and it was actually European Economic

Table 4.1: Membership evolution in the European integration

Year	Membership or Treaty	Number of members
1951	Paris Treaty	6
1951	BE, NL, LU, DE, IT, FR	6
1957	Rome Treaty	6
1973	IE, UK, DK	9
1981	GR	10
1986	PT, ES	12
1992	Maastricht Treaty	12
1995	AT, FI, SE	15
2001	Nice Treaty	15
2004	EE, LV, LT, PL, CZ, SK, SI, HU, MT, CY	25
2007	BG, RO	27
2007	Lisbon Treaty	27
2013	HR	28

Source: Based on Winzen & Schimmelfennig (2016)

Community. The number of nodes for this period, 20, does not correspond to the number of countries on the integration's actual moment of the integration, 12. The number of edges is 22, describing a small portion of collaboration between countries. Peripheral countries, Hungary, Spain and Poland, tend to migrate to an inner position relative to the network in the following periods. The same does not apply to Slovakia and Malta, for example, which remain far from the centre. Even though the central position of units is an important factor, it will be analysed later in this chapter. Moreover, since 1951 there were three EU widening treaties[1]: 1973 with the entry of the UK, Denmark and Ireland; 1981 with the entry of Greece, and; 1986 with the entry of Portugal and Spain.

Even though enlargement treaties play decisive roles in the institutional integration, this might not apply in terms of knowledge. P1 is marked by seven isolated countries and two research communities. The red one, on the left, with seven States and the green one, on the right, with six. According to our data, DE, the UK and FR are the three units with the highest knowledge production since the very beginning. Their central position on the whole sociogram plus their relative position as a communicator with other clusters reveals a potential knowledge flow between them. Important to notice, as our data on knowledge production shown, IT, NL and AT, as someone might notice, are also in this central position, with Italy and Belgium being units with a lot of knowledge passing through them from one

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[1] There are two main differences between treaties that govern the European integration: widening and deepening. Widening refers to those treaties dealing with the enlargement of the integration by allowing applicant countries to join. Deepening refers to those treaties dealing with the advances in institutional, economic and political advances or changes in the integration.

cluster to another, which is indicated by the red lines.

The European integration passed the first 30 years as a segmented market, with lots of isolated and protectionist trade policies between member states, contradicting some integration theories (Alter & Steinberg, 2007). It would not be so different in terms of knowledge collaboration. But, of course, the means of communication were precarious and not so efficient compared to the XXI Century. The polarized world between capitalist and communist economies materially represented by Berlin Wall made the exchange of information, even scientific collaboration, difficult to happen. Even though the Schengen Agreement, whose function was to eliminate barriers for people, goods and services movement, already exists since 1985, there is an international context in Europe that does not pay a lot for integration. However, in 1992, the Maastricht Treaty comes to celebrate the creation of the EU, followed by more institutional changes that would allow a deeper integration, such as the provisions needed for the Monetary Union by dealing with the preparation of the Euro, also the creation of the Association of European Renewable Energy Research Centers (EUREC). This last one had a tremendous impact on the country level cooperation by facilitating the collaboration of several research institutes dealing with RET (EUREC, 2020). Once again, the policy mix's evolved cohesively and coherently, as shown in Chapter 3, may have contributed to these advances. The SET-Plan, as we noticed, is an important instrument to enable collaboration among States, followed by their peculiar issue-area plans. It may help the political coordination to develop the RETIS toward a broad diffusion of renewables.

P2, even though it has the same number of clusters as P1, is formed by 6 isolated units and 3 clusters. The difference is in the number of nodes now 25 and 35 edges. Now 15 Member States after the enlargement process in 1995, and, although Poland and Czech are not formally in the integration, this might be the reason they created a 2 units cluster, that cooperates with two different countries, France and Germany, each one in a different community. However, the grouping starts to show more links in P3. Still, with 25 nodes but 57 edges, there was no enlargement in the integration from P2, but actually a deepening process in the collaboration of knowledge. P3 is marked by the grouping of a large community with 16 units, integrating two of the biggest knowledge producers, Germany and the UK, and revealing a preference of collaboration of France with Poland and Czech. France joins the network centre, establishing a connection between its own group and the bigger one. Denmark and Latvia are connected to three other countries: Germany, Austria, Sweden, and central actors. Four non-Member States appears to be away from the central part of the main component of the network. Bulgary and Slovenia isolated, and an isolated community made of Croatia and Slovakia.

P2 and P3 contextually dealt with the provisions for the Euro that ends in 1999.

Through these 7 years, the integration renovated itself, moving far from the original ECSC. Schuman and Monnet citepalter2007theory. As the world has changed after the end of the cold war and the fall of the Iron Curtain[2], the collaboration seemed to intensify itself. From a segmented and fragmented market, the Monetary Union along with the Three Pillars of the now well-known as European Union[3] created some path toward a non only bilateral community of units, but actually a more strong and decisive profile of integration. During this period, the Green and White Paper on Energy were launched, contributing to the demand and further diffusion of more RET. After both documents describe the current situation of RET, they paved a long road for its development in the following years. Provisions for GHG emissions reduction by 12% and penetration of green energy technologies by 12% around 2010 were set. Although with a low level of the penetration of the EU institutions in the national governments, the decisions were important to identify possible tracks for innovation in alternative energies, followed by the First Energy Package as discussed in the Chapter 3.

P4, P5 are marked by a constant reduction in the number of communities. P4 has 25 nodes and 56 edges, indicating a small loss of 1 edge comparing to the previous one, but remaining with 15 Member States. P5 comprehends when the largest enlargement process in the EU moves to 25 countries integrated. It has 27 nodes and 91 edges, indicating an increase of almost 40% in knowledge collaborations. Cyprus is an isolated country in both periods and Slovakia in P4. While in 2001 the Nice Treaty is under discussion to prepare the institutions to reform and receive the biggest enlargement, our interest is in P5, when the enlargement brought political consequences for the European Union after the entry of some post-soviet (Baltic countries) and Central-Eastern-European countries[4]. A process of constant adaptation followed changes in the EU budget and the newcomers' fiscal laws. According to the EU determinants, the conditionalities to join the EU (Copenhague Criteria from 1993) had to be progressively attended by them, including energy and climate policies (Alter & Steinberg, 2007; European Comission, 2020). The consequences of this enlargement are better discussed in P6.

P6 tells a different story. With 28 nodes and 117 edges, the integration starts with

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[2] Iron Curtain is the political division establish between communists and capitalist economies in Europe during the Cold War

[3] 1) European Communities, dealing with economic, social and environmental policies; 2) Common Foreign and Security Policy, and; 3) Police and Judicial Co-operation in Criminal Matters

[4] Post-soviet countries are those whose during Cold War were part of the Soviet bloc, and after its dissolution, became independent. Like the Baltic countries (Estonia, Lithuania and Latvia), some are already part of the EU. East-Germany and East-Berlin, as part of the treaties after the Second World War, was annexed to the URSS, and the separation was ceased after the end of the Cold War and the German reunification. Some Eastern-European countries were converted partially to the URSS. They were, East-Germany, Finland, Poland, Czech Republic, Slovakia, Hungary, Austria, Slovenia and Romania. Important to mention is that Czech Republic, Poland, Slovakia and Hungary formed the Visegrad Group in 1991, and some of their decisions toward the EU comes in group

25 but ends with 27 countries. The number of nodes is larger than integrated countries, just missing Croatia. The enlargement treaty divided the grouping one more time into 5 communities. The larger red one with 28 countries; yellow one with 3 countries; green one with 2 countries, and; 2 isolated countries - Latvia and Malta but now they are connected with the big cluster. The enlargement brought many folded opinions about the European Union climate and energy innovation, varying from complete scepticism to complete coordination of the policies or even an East-West cleavage. While the Baltic and Eastern-European countries were reluctant to adopt climate-energy policies such as the ETS phase 1 and the Energy Package, the EU institutions had trouble encouraging them to join the Framework Program 6 and 7 (Ćetković & Buzogány, 2019).

The last newcomers had a dependence on fossil fuel from Russia, which endangered the energy security in the EU. Still, at the same time, they were strong supporters of the EU integration, advocating for a unique voice in energy issues (Bocquillon & Maltby, 2017). Although the full support, the countries joined with several domestic problems that made compliance with energy climate technology issues more difficult. Their economies were defined as Dependent Market Economy, characterized by low labour cost, relatively skilled workers, and favourable to tax regimes in the economic dimension. In general, on the political dimension, they have significantly lower transparency, more centralized decision-making, a higher propensity to clientelism, and higher corruption levels (Ćetković & Buzogány, 2019). Although these countries match the conditionalities to join the EU, the decisions toward energy and climate innovation are differentiated if compared to Western-European countries, once they are more concerned with their national development of energy infrastructure rather than a europeanization of the energy market. They had less tendency to collaborate with old Members, and old Members disregard their collaboration for renewable energy knowledge (idem). This perspective toward energy integration has important impacts on the geopolitical discussion and will be discussed later4.2.

The end of P6 is marked by the discussions in 2007 around the new deepening process, Lisbon Treaty. This is the most recent EU decision toward the integration structure, which also develops provision for the EU as an international actor, joining diplomatic conferences and making Peacekeeping Operations. Moreover, the Climate and Energy Package was presented in 2008, with the Renewable Energy Directive of the European Commission setting binding national targets according to the 20-20-20 EU strategy (European Comission, 2020). The results of P5 and P6 indicates that all countries forming the EU were collaborating among themselves to produce knowledge for RET. However, those which came after the Iron Curtain or from the Central-Eastern-Europe seem to have a different position according to centrality, which will be discussed later4.1.2.

Despite the differences from the 10 new Members, the process of europeanization seemed to have worked fruitfully. Moving from a disturbance moment in the knowledge flow and integration, P7 increase the number of edges to 193, remaining with 28 nodes and 27 Members. There are only two communities, one formed by 7 and the other by 21. After the conclusion of Lisbon in 2009 with the Climate Energy Package, the newcomers required some help. The economic disparities among Members was something expected after the enlargement. Baltic and Central-Eastern-European countries claimed about the energy and climate instruments such as the ETS because it might break their renewable energy knowledge development, increasing the dependence on Russian Fossil Fuels exports (Ćetković & Buzogány, 2019).

But something interesting happens in P8. The number of edges drops to 176, and nodes and Member States are officially the same, 28, after the opt-in of Croatia in 2013. There are two communities, one formed by the three Baltic countries (post-soviet members) and a bigger one with the other 25 countries. We observe that the Baltic countries have a strong connection with each other, but they also seem to collaborate with central countries of the network. The Visegrad Group seeks to be independent of the Russian imports, and they have strengthened their investments in RET since the very beginning in 1991 and their support for the EU integration. Even though Poland represents a great opposition to energy policies in the EU, it is still a country that collaborates with renewable energy knowledge production (Ćetković & Buzogány, 2019; Bocquillon & Maltby, 2017).

According to Štreimikienė et al. (2016), the Baltic States have a preference to collaborate among themselves. Each one has its own goals for the energy sector, but they interconnected transmission streams of electricity, and their political goals toward energy transition are interdependent. Since 2007, with the Baltic Energy Strategy, the three countries tend to mobilize co-fund projects to strengthen the educational, research and development in the energy sector. By co-funding projects toward renewable energies, the three countries increased their collaboration right after the EU integration. This was a response to the complicated political relationship with the Western countries and their observation of the future energy geopolitics. Since the countries are really dependent on fossil fuels from Russia and nuclear energy, they prefer to cooperate among themselves under the goals of the EU (Stockholm Environment Institute Tallinn Centre, 2019).

With the Renewable Energy Directive from 2009, Member States agreed to propose the National Renewable Energy Action Plan (NREAP). The Baltic States presented their Plans, taking wind energy as their main driver following the potential for generation both on and off-shore in the Baltic Sea. Furthermore, they intensify their collaboration to achieve in the following years the independence from Russian exports (Štreimikienė et al., 2019). As a result, all Baltic countries achieved the 20% share in total energy from renewables regarding the 20-20-20 Strategy. Estonia had better results during P8 mostly because of its high collaboration level between the Baltic States but collaborated 50% more with the rest of Member States than Latvia and Lithuania (Štreimikienė et al., 2016). The Baltic States have a progressive investment in the energy sector in terms of electrification, dealing with collaborative initiatives since 2007 and receiving funds from Seventh Framework Programme at that time, which could have financed many projects. They were responsible for 57 participation (0.04% of total), receiving 10.95 million euros (0.02% of total) to develop projects in collaboration among themselves and with other Member States (European Commission, 2021a).

Finally, P9 is the last period in our sample. It remains with 28 nodes and 28 Member States, despite the opt-out of the UK in 2020. The number of links grew by 60% from the last period, reaching 282 links. The evolution in terms of knowledge collaboration is tremendous. If compared to the first period, there was an increase of 1118% and a complete integration in the knowledge production of the 28 countries. This period starts with the Paris Agreement and the Sustainable Development Goals (SDG), reborn environmental and climate concerns and energy security. After Lisbon Treaty in 2007, the European Union was reformed one more time, giving the Union the status of international persona. After Paris, the EU was able to design its own Nationally Determined Contributions (NDC), setting targets for all Member States. This international skill allowed more coordination and governance for climate and energy policies, creating a single NDC for Member States. As a result, this triggered the new Energy Package with the Energy Union and the demand of the National Energy and Climate Policies (NECP) following the new international agreements (European Comission, 2020).

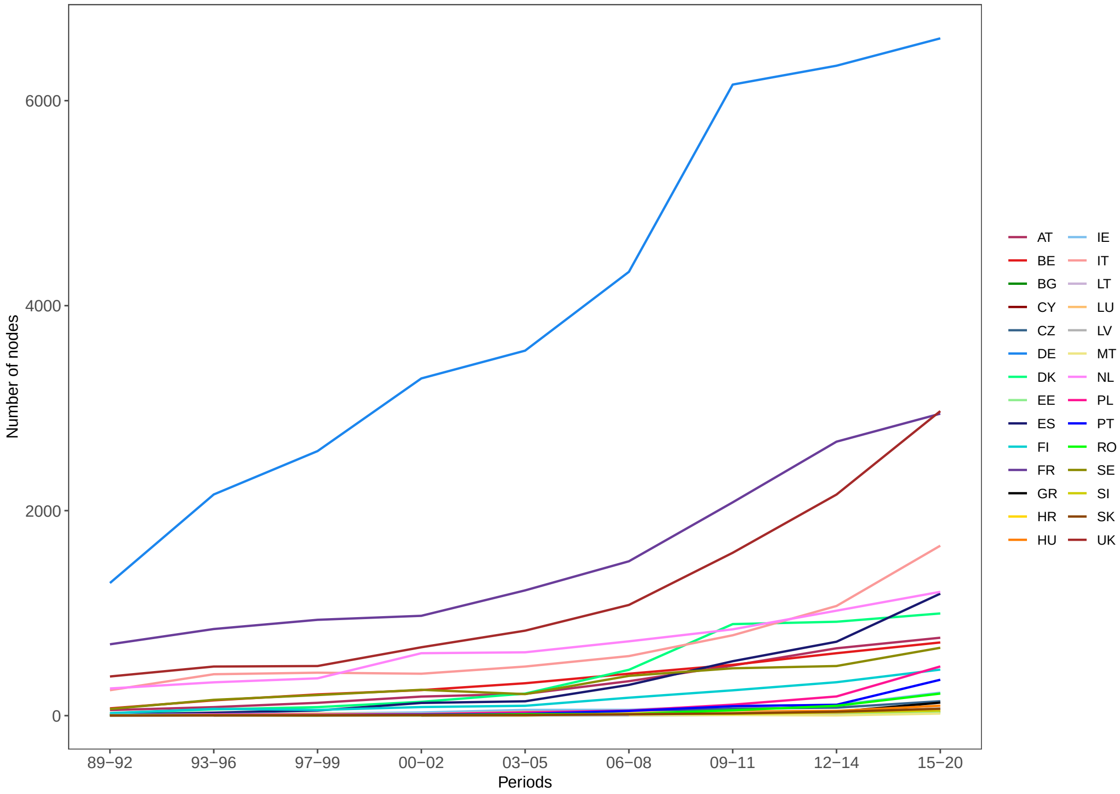
One important point is about the central-periphery relation. The majority of the countries are in a central position, which will be discussed later, but we observe some countries such as SK, EE, LV, LU, CY and MT with small degree centrality, demonstrated by their shorter size. Except for Luxembourg, the other Member States are part of the two last enlargement processes, and they present inferior economic performance within the integration. Based on the discussion above, the Baltic States had a difficult collaboration for renewable energies with Western countries, but Lithuania changed this perspective and strengthened its collaboration with them. Moreover, Malta is the farthest one in P9, with few links pointing to central countries and one to Cyprus. The country does not have a good history in terms of knowledge production, not even for collaboration, reflecting its short renewable energy R&D investments, production and consumption (Eurostat, 2019b, 2020b).

The community detection served to identify with which Member States prefer to collaborate to generate RET. The algorithm provided good insight for the analysis. For example, we understand that enlargement treaties did not allow collaborations in this manner, but they came after over time. Also, it revealed a tendency of centrality from some countries in the network, even if they are in different communities, which suggest that they prefer different partners to collaborate often, even though knowledge constantly flows through these central edges. We move to the next section for the centrality measurements analysis.

4.1.2 Knowledge concentration and centrality measures

There are different forms to measure centrality in a network, and they vary according to what one intends to analyse. Centrality helps to identify the most important node or nodes in the network (Wasserman et al., 1994; Scott, 2013). In this case, it suggests the more influential country in the development of knowledge production. Although the number of nodes of every country indicates centrality *per si*, it can help us visualize the evolution of each member state's units over time. Figure 4.4 display this calculation for every node representing a unit that produces renewable energy knowledge.

Figure 4.4: Number of nodes from EU-28, 1989-2020

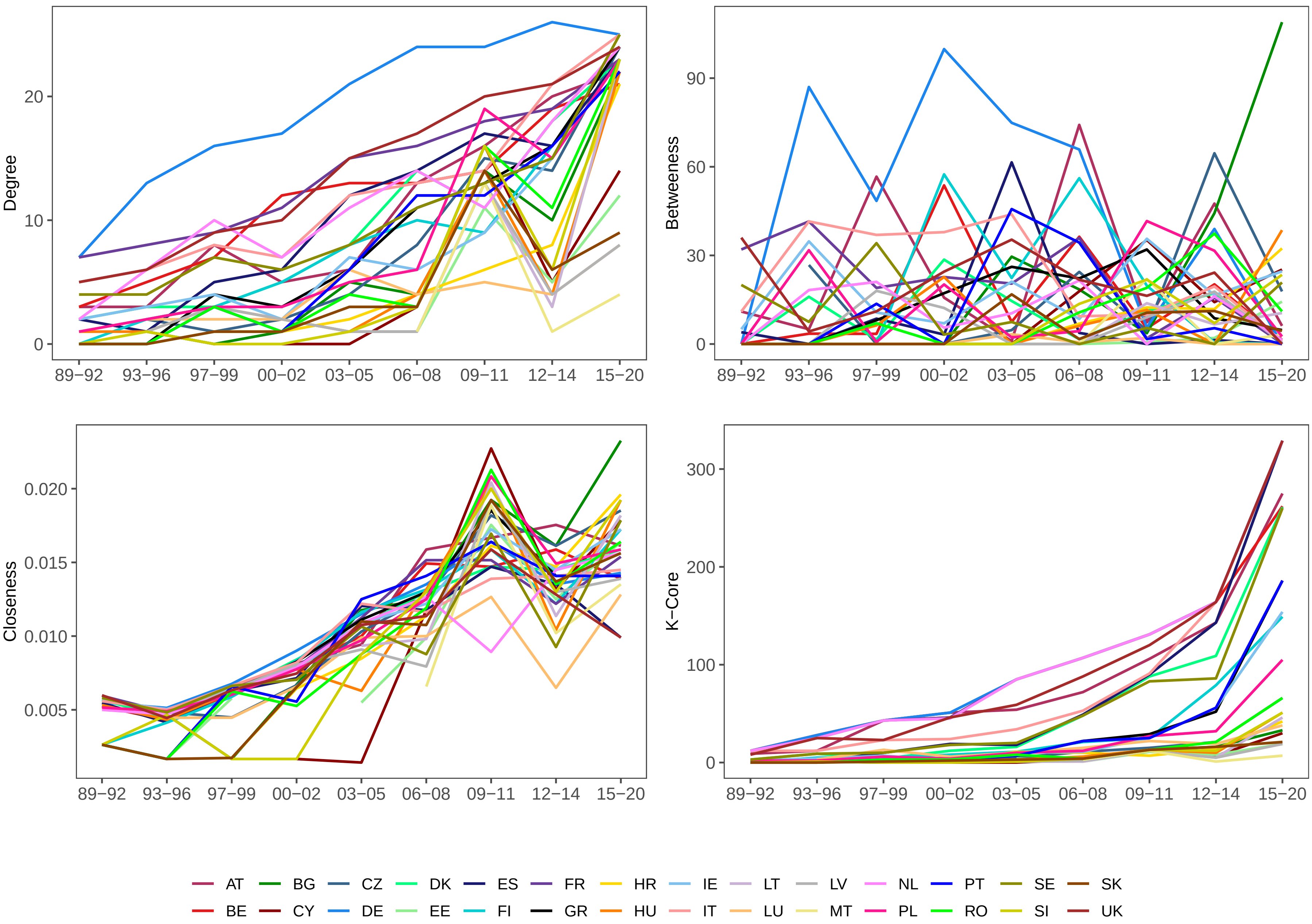


We observe that the top 3 countries are Germany, France and the UK. The number of nodes of Germany is really higher than the other two, which tells us that Germany is an important country in promoting researches in RET both in terms of patents of publication.

This reflects the high level of investments discussed and the economic performance compared to other Member States. The difference in knowledge production from P6 (06-08) and P7 (09-11) reveals that maybe the Fukushima accident in 2011 or other similar events might have triggered interest in the academic community to research alternative energies. France and the UK have a similar development pattern over time. Both countries seek their independence from fossil fuels. The increase of interest in producing knowledge over time with the two other countries with good economic performance and investments in RET is something to be taken seriously. They both invest more in wind than solar power, partially because this industry is more advanced in the European context, partially because they share the Baltic Sea, a potential site for wind energy investments shortly. Also, Italy, the Netherlands, Spain and Denmark have a similar pattern of interest toward RET. Denmark and the Netherlands are countries with renewable energy companies that were important in the first years of expansion of the industry, contributing to the evolution of efficient models (Wind Europe, 2020).

Despite the fact that the number of nodes can reveal the number of potential influences a country has in the network, the centrality measures can contribute to understanding their position within the network. Degree, betweenness, closeness and k-core are different types of centrality but all related to the number of links and not just the number of nodes. Degree is the simple count of links according to their intensity, or how many connections a unique node has. Betweenness is the number of shortest paths through the network of which the nodes part, or how often the information of the network goes through a node to reach other nodes. Closeness is the inverse of the average length of the shortest path to/from all the other nodes in the network, or how important a node is for the whole network. Finally, the K-core is the maximal subgraph in which every node has at least degree k, or if a node is more central or peripheral (Graf, 2017; Graf & Kalthaus, 2018; Wasserman et al., 1994; Scott, 2013). Figure 4.5 displays the four centrality measurements for 28 EU Member States.

Figure 4.5: Centrality measures for EU-28, 1989-2020



Degree shows that the three countries with the larger number of nodes - Germany, France and the UK- have a similar trend in the number of connections, with a consistent number of collaborators increasing over time. Germany starts with similar connections as France but right in the second period, the country runs far away from the other countries enabling more collaborations than all the others. Interesting to notice is the tendency for most Member States to reach over 20% of links in the network. Some countries, for instance, Denmark, Poland, Czech Republic, Hungary and Ireland, that had few connections in the first six periods, they received a boost in the seventh. After some downgrade, they are rising the number of connections compared to those traditional collaborative countries, like the top 3. Latvia, Malta and Slovakia and others have a low tendency to collaborate with other Member States, even after the boost in P7 (09-11).

Differently, the betweenness centrality tells us how often a country is a mean of transport of information in the network. Surprisingly, Germany is a central node only in the first six periods, but different countries achieve this central position to flow knowledge in the network in the following periods. Despite the crescent degree over time, Germany lost its position to access or even control the knowledge flow in the network. Surprisingly, Bulgaria seems to be a country that seeks to be central in the knowledge of RET in the last periods, followed by Hungary and Croatia. An interesting trend is the last two periods when many countries' positions are nearly zero, mainly those that traditionally have more nodes and knowledge production.

Closeness centrality tells us about the nodes which are able to spread information very efficiently through the network. Surprisingly there is little distinction in average. Excepting Slovakia, Slovenia and Cyprus, considering the first periods of each in the network, the rest of Member States can spread information efficiently over time. Even though the number of nodes and knowledge production are different among them, they are more homogenized to collaborate, developing the capacities similarly to build RET. In the last period, we observe Bulgaria once again as a more efficient node, which tells us that the country is a 'checkpoint of information' in the network, the majority of information pass through it and also is actually spread in the network, revealing a central actor for the functioning of the network even though it is not in the top 10 countries of knowledge production.

The last measurement, k-core, tells us about the tendency of some countries to remain in the core of the network while others are compelled to be in the periphery. There is a tendency that old Member States in the integration reinforce their central position over time by collaborating more often with each other. Germany, France, the Netherlands, the UK, Spain, Austria, Denmark and Sweden, are clearly more central, with the three first mentioned almost evolving together. Some countries are far-fetching this central position, such as Portugal, Greece, Ireland, Finland and to a lower extent Poland. But the rest figures in a peripheral position. Which is the case of the Baltic, some Visegrad States, and latter integrated countries. Interesting to notice is Bulgaria. Its 'check point' position does not pay well by raising its importance as a preferred collaborator among all possible units.

So far, we analysed the centrality measures of the network, achieving some interesting insights. Germany is an important node in the network because of other statistics and political data already exposed. However, it lacks the skills to coordinate the knowledge flow in the whole network. It may have lots of collaborations, but they might not be so diverse across the 28 countries. German collaborations actually prefer traditional partners to develop knowledge. As possible to see in Table 4.2, Germany has the most intensive collaboration varying only the partner in all periods. The country seems to prefer to collaborate more often with countries with higher economic performance or with those having traditional experts in RET to speed up their energy transition.

Table 4.2: Most intensive relationship in all periods

Period	Country 1	Country 2	Frequency
P1	DE	NL	12
P2	BE	DE	28
P3	AT	DE	41
P4	AT	DE	51
P5	DE	FR	60
P6	DE	FR	76
P7	DE	FR	103
P8	DE	FR	139
P9	DE	UK	175

France and the UK (the last one has opted-out) always have run in a secondary position, watching the German development of RET closely, collaborating, but never passing over. Together with the Netherlands, Denmark, Spain and Italy, they tend to be central in the network mostly because of their preferable collaborations with Germany, which has an advanced knowledge base and strengthens the collaboration within this group. This might explain why these countries have a better position in the energy transition on average (this will be discussed shortly in the next Section). They together are responsible for over 70% of the knowledge production and renewable energies generation. These top countries use the integration and programs to advance research in the energy sector to accelerate their own modifications and achieve the EU targets for climate and energy policies sooner.

Interestingly, retarded countries in the integration tend to do not advance faster in creating knowledge for renewables, even though they also have to achieve targets over time. When they achieve, they do it partially, demanding finance from other countries and claiming that ETS is a barrier in developing the energy sector (the case of Baltic States) (Štreimikienė et al., 2019). Since their emissions compared to Germany of France are lower, this figures as a top priority for energy policy, but they have more space to reevaluate programs and do not present National Energy and Climate Plans so bold. This may indicate a position in the energy transition of last runners or even free riders.

It is worth noticing that the Energy Union, or any other energy program or plan, was designed to coordinate a transition with all countries similarly. Of course, there is a high degree of collaboration, even more in the last periods, but the differences between the countries' capacities are still high in many factors. Since solar and wind energy mobilize renewable sources, they appear to be in the whole World. The potential of generation varies according to the latitudinal position of each country. Those close to Equatorial Line have the highest solar power potential, while those in places where the wind blows more often have more wind energy potential. Notwithstanding, the position of the countries means nothing if they do not have the technologies and budget to deal with the natural sources.

Although coordinated by the common policies, the development of the energy transition in the European Union is far away to move all Member States to a single path. Therefore, this presents another discussion about the power of each country to mobilize its resources to deal with energy transition. Moreover, to deal with the geopolitics of renewable energy within the integration. Therefore, the next section discusses both power in energy transition and geopolitics of renewable energies in a European Union context.

4.2 Power and geopolitics of renewable energies

The discussions about the geopolitics of renewable energy and power relations in energy transition are new, even for the European Union context. The level of interdependence of the energy sectors was always high since the ECSC. But in the last years, the evolution in terms of knowledge production and RE production and consumption have changed significantly how the geopolitics and power discussion moved to. Studies toward energy transition (perhaps every sustainability transition) have to consider how innovation processes and, in our case, innovation systems are important to understand the distribution of power and its dynamics. The position of states in the world order can be shift when they have the correct mobilization of resources to boost the energy sector via investments in renewable innovations (O'Sullivan et al., 2017; Criekemans, 2018). But scholars also understand a change in patterns of power and politics considering the use or availability of RET (Avelino, 2017;

Scholten et al., 2020). This new reality can not perpetuate the traditional geopolitical and power tradition, but actually change how geographical characteristics and resources can give advantages or handicaps in world politics.

4.2.1 Power dynamics in the energy transition

We begin by analysing power dynamics in the European Union. Reminding, power is defined in the current study as: ”The capacity to mobilize resources is ‘owned’ in the sense that one can ‘have’ this capacity and ‘own’ resources, and it is exercised in terms of actually mobilizing resources” (Avelino & Rotmans, 2009). We follow this perspective Avelino (2017) by defining the type of power relation as ’Different power to’, with three different dynamics: Synergy, Antagonism and Neutrality. The authors also define three forms of exercise: expressions of power within a dynamic, and they can all be found here. They are: Innovative, Reinforcive and Transformative. These can be constituted of different resources: Mental, Human, Artifactual, Natural and Monetary.

Reinforcive power is the capacity of actors to reinforce and reproduce existing structures and institutions (Avelino, 2017). We observed many types when conducting our policy and TIS analyses, and the power here seems to be exercised by mental and monetary resources. Since the formation of the EU after Maastricht in 1992, there has been an increase in RET policies. The Energy Fund Project from the EU in 1985, and the Green and White Paper in 1995 and 1997, respectively, are the beginning of a long road toward the reinforcement of the EU institutions to deal with RET and energy transition (European Comission, 2020). It stands for a progressive researching project to learn how efficiently use the natural resources, mainly wind and solar. Since the 1990 decade there has been a progression of policies toward the diffusion and acceleration of RET sponsored by the EU institutions. The creation of the SET-Plan in 2006 with its Steering Groups and Technology and Innovation Platforms (European Commission, 2021b; European Comission, 2020) reinforces the role of institutions to overcome the critical situation of both climate change and energy security focusing on the share of RE.

Moreover, after the Lisbon Treaty and the international role of the EU, the integration was able to launch programs for RE and economic and regulatory instruments, such as the Energy Packages the RE Directive in 2009 and the Energy Union in 2015 after the Paris Agreement (UNFCCC, 2015; European Comission, 2020; Energy Union, 2019). The existence of these measures, and many others that have already been pointed, seems to indicate a Reinforcive power to create and diffuse more knowledge across the units but specifically by mobilizing the power of the institutions to efficiently coordinate Member States on the way to the energy transition.

Innovative power is the capacity of actors to create new resources (Avelino, 2017). Overtime, it is possible to observe the increase of knowledge production, indicating the mobilization of lots of different resources type. This knowledge production can be seen as foundations for increasing installed capacities over time and technologies that can overcome the energy dependence from Russia. Although the dependence rate is still high, in 2018, it was around 58%, experts in some of our interviews reaffirms the role of Russian gas in the energy transition (we discuss this later). We are not going to extend the discussion because we already present, over the last pages, how innovative actors mobilized the resources to develop the RETIS and pressure for an energy transition.

Finally, Transformative power is the capacity of actors to develop new structures and institutions. Although fossil fuels are still important for the energy sector in the EU, and there are still legislations for the market. There have been lots of agreements among Member States to reduce their use. The 2020 Climate and Energy Strategy may represent this idea because of its goals: reduce 20% GHG emissions, enhance 20% energy from renewables, and reach 20% energy efficiency (European Comission, 2020). On the one hand, the Strategy's goals are on the way for a low carbon economy. On the other hand, the following plans after the Strategy touch upon the progressive reduction of the use, overall for oil and coal. The Clean Energy for all Europeans Package, from 2019, is an example of a Transformative power. To reaffirm the goals of the Energy Union, the Package intends to reduce the consumption of energy via oil and coal by 2030, but at the same time, natural gas plays an important role in this interim. As some of our interviewed affirms before a large scale of electrification in the energy sector, electric cars in large scale, electric public transportation, cooling and heating, it is important to progressively diversify the sources of gas supply. Gas is still important because its emissions are less damaging, emitting 50% to 60% less than other fossil fuels (Labussière & Nadaï, 2018).

Discuss the evolution of innovation toward the sustainable use of unconventional hydrocarbons (shale gas) and natural gas were not under our scope. However, it is worth noting that from 2014 to 2016, the Commission established the European Science and Technology Network on Unconventional Hydrocarbons, which concluded with projects on the exploration of these sources in the EU. The document was useful for the publication of a guidance document with good practices for interested industries and regulations for governments in terms of exploration. But at the same time highlighting the potential damage to the environment and human health (European Comission, 2020). By and large, the efforts for unconventional hydrocarbons or natural gas diversification of suppliers represent the EU institutional capacity to create normative provisions for an energy transition.

However, the idea of transition would be nothing without looking at the goals of

Member States. Therefore, the National Energy and Climate Plans (NECP) were very important in mobilising the different types of resources to build bold expectations on the fight against climate change (European Comission, 2020). Every individual plan outlines: energy efficiency, renewables, greenhouse gas, emissions reductions, interconnections and, research and innovation. The goal was to update the energy and climate policies after Paris, the Energy Union and the Clean Energy for all Europeans Package. In time, Transformative Power demonstrates the reconfiguration of political structures by creating entirely new things to coordinate the energy transition, as shown in the Figure 3.1, where we divided into 4 phases to understand the evolution of TIS and mix of energy policies.

To a great extent, it seems fair to consider that the power dynamics here are, in most of the case, a Synergy type. The Synergy type can be simply identified when actors on a transition exercise different power (Reinforcive, Transformative and Innovative) to enable and support one another (Avelino, 2017). As one might have noticed, Transformative and Reinforcive powers are quite different expressions of the same actors. The theory expects this because they are representations of institutional actions. On the one hand, these institutions can recur to their bureaucratic capacity to reinforce their importance in the transition by gathering incumbencies to create political and economic instruments to regulate under its responsibility. On the other hand, these institutions can use their specialized competencies to pave the way for new institutions and structures to exist by recombining mental, economic and environmental resources. It is possible to mention that, on the road to energy transition in the European Union case, the institutions during the 1990 decade were not really aware of their incumbencies. Reinforcive and Transformative power were more neutral at that time since they did not break or support RET. But after the Green and White Paper, the situation has changed to a progressive synergy.

Innovative power seemed to receive a boom in terms of resources to be mobilized. Institutions at the international and integration levels created explicit demands for RET. Mental and artifactual resources played a decisive role over time in the development of the RETIS. Research institutes, R&D departments, and other organizations developed large capacities to innovate in terms of products, processes, as shown in the RETIS and on policy advising. So far, the dynamic pass from neutral to synergy. The existence of diverse networks and epistemic communities dealing with renewables, such as the EUREC, ERA-NET, or the Steering Groups and Platforms of the SET-Plan, are merged between public and private sectors around Europe (EUREC, 2020; European Commission, 2021b, 2000).

Nonetheless, Innovative power is not only about the dynamic of power within the European Union. One important trace of this power is the capacity to overcome the actual structures of power and dependence, making actors less dependent on fossil fuels and physical structures and dominant actors that control traditional resources (Avelino, 2017). Of course, we mean the energy dependence from the EU on Russian fossil fuels. The innovative power was built over time to reduce this, which is a discussion about the geopolitics of energy. So Innovative and Transformative power are antagonists of Reinforcive power.

The dependence rate is still high, even with lots of political efforts and knowledge accumulated as exhaustively affirmed. Some of our interviewees affirmed that these relations between Russia and the EU tend to continue for some decades ahead. Energy dependence or energy import is not necessarily a negative thing. Since solar and wind are intermittent, an energy transition without any traditional supportive resources would be impossible. While there has been regulation and innovation for more efficient technologies using natural gases to decline the demand, there has also been the process of electrification of the energy sector, including transport to reduce demands of oil, for example. Some interviewees affirmed that the gas demand, for GHG reduction purposes, may suffer a small slope in the short sight until renewables really pay off.

However, one thing that really concerns European integration is the presence of eastern countries. They have received a ”shock therapy” after 1991 with the end of URSS to frame their economies in a capitalist way. The EU sponsored this as a Marshall Plan for new neoliberal wannabes (Bohle, 2018; Sadurski, 2004). As we mentioned in the last section, the East European Countries from the enlargement of 2004 are constantly referred to as economies that do not go well. Still, they depend on the EU budget and financial support to answer demands from the integration, including energy transition (Štreimikienė et al., 2016). Some of the interviewees mentioned this same argument. In addition, the Eastern countries depend on a large extent from Russian’s oil for transportation means. Overall, they tend to believe that the energy imports/dependence will go down, but to reduce GHG emissions, they will have to increase the imports of natural gas to compensate for the reduction of coal and oil.

So far, we analysed the dynamics of power on the energy transition, but we pointed to something really intriguing. Although there are many resources to be mobilized, the transition is different among countries due to their inner capacity to mobilize them. Moreover, this difference in the energy transition is followed by energy dependence. Therefore, we believe that this discussion might be better addressed regarding the geopolitics of energy and renewable energies in the European Union.

4.2.2 Geopolitics of dependence and renewable energies

Traditional geopolitics of energy touches upon the coal, oil and gas and the world distribution of such resources. This distribution creates different power relations between

States that possess the resources to export and those which have to import. Moreover, this relationship creates a foreign policy tool because streams of oil and gas or coal shipping can be suspended in response to sanctions or even be aims of military attacks. These factors give energy the status of a strategic resource and a security issue for States in the world order (Högselius, 2018).

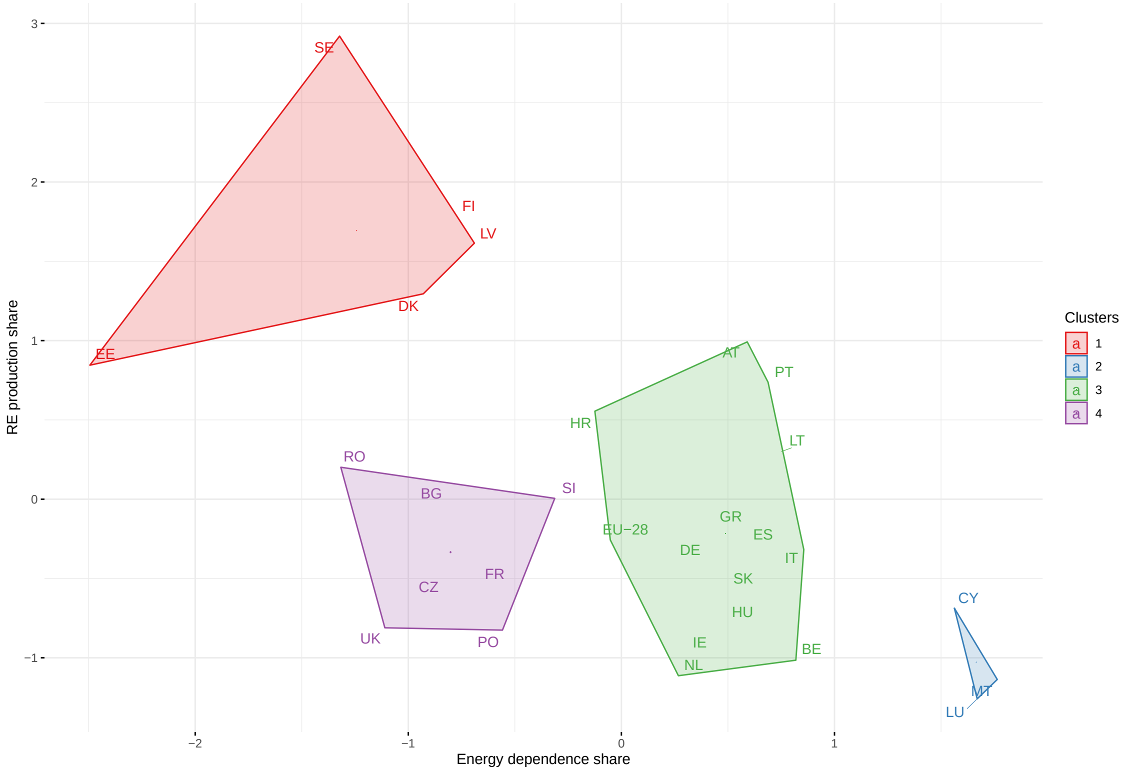
By and large, these security relations open spaces for dependencies both from export and import. Export countries face the dependence by identifying that energy is a large share of its international trade. It might be not easy to reduce these exports with an energy transition with more renewables. Import countries face the dependence of supply from one or more partners, in a sense that, without the trade would be difficult to keep the economy running and social living (Högselius, 2018). The dependence rate is an astonishing situation in the European Union if such plans like Energy Union, Climate and Energy Package and so on are meant to be successful. So, part of the energy transition in geopolitics is the correlation between dependence and renewables production. The electrification of the energy systems is highly dependent on the level of investments in RE innovation, and the level of share of this knowledge can accelerate the pace. As we argue in the last section, the transition is happening, but the mobilisation of resources is different from country to country, eventually making the process completely different. As we noticed, the collaboration among countries created a universal community, exchanging information with each other. Some Member States' inner or outer position happens because of the current geopolitics of energy transition in Europe.

To demonstrate the correlation between renewables production and energy dependence, we use the k-means clustering method. K-means is a clustering algorithm that consists of partitioning the data set into groups of points with high similarity (Galluccio et al. 2012 apud (Pacesila et al., 2016)). Originally this method was used for the first time with energy data in Pacesila et al. (2016), and they use it to identify the position of the EU countries ”according to their energy dependence and the contribution that renewable energy can have for energy dependence reduction” (Pacesila et al., 2016, p.159). We follow the same approach, but to serve for a different analysis. Figure 4.6displays the correlation between the variables, share of renewable energy production and share of energy dependence with the earliest data from 2019.

The application of k-means, using the R function for this purpose, spread the countries according to their percentage of each variable and grouped the similar ones. According to the algorithm measurements, the best number of clusters would be 3 or 4. Therefore, we opt for 4 clusters to capture the best division. The countries in each group are:

1. Red: Sweden, Estonia, Denmark, Finland and Latvia.

Figure 4.6: Member States grouped in clusters



Source: Eurostat (2020b, 2019a)

2. Blue: Cyprus, Malta and Luxembourg.

3. Green: Austria, Portugal, Croatia, Lithuania, Greece, Spain, Germany, Italy, Slovakia, Hungary, Ireland, the Netherlands and Belgium. Also, the EU-28 is here just for comparative purposes.

4. Purple: Romania, Bulgaria, Slovenia, Czech Republic, France, United Kingdom and Poland.

In order to overcome the dependence rate, a country might have two general alternatives: or reduce the energy demand and consumption or increasing the production by other sources (Nersesian, 2016; IEA, 2020). Reducing energy demand and consumption is a little complicated to fulfil because it can cool the economy by reducing resources. But policies toward energy efficiency, among other things, touch upon the energy intensity indicator, which is energy consumption per GDP (Eurostat, 2020b). The larger the number, the more intensive the energy use saves and can contribute to the dependence rate. The unit of measurement is kilograms of oil equivalent per thousand euros in purchasing power standard (KGOE-PPS), and in the year of 2019, max 199.93, min 50.94 and mean 117.82 KGOE-PPS

(Eurostat, 2020b). A second option would be to increase the production by other sources, which can be by diversifying the suppliers or increasing the production by renewable energy technologies. The focus is on the electrification of transport, for example, or on the increase of energy consumption from renewables. The advantages and disadvantages of RET have been exhaustively discussed in Chapter 2.2, so we will not mention them again. However, this explains why the correlation between dependence and renewables production matters in this analysis.

We observe that clusters blue (2) and green (3) are those with the most dependence rates, red (1) is the complete opposite of them with the highest renewables production, so we focus our analysis on these. Blue (2) countries are those with the highest dependence and lowest RE production. They are the smallest in the area, and with less share of the population, they do not reach 0.5%. They remain largely on fossil fuels to generate energy and might not have efficient or bold policies to speed up the knowledge production and depletion of the technologies. Once again, all countries in the EU submitted the National Energy Climate Plans (NECP) since 2015. IEA (2021) Policies DataBase presents a compilation of energy policies from its members, and we can use them to track the current status of Member States. Even though we recognize that the database does not reflect all existing policies, it is good to notice some of them. Malta has around 22 policies counting from 2000 until 2012, concentrating on solar thermal and PV. Important to highlight that the National Energy Policy from 2012 was composed of feed-in tariffs and call for PV and solar water heaters, which express a willingness to diffuse RET throughout the country. However, Malta has the highest dependence by 97% and renewables production of 8% in 2019. In the same year, the energy intensity is the largest measure, 199.93 KGOE-PPS. The governmental expenditures are around 22 million euros for renewables which is really shorter than the mean, 2,601 million euros. The situation of Malta has not evolved so much in the last 10 years, and it actually remains the same in all indicators. It is entirely dependent on fossil fuels and cannot use agricultural lad purposes other than food, making the diffusion of wind or solar farms a little more complicated (Pacesila et al., 2016; IEA, 2021). Intriguing is that Malta is located in the middle of the Mediterranean Sea, and wind energy diffusion lacks support.

Cyprus has around 13 policies from 2003 until 2017. Most of its policies are around solar heating, PV and biomass. But since their RE production is around 13% and dependence around 92% in 2019 (the third more dependent), it seems they are not very efficient, revealing an energy intensity of 118.28 KGOE-PPS. For comparison, the government expenditures for renewables in 2018 were 45 million euros. Despite the high potential for solar generation due to its latitudinal position, the country still cannot advance in technology diffusion, even though the government aims to support electricity from renewables. The commitment to the

EU energy standards are not so high, so Cyprus resulted in being highly dependent on fossil fuels and eventually the highest GHG emitter (Eurostat, 2020c,b).

Finally, Luxembourg is a country with good economic performance, presenting policies for renewables from 1989 to 2014, counting 25 in total. The design of most policies addresses fascinating measures, regulations and support schemes for renewables. The country is part of the foundation of the EU and has been following the tendencies to stimulate RE from the very beginning. But the actual situation does not reflect any of these. It has the lowest renewables production share, 7%, and the second in dependence, 95%, but with an energy intensity of 90.13 KGOE-PPS. Unfortunately, the government expenditures for RE from 2018 were not shared, but from 2017 it was 4,038 million euros, a number over the mean of 3,350. Even with a high dependence on fossil fuels, the transport sector has increased from 2% to 7.6% from 2010 to 2019, supported by feed-in tariffs, subsidies and tax benefits. Luxembourg is an intriguing case and might deserve more research on this behalf, which is impossible in the current study.

In the green (3) cluster, there are 13 Member States, the largest share. We are not going to discuss every country here, and we focus on the EU-28. We already discussed the amount, complexity, coherence and evolution of renewable energy policies. IEA (2021) database presents 19 policies, but it does not reflect the actual picture of the mix of policies. Overtime, the EU became aware of the high dependence rate from external sources, mainly from Russia. In 2019, more than half of energy needs were met by net importers, 57%, and renewables production was 18%, with an energy intensity of 104.23% KGOE-PPS. Different from Member States situation, these numbers represent a regional dependence and a problem for the integration, with a lack of resources since the beginning. With the Electrification of the Transport System Report provided by an expert group in the European Commission, the milestones for 2020, 2030 and 2050 progressively describes the achievement of a complete CO2 free road transport in the last year (Meyer, 2017). The progress for 2020 with a 5-10% market share for electric passenger cars has been achieved with over 8% in 2019 (Eurostat, 2020b). The report also addresses strategic implementation plans for aeronautics, water boats and rail transport, expressing the barriers and gaps in doing such transformation in the sector, and evaluating the competitiveness of the EU transport industry. Despite the fact that transport is suffering modifications and these efforts contribute to reducing GHG emissions, the reduction of oil in transport tends to open up a new market share for electric means of transportation. At the same time, it can pressure the R&D expenditures to speed up energy innovations in the forthcoming (Meyer, 2017). The diversification of oil suppliers is not a huge problem for the EU, but the dependence over Russia for natural gas is by far the historical energy security problem.

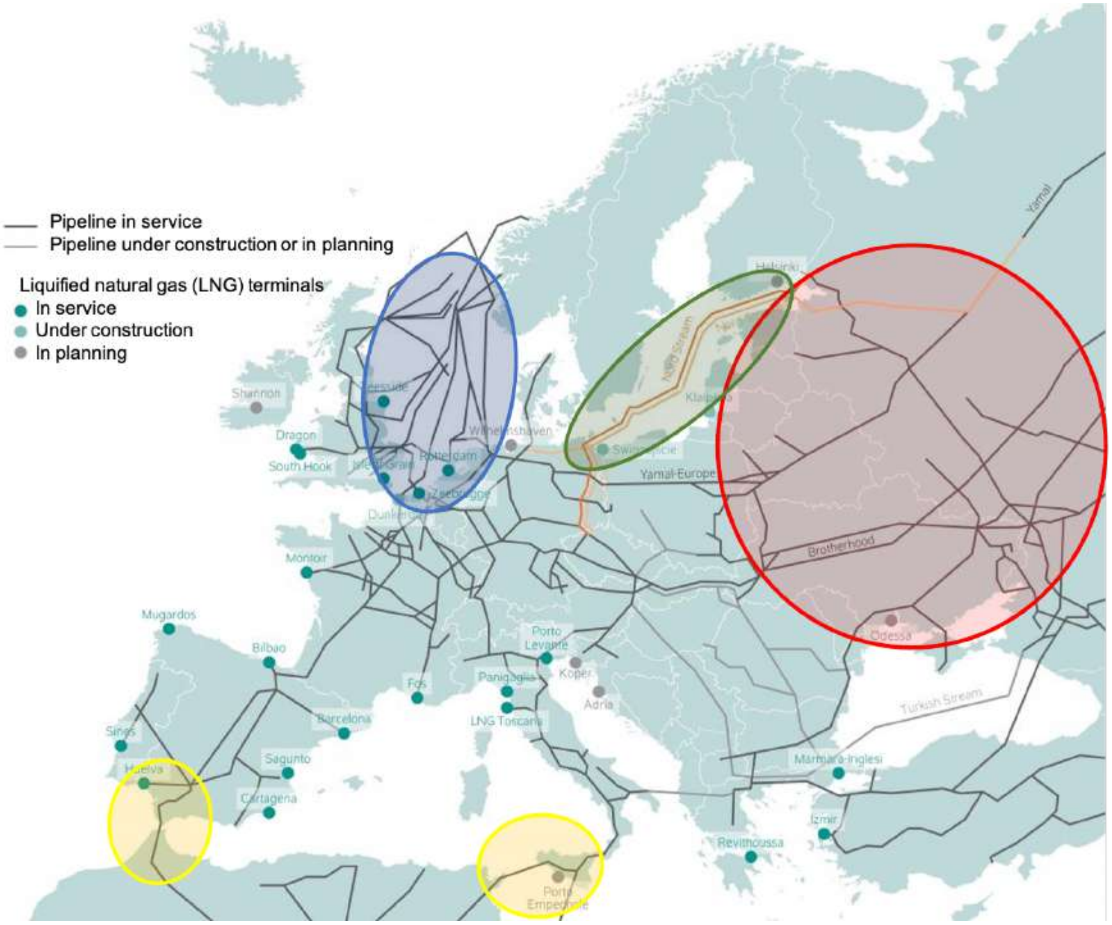
Russia, Norway and other Mediterranean countries are the main suppliers of natural gas. These partners deliver, respectively, around 180, 95 and 40 billion cubic meters (bcm) per year (Eurostat, 2020b). The European gas market network is really dense and counts with lots of cross border pipelines from the EU partners and internal connections. Figure 4.7 presents a simplified map of the key gas supply routes. The circle in red represents many firms delivering gas on the borders, and the leading one is Gazprom, a Russian national industry since 1990. In 2019 it exported over 180 bcm, covering around 40% of the total imports to European Union (Eurostat, 2019c). The delivery before 2011 was made entirely on-shore, via post-soviet countries sharing borders with the EU countries, which was completely changed with the inauguration of the Nord Stream by the Nord Stream AG Company, whose Gazprom is the majority shareholder. Nord Stream is a transnational cooperative pipeline project between Russia, Germany, French and the Netherlands that goes from Vyborg in Russia, in the Gulf of Finland, through the Baltic Sea until the Greifswald in Germany. The pipeline is an object of national security in Germany and regional security in the EU because it is responsible for around 30% of the gas supply, a capacity of 55 bcm, to the Western European countries (Gazprom, 2021).

The problem emerges right after the beginning of work with the Nord Stream. From 2011 to 2012, the company evaluated the feasibility of an expansion in 2015 consisting of two additional pipelines, the Nord Stream 2. In the same year, five European energy companies: ENGIE, OMV, Royal Dutch Shell, Uniper, and Wintershall, signed a contract to provide 50% of the whole finance (Gazprom, 2021). The project is on but delayed due to geopolitical interdependencies between the EU, Russia and the US. First, the energy issue between EU-Russia is well-known as an uneasy marriage. Russia needs the revenues, the EU needs the security of gas supply, and the level of delivery, as we have shown before, is really high and cause dependence.

The US comes into play with the Crimea crisis. In 2014, Russia demanded that Ukraine pay back its energy debts. The latter refused to do it, leading to an eventual cut off the gas supply. Of course, the sanction was against Ukraine, but the country is one of the main routes to feed the EU, disrupting several Member States. As a result, this action led to anxiety regarding the supply security coming from Russia-Ukraine routes, pressuring the Commission for more rigid measurements toward gas supply and energy efficiency in the Energy Union policy. Gas is one of the main drivers in reducing coal dependence for heating purposes, and with the energy transition plans, the supply has increased in the last years (Sharples, 2016; Wettengel, 2021).

The anxiety that once again a Ukrainian disruption would sentence the EU to supply scarcity, forcing to rethink the supply policy, provisioning investments and funds for

Figure 4.7: Gas infrastructure pipelines in 2021



Source: Based on Wettengel (2021)

renewable companies inside the integration, and seeking diverse partners, such as the Middle East and the US. With the end of Trump and the beginning of the Biden administration in the US presidency, the country poses a sanction on involved companies in the project. The completion of the project was scheduled for 2020, but due to pandemic delays and the complicating relation between the US and Russia, it was delayed even more. The reason for the sanction is that it will deeper the dependence of the gas supply from the EU and divide Europe. In addition, the Nord Stream 2 reassures the difficulty to commit to climate and energy targets self imposed by the EU and Germany. Behind the ”moral” reasons, it is worth noting that the US has invested in shale gas, which is an energy resource found inside shale sedimentary rocks and has a considerable availability in the US. Since the EU is a large gas market, shipping gas by ships from the US to the EU may increase the market share for the US (Wettengel, 2021).

So, the geopolitics of energy in the area imposes critical elements for climate and renewable energy targets from the EU. In this context, although gas is the supporter for the long-term energy transition, Innovative power comes into play in terms of knowledge production to overcome the 40% dependence on Russia gas supply (Avelino, 2017). The sanctions were followed by other Member States criticizing Germany's decision to support the project for so long. However, it is necessary. Germany has spent a huge amount of political and economic capital on this project and foreign policy with Russia, remaining the main importer from Russia and the biggest gas importer worldwide, (Wettengel, 2021). Moreover, Nord Stream 2 is critical for Energiewende, the German energy transition. The EU has supported the project by implementing policies to avoid critical disruptions with another Ukrainian-Russo crisis. It is all set, and the Nord Stream 2 is in its final steps, after over 10 billion euros from five different countries (Gazprom, 2021) as some of our interviewees pointed out. The transition follows a partial increase in gas use in the EU because coal and oil are more detrimental for the environment and future generations than gas. The relationship between the EU and Russia remains pragmatic. Finally, more countries in the green cluster might deserve attention, but we will nearly discuss them in another approach.

Red (3) cluster countries disagree with what interviewees sad about some Baltic States and their current position. Of course, Sweden catches the attention because of its high position according to the RE production axis. The country is leading the way on the share of renewables with a dependence of 30% and renewable production of 56%, the highest one, and energy intensity of 136.04 KGOE-PPS. Also, it has policies dating back from 1975, one of the pioneers in Europe, and the most recent was in 2018. However, we observe that Latvia and Estonia are here, which, according to some literature Štreimikienė et al. (2019, 2016) and some opinion of interviewees, they are in a position that was not expected. According to our data, Latvia has a dependence of 43%, RE production of 40%, and energy intensity of 120.15 KGOE-PPS. Policies supporting RE are old 17 in total, counting from 1997 until 2010. To a large extent, the policies are related to price regulation. Hydro is the largest share, 45%, in the electricity generation, with few onshore wind farms. The transport remains on sustainable biofuels, with two bioethanol and five biodiesel plants (Eurostat, 2020b; Pacesila et al., 2016; Štreimikienė et al., 2016). Therefore, we can suggest that the position of the country is not explained by its investments in renewables technologies and contributions to knowledge production, rather the energy mix with different sources. Therefore, the dependence is not high and stays under the average. But the EU plans of electrification of the transport sector or the increase in the share of renewables, mainly solar and wind, are not accountable, are not contemplated on energy security plans for the country.

Another Baltic State that appears in an intriguing position is Estonia. The dependence is 4%, the share of RE is 31%, and energy intensity is 144.75% KGOE-PPS, suggesting an inefficient economy. Since 1998, Estonia presents renewable energy policies, with the last one in 2018, summing up 19. Policies are more related to planning the renewable energy market in the country than on specific technologies and some instruments such as feed-in tariffs. Although the dependence is close to zero, the country still has some long roads to develop renewables. From the 31% share of RE, wind is responsible for around 7%, the rest is biomass, with a large extent of over 20%, and hydropower with the rest, but biomass is exclusively used for heating. So, for electricity, only 13% actually is the share of renewables, wind and hydro, and the rest is entirely from fossil fuels. Despite the position in our graph, the country can still commit to the EU targets for the energy sector and reduce fossil fuels use (Eurostat, 2020b; Pacesila et al., 2016).

About the Baltic States, although their position in the graph, considering dependence and RE production share, their energy mixes are still inferior in renewables, and in the long-term, there is a small innovation effort or economic and financial provisions to boost the sector to attend the EU standards. This implicates on an intrinsic difficulty to fulfil an energy transition. In our last period (2015-2020), the increase of knowledge production suggests an Innovative power from mental and artifactual sources to fight back the dependence on fossil fuel imports and high fossil fuel share. The knowledge might be collective, but as we notice in the community detection, Latvia and Estonia are in this periphery with a low degree of nodes and less centrality in all measurements. The collection of these pieces of information suggests a complete unequal road toward energy transition. While some Member States lead the way, in terms of knowledge production or share of RET or even superior expenditures, we see others in a critical situation. Policies have increased over time, and actually good outputs for the sector were achieved, but we still see regional geopolitics of the energy transition. We are going to deal with this analysis in the next section.

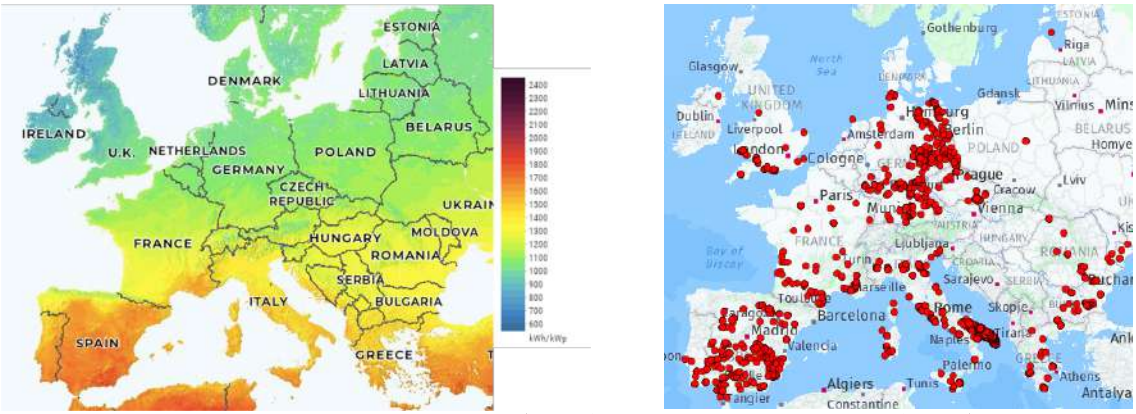
4.2.3 Geopolitics of energy transition

On the one hand, the European Union RETIS reveals the evolution of a highly collaborative network. The share of RET evolved because of the factors described in the three levels: international, with the climate conferences of the UNFCCC other related to climate change and energy security; regional, with the coherent political and economic plans, programmes and instruments for renewable energy innovation as a probable answer for the international commitments, and to set the EU in the forefront of the renewable era, and; national, by the political and operational measurements to support and diffuse RET. But, on the other hand, the RETIS may not accomplish an even energy transition in European Union. Some are running far away on the front, and some are biting dust a way behind.

The term, geopolitics of energy transition, is related to the geopolitics of renewable energy (Criekemans, 2018; Scholten et al., 2020; O'Sullivan et al., 2017). We move forward by explicitly considering renewable as the goal of this transition as we built our argument until this point. So, to understand the implications, we should look at first on the actual situation of renewables potential and use. Figure 4.8 presents the potential of solar power generation based on solar incidence and an approximated distribution of installed solar stations in the European Union. The closer of Ecuadorian Line, the higher is the solar incidence. As expected, the Iberian Peninsula has the highest potential, followed by Greece and Italy. But the Solar stations (Solar roofs and parks) are concentrated in the Peninsula, Italy, and Germany. The viability of solar power in these countries is actually higher than other Member States, which can support them in the energy transition because they have the technology. The top five countries in solar power production are (Eurostat, 2020b):

1. Germany - 49GW
2. Italy - 20GW
3. UK - 13 GW
4. France - 10GW
5. Spain - 8GW

Figure 4.8: Solar power in European Union


(a) Solar power potential

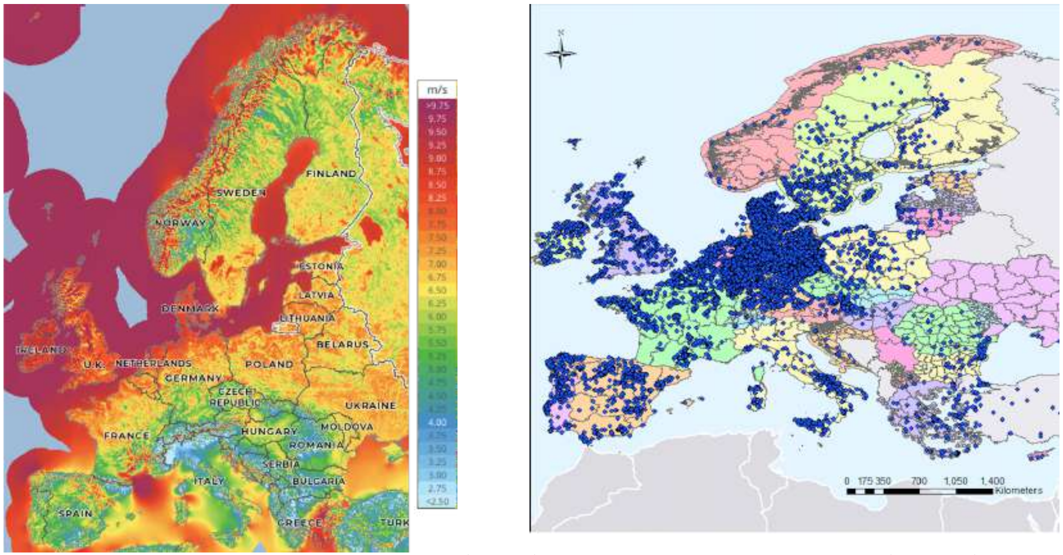
(b) Solar stations

Source: Global solar atlas (2021); Solar Energy Maps (2021)

Figure 4.9 presents the wind energy potential based on wind speed and the approximated wind farm stations mostly onshore. The viability here is different from solar. Northern countries would have more wind viability, but every coast also has. The wind farms potential is densely concentrated in Germany, Denmark, the Netherlands, the UK and France. The top five countries in wind energy production are (Eurostat, 2020b):

1. Germany - 60GW
2. Spain - 25GW
3. UK - 24GW
4. France - 16GW
5. Italy - 10GW

Figure 4.9: Wind energy in European Union



(a) Wind energy potential **(b)** Wind farm stations

Source: Global Wind Atlas (2021); European Commission (2021b)

Once again, solar and wind are the main technologies for the energy transition, certainly, because they can be a transformative power to overcome the current dependence imports. But renewable innovations in the European Union are now more focussed on wind offshore technologies. Figure 4.10 presents approximately the offshore wind farms in Northern, Irish and Baltic Sea. Red dots are the farms under planning, construction or in the final stages of bureaucracy to function. Blue dots are the online or partially online farms. We observe an increase in the number of forwarding installations in the Baltic Sea, which can impact the actual difficulty from the Baltic States to generate more energy by renewable one and maybe contribute to its systems' electrification. Moreover, we notice a concentration of farms in the south of the Northern Sea, mainly around the UK coast, contributing to the Highest offshore wind capacity. Finally, the Irish Sea accumulate the second position in respect to installed farms.

Table 4.3 presents the offshore wind connection from main producers in the EU. By the end of 2020, there were around 25,023 MW connected and 5,403 Turbines (Wind Europe, 2021). From 2019 to 2020, there was an increase of 2,951 MW and 356 new turbines. The UK is the largest producer, accounting for 40 farms, Germany with 29 and the Netherlands with 9. These countries represent around 83% of total offshore wind energy cumulative capacity, the UK leading with 43%. Until 2023, a connection of 13 new farms is expected, mostly 4 in the UK and 4 in France.

Figure 4.10: Offshore wind farms

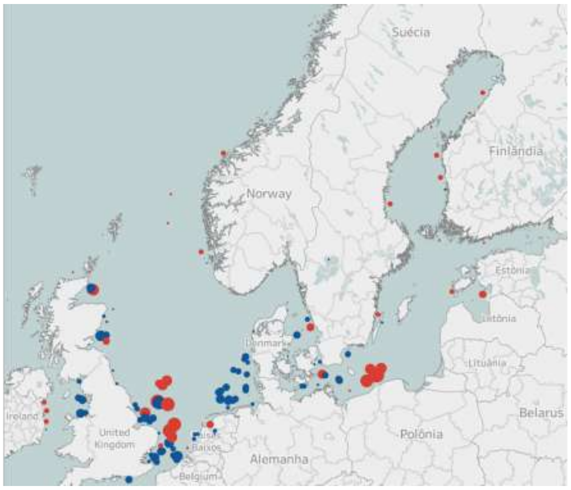


Table 4.3: Offshore connection

Country	MW connected	Turbines connected
UK	10428	2294
Germany	7689	1501
Netherlands	2620	538
Belgium	2261	399
Denmark	1703	559
Sweden	192	80
Finland	71	19
Ireland	25	7
Portugal	25	3
Spain	5	1
France	2	1
Norway	2	1

Source: Based on Wind Europe (2021) data and edited by the authors.

Notably, offshore wind is the trend for renewable energy generation in Europe. The technology has been growing in terms of investments and also knowledge over time. Since on high seas the wind blows over 9 m/s, the potential can address a high contribution for the generation. The EU Green Deal, the economic strategy to deal with climate neutrality in the next year, project for Europe a contribution of 300 GW by 2030 and over 400 GW by 2050 (Wind Europe, 2020; European Comission, 2020). Offshore wind accounts for over 12 GW by 2030 if the progress keeps on. These goals are dependent on a high capacity to share knowledge. Including more investments in R&D departments and research institutes to provide over 20 billion euros in the next 4-5 years.

Shell New Energies and Eneco are the newcomers in the next investments in RET.

Shell, one of the seven sisters of petroleum, is now moving faster toward the new renewable energy market, owning 5%. of new installations. Eneco follows the same. The decision of a big company seems to indicate a market trend in the energy sector over the years, moving from the geopolitics of traditional fossil fuels and entering the geopolitics of energy transition. Moreover, Siemens-Gamesa accounts for 68% of all wind turbines connected offshore, followed by Vestas with 23.9%. For the manufacturing of offshore wind turbines, the market can be seen as monopolized by Siemens-Gamesa in 2020, with little expectancy to be changed. Siemens-Gamesa is a fusion between the German Siemens and Spanish Gamesa, spreading their manufacturing knowledge worldwide. It is the company that has almost the more efficient offshore wind system and faster installation of assemblages (Wind Europe, 2021).

All of these potentials have to be followed by high investments and knowledge. At the forefront of the energy transition, we see the same countries and their traditional companies. Although all the knowledge collaboration, coordination of European institutions and political agreements between Members, energy sources potentials and actual installations, the capacity to run renewables is not even among Member States. As we discussed before, there are different levels of investments, knowledge and other energy and climate variables that helped us understand the actual path of the energy transition.

In order to understand the geopolitics of energy transition in Europe, along with the potentials and actual installations of renewables, once again, we mobilize the k-means. This time, we create an energy transition index composed of seven variables, as Table A.4 presents. We based this on the IEA (2020) category 'Energy transition indicators' for the first 3 variables; variables 4 and 5 are based on Pacesila et al. (2016), and; 6 and 7 are important for this study. A table containing all data is available in the A. Since there are different units of measurement, a standardizing process was used.

Figure 4.11 presents the output with the energy transition clusters and their interpretation. There are four clusters:

1. Grey - Malta, Luxembourg, Cyprus, Belgium, Slovakia, Ireland, Hungary, the Netherlands, Greece and Lithuania;

2. Yellow - Portugal, Slovenia, Croatia, Czech Republic, Austria, Bulgaria, Romania, Latvia, Denmark, Finland, Estonia, Sweden;

3. Blue - Germany;

4. Green - Spain, Italy, Poland, United Kingdom and France.

Table 4.4: Energy transition variables

Variable	Acronym	Unit	Year of reference
Renewable energy technology consumption	RET.cons	GW/h	2018
Renewable energy production	RET.prod	MW	2018
Greenhouse gas emissions	GHG.ems	k t of GHG	2020
Energy import dependence share	nrg.dep	% 2019	
Renewable energy technology maximum installed capacity share	RET.mx.capac	%	2019
Energy investments	nrg.inv	Million euros	2020
Knowledge production	knw.prod	units of	2018

Cluster 1 (grey) is characterized by higher energy dependence and difficulties fulfilling RET's diffusion to promote consumption and production. We observe the presence of the Union of Benelux (Belgium, the Netherlands and Luxembourg), whose advances in the energy transition is not so high. Although they have planned political targets to strengthen their cooperation with the EU by coupling energy policies together and investing in low-carbon technologies (Benelux Business, 2018), Their positions show different and underrated achievements. Also, we observe other late countries in the integration. Although their knowledge collaboration dates back to their actual europeanization, as shown later, they have a relatively clean energy matrix but lower expectancy to overcome the current fossil fuel dominant energy sector.

Cluster 2 (yellow) is characterized by a high level of renewables production but with short investments and GHG emissions, and mostly all they have fewer renewables consumption. Three countries of the Nordic council are here, Denmark, Finland and Sweden. They are the largest renewable producers, also presenting lower dependence. Although the Nordic Prime Minister emphasizes "A green Nordic region" promotion, RET still requires more investments (Nordic Council, 2020). Moreover, for all countries in this cluster, the advising would be to invest more in RET and collaborate more often with top experts to increase the pool of knowledge to be applied in the countries. As a result, most countries experience a shorter dependence, but they still demand more RET and maybe electrification in the energy sector.

Cluster 3 (blue), we expected that Germany would be in the forefront, but it is in a far position according to the cluster. It is possible to notice that Germany is the country with the best profile to deal with the energy transition, except for the number of really high emissions. So, one policy advice would be to focus on more policies to reduce GHG emissions over time because, compared to other countries, the level of air pollution is above the average. The Energiewende traces back to the 1970s but saw a rapid growth toward RE policies after the Fukushima accident mobilizing bold targets for energy security and climate in Germany (de Souza & Ferreira, 2020). There are different but coherent renewable innovation policies that boost the availability of energy from renewable sources (Cantner et al., 2016). Moreover, since consumption and installed capacity are targets from the SDG, Germany seems to have concluded the homework agreed on in Paris and past meetings. In addition, it is possible to notice that Germany is the country with the best profile to deal with the energy transition, except for the larger number of emissions. So, one policy advice would be to focus on more policies to reduce GHG emissions over time because compared to other countries, the level of air pollution is above the average.

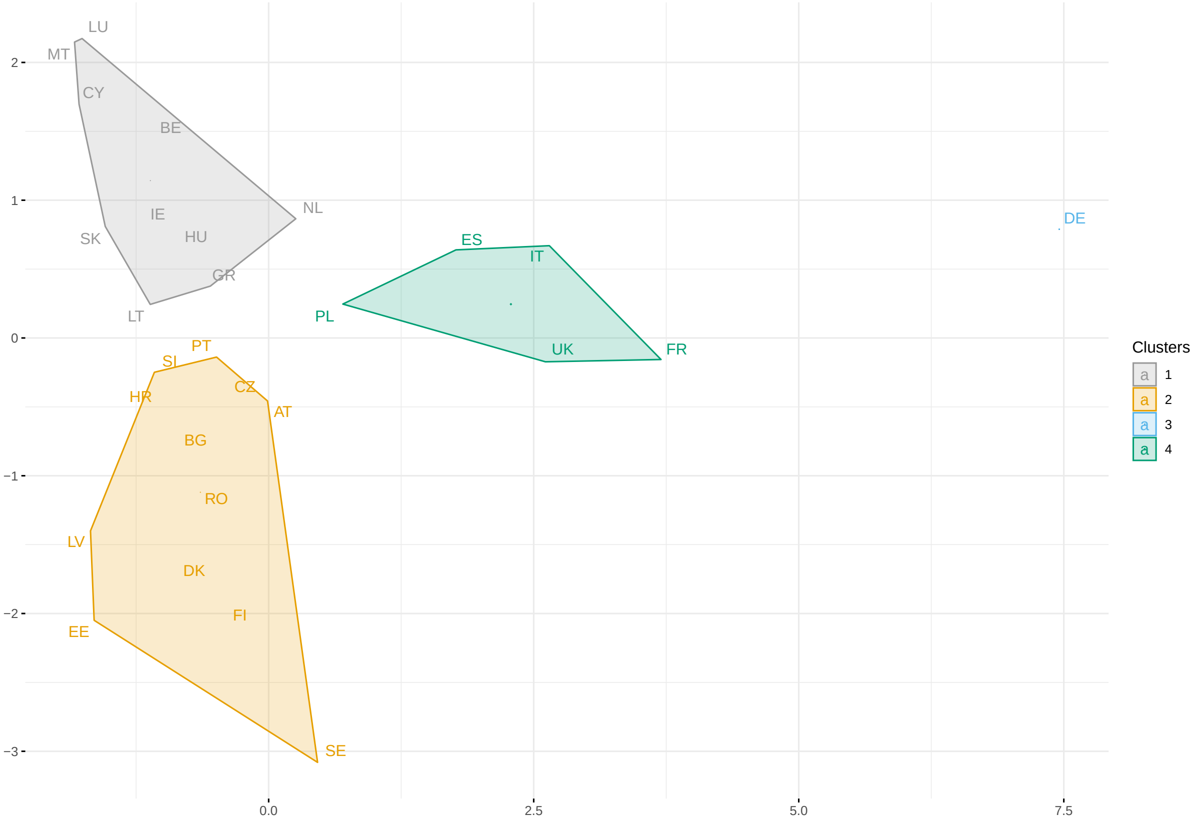
Cluster 4 (green) is characterized by the highest GHG emissions. These countries stay at the forefront of the energy transition, very similar to the German profile. Except for Poland, all of them are in Western Europe, with efficient economies and presenting renewable energy plans (Ferreira, 2017), So they are in a catching-up process in transition. Poland would need more renewable investments and collaborate more to develop good innovations for the country.

The position of Member State suggests that, despite the existence of coordination of energy policies under the EU targets, every country has different indicators that allow it to couple or not with the targets. While Western European countries (green and blue clusters) are running faster and acquiring a different position in the world order when it touches upon the climate and energy issues, clearly, others will far-fetch. Therefore, a high level of climate and energy commitment at the European level is more than demanded. It is urgent. It does not matter if seven countries are moving forward for climate purposes because the consequences are global. The European Union RETIS can produce a comprehensive network of common practices, knowledge and technologies to deal with this problem. The answer is systemic, interconnecting different actors from different countries to support, accelerate, and compensate when necessary.

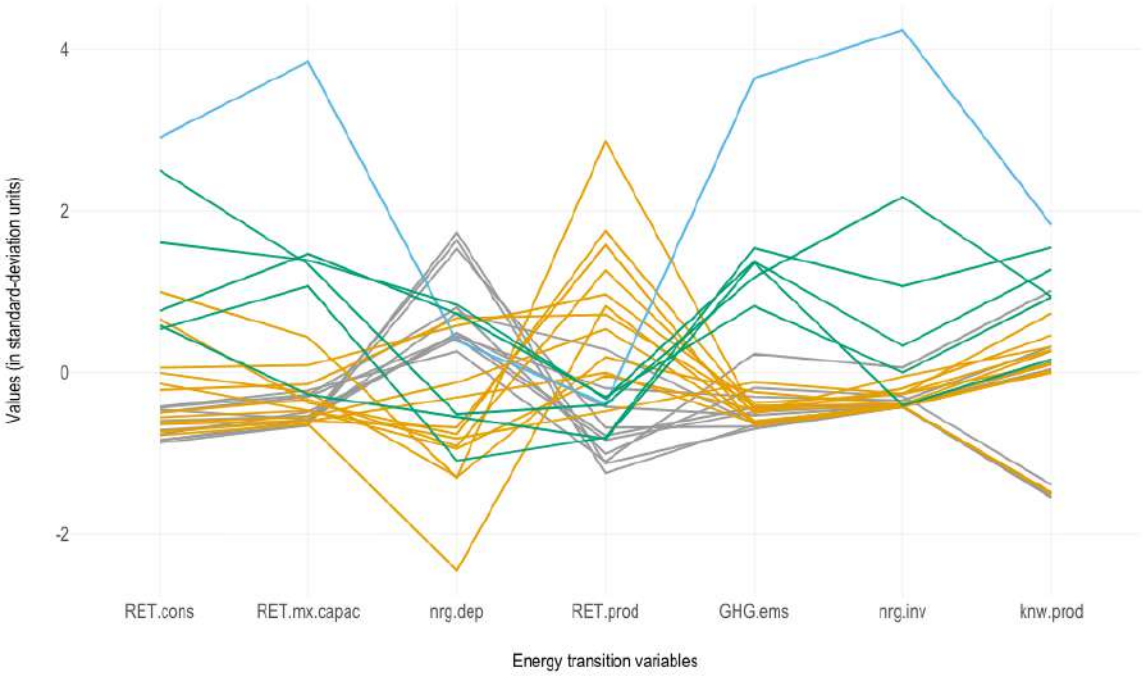
Finally, there are some European Union proposals, from firms to politicians, to build up a super energy grid in Europe based on renewables. Electricity is already fully connected with some countries, such as Germany and France, being the largest exporters, but renewable innovations are in high demand with the climate and energy targets. One example of collective actors making another epistemic community comes from the Renewables Grid Initiative, a coalition of Europe's 29 largest environmental NGOs and grid operators working together to ensure grid transformations at a European Level since 2011. In the last years, they have been working closely with the European Commission by proposing plans and schemes for a large and both centralized and decentralized renewable energy grid based on the fast electrification of the sector (RIG, 2021). These initiatives can overcome the difficulties of some countries to deal with energy transition and contribute to the development of more collaborative technology shared by countries with fewer capacities to invest. Moreover, energy transition is a collaborative task, which has been requiring a high level of societal transformations. The European Union has been answering it, but the process is far from being completed, demanding even more bold commitments.

Figure 4.11: Cluster of geopolitics of energy transition

(a) Energy transition cluster



(b) Cluster interpretation



Source: Eurostat (2020b)

CONCLUSION

We can start by mentioning, once again, that the study was designed to merge three distinct but complementary disciplines to understand some of the world politics concerning climate and energy problems. They seemed to work well. International Relations take the background and frame the whole research design while Innovation and Sustainability Transition Studies remained with the main role. The lack of IR theories to provide insights about it is really important to be noted. The energy transition is approached as an international phenomenon replete with political and power relations and fully dependent on that. There can be countless innovations and technologies out there, but if policymakers do not attend to this and its probable benefits for society and economic growth, it is like nothing. Contrary, in the EU, they are aware of this tendency, as we observed, represented by the evolution of policies and its contextual relationship with knowledge production. So energy transition is a thematic that IR should entail.

It seemed that the interdisciplinarity of the research served well for the study. But, of course, when merging them, the problem would be about what can or cannot be merged, and if something is not merged, does it really stays out or is it just a misunderstanding of the problem, theories and object? Not to mention that sometimes a certain discipline predominates the analysis or sometimes is inadequately to conduct some others. Play this dance sometimes is stressful and often leads to a dead-end, but it takes easier to overcome by the research question and objectives.

Our research question **How the European Union coordinates the collaborative knowledge and technology developed in the Renewable Energy Technological Innovation System (RETIS) to disrupt its energy dependency and speed up its energy transition?** seemed to be answered. But it was followed by lots of new thoughts and insights that we can discuss from now on. The collaboration of experts to produce both patents and academic papers has evolved over the years regarding the energy transition topic. It was not possible to correlate the policy-mix with the knowledge production itself. To do so, one should be able to track in each patent and paper the institutions, policies or something of the genre that fund or support the production of such. But we were able to notice a closely contextual relation. One can observe that the more policies appear the more innovations appear and vice-and-versa. Another important conclusion is that there are more papers published than patents. This is somehow connected with the time lag between an invention and innovation and the hype of some technologies.

Sometimes an innovation hits the market and society 10 to 20 years after its invention. RET are not different, even though they are embedded in an environment that seems to speed up their creation and diffusion. If one conceives 1970 or earlier as when the prototype for solar or wind power came up in the EU, it took almost 40 years to be actually mean in terms of share in the energy mix and importance for energy security. Academic papers may take a shorter time to be written and published, different of patents which are actually the product of firms R&D department and chance to reach more market share. So the rapid growth of paper instead of patents might be explained by this. Moreover, RET became really a thing after the Cold War and the open for new agendas far from military and defence in world politics. But as we analyse the policy mix, it was in 1996 that it actually caught international society attention. Experts have more time to reflect in the academic environment about new ideas and publish a paper than properly moving to a product or process. So the idea that international order might have driven the attention and scale up the creation and diffusion for RET via papers and patents seems to make some sense.

On the European Union integration level, we can find something else. When studying energy transition, one shall face hundreds of relevant actors. This happens for some reason. The first one is the level. EU is an integration project relying on complex bureaucracies that cut across different nations, forming governance of the energy sector. We have the market and its agents as the firms and their R&D departments, research centres, universities and other public or private sector actors that together might form an epistemic community to inform and push some decision. Political institutions legislate and execute different plans, projects, and proposals to lead the sector in some directions. Sometimes the actors are innovative to change the sector. Sometimes, they reinforce traditional energy generations because of their profits and capacities. Or sometimes, they transform because they understand the normative or future chance that may apply to the RET technologies.

Energy transition becomes a complex and perhaps contradictory process in the EU because of the actors. But, as we observed, there is a convergence of interests regarding reducing fossil fuels and increasing renewables in the energy mix. So, it seems the integration of the EU, since its origins are dependent on energy, and despite the issue has not been neglected, a clear mission-oriented policy toward the diffusion and enlargement of the renewable energy market must be achieved. Furthermore, policies must call for more compromise of national governments because of the climate change effects when using fossil fuels and creating similar innovation capacity focussed on RET to make the market more competitive.

However, as one might have seen, until now, when observing the Member States level, there are different advances in the energy transition, different innovation capacities and political commitments among them. So, the energy transition is not happening in a perfectly coordinated way as we thought. The coordination is institutional and the effort either, but some countries are lagging. The last section of the Chapter 4.2.2 suggests that some countries with more influence within the integration lead the way. Germany, France, Italy, and Spain are far ahead, emitting more GHG and investing more in RET because of its economic performance and the highest RET consumption. These countries have large populations and are really interested in developing more efficient energy generations.

Although the geopolitics shows an asymmetrical development of national energy transitions in the EU, these countries are always on the top five regarding budget contribution to the integration. As far as they could go, if chosen a lonely walk, they still contribute to the EU interests, and energy is one of those interests. Some Members indeed pay more to the budget than they receive, and this includes energy issues. But if the energy transition has to be done at the EU level, achieving digital economy and 4.0 industry across the integration and the most efficient energy use in the future, our study suggests that these countries are paying now for the development and rapid growth of those behinds so that they can reach to an energy sector competitive in EU with a coordinated energy transition in the future.

We face the question: if this is really happening, when will it be the turning point for the lagging countries? Moreover, those who are paying more and leading the way will continue to doing so? This is an exercise of futurology, and we can no longer answer. But if the EU integration wants to last for more decades, it has to find ways to speed up this part of the integration. The energy market is fundamental, and projections reveal that it will be even more. Solutions are popping up in Europe to speed this up. Renewable Grid Initiative, intercontinental energy grid and increasing investments in RET are on the horizon of EU energy integration. Understand more of these EU dynamics, and the political solutions forthcoming would be interesting for future researchers.

On the international level, the geopolitics of energy transition plays a different role. Certainly, the USA during the Trump administration diminishes its participation in several international discussions. From Paris Agreement to migration and COVID-19 pandemic crises, the US lost a certain prestige and trusteeship. During the Trump administration, it was possible to observe the rise of two other poles, the Asian led by China followed by India and Japan. And the European Union led by Germany, followed by Italy, Spain and France. EU and China launched in 2019 the EU-China Energy Cooperation Platform. Besides the cooperation to reach excellence in RET globally, China is responsible for almost 1/3 of total investments in RET in the world. Therefore EU and China are partners in the effort against climate change impacts and clean energy transition. Nevertheless, they are also competitors in the same international energy market.

Despite this cooperation, the EU still relies on Russian imports. They are good to keep the transition going because gas is less polluter than oil or coal. But reducing the dependency by diversifying suppliers such as the US shale oil and LNG brings the US back to the energy market, even though the sources are not renewable. So, international politics and world order seems to start to change. EU integration can be seen as an important competitive market, responding as a unique sound for the Members. China leads the investments and the rare earth mineral, a topic that unfortunately we did not have time to discuss and has a profound complexity in the geopolitics of energy transition. India and Japan are also on the same track. The US, under the Biden administration since 2021, seeks to recap its lost credibility on international agreements and world politics.

Sadly it was not possible to provide an analysis regarding the international geopolitics of energy transition. However, some good researches can be designed on this topic. Elsewhere, This study reflects only EU reality about transitions, and the methodology, with some modifications, can surely be used for other regions in the world. Especially in the global south, where these types of studies are still not strong enough.

Finally, we believe that this study is one of the first to use the term geopolitics of energy transition. Since this merge of three disciplines is a newcomer in science, more scholars should bite this opportunity to reflect deeper and deeper on that. Innovation, energy, and technology are acquiring more importance in the XXI Century and especially for international politics as we believe it will be.

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Appendix A

METHODOLOGICAL APPENDIX

The Methodological Appendix is composed of all methods and techniques used in this study. Since we opt for qualitative and quantitative methods, describing how we proceeded might be valuable for future research dealing with related problems or improving the methodology to deal with Innovation Studies, Sustainability Transition and International Relations. Therefore, we organized this Appendix into two main sections: the first and subtopics describing the qualitative methodology and; the second and subtopics describing the quantitative methodology.

Section A.1 describes the qualitative methodology. First, in A.1.1, we describe the identification and definition of the actors related to our investigation and how they can be categorized to enter on the following analyses. Second, in A.1.2, we describe the political dimension, power and geopolitics analysis, the resource data collected, and how we mobilized them to build the arguments. Third, in A.1.3, we describe the process of preparation of the interviews and how we analyse the results.

Section A.2 describes the quantitative methodology. First, in A.2.1, we reflect on coding for IR scholars and the urgency for more experts within the field dominating these techniques and some problems regarding computational power and probable ways to solve it. Otherwise, the entire research can be compromised when the researcher does not use the correct tools as tools for creating and analysing a network, statistic software (in this case, R Studio) is required. It is easier to manipulate data from official databases or even feed and create data based on theoretical and methodological assumptions. They also provide us with a good approximation and estimation of the reality since the data that has to be analysed is huge. Second, in A.2.2, we describe where and which data regarding energy statistics were collected and for what purposes. Third, in A.2.3, we describe the database, selection criteria, filtering and other steps to selected RET A.2.3.1 patents, patents improving fossil fuels A.2.3.2, and RET publications A.2.3.4. Fourth, in A.2.4, we describe how the data regarding publications and energy statistics were transformed into a social network and then retrieved statistics data in two levels: the experts level A.2.4.1 and the country level A.2.4.2. Fifth, in A.2.5, we describe how we manipulate the k-means algorithm to apply a clustering analysis based on the data for energy statistics and knowledge production.

A.1 Qualitative methodology

Here on, we provide a short description of the qualitative methods and techniques used.

A.1.1 Definition of relevant actors

Defining relevant actors in large networks can be complicated due to the variety and many actors. To create a framework of relevant actors, some steps were taken according to the TIS approach (Hekkert & Negro, 2009; Bergek et al., 2008a) and according to the SNA approach provided by Wasserman et al. (1994). In the process of identification, not every actor enters as a specific node on the network. Instead, they may represent an institutional background that creates and enables conditions for further enlargement and evolution of the network. The steps that we designed are named: extrapolation, aggregation and exemplification.

The first step, extrapolation, requires identifying the larger possible amount of actors related to the topic. They would be not divided into categories of anything. The idea is to extrapolate from the important individual until international organizations all possible market and political actors related with the topic, in our case, with renewable energy technologies. In our case, the level of analysis range from regional to international, so we track actors that act somehow between these levels. But, of course, one should follow the track concerning the interesting level. This step is necessary to offer the researcher the opportunity to meet various elements that can create and take part in the network. Also, one can find chronologically what actors were important during a period and that lost relevance. To identify those actors is important to broaden the research by identifying as many as possible actors from categories such as firms, regulations, industries, enablers, institutions, scholars, research centres and other broad categories related to the main topic in our case RET. This would form a large N.

The second step, aggregation, demands the identification of similarities between the elements found in the first step. It is an important step because they will be mobilised quite often at the moment of analysis. Hekkert & Negro (2009) advises an aggregation of those actors in the following categories: knowledge institutes, educational organizations, industries, market actors and government bodies and supportive organizations. This aggregation will be enough if we do not have to deal with politics and two different levels. Finding a track for the aggregation step, we first looked at the Table 1.3 summarizing the functions of a TIS also contemplating their probable international indicators. This helped us identify from the most obvious one to the complex which actors would be aggregated at the international or regional level. But the aggregation would be difficult to complete if we have to fill two levels and the categories. To solve this problem, we called the literature related to the Triple Helix approach (Leydesdorff, 2012). This approach affirms a relation between university, industry and government in the development of innovation. Although it has some critics related to the importance of each of them and not mentioning civil society, social movements, and international actors, it offers interesting insights to aggregate actors toward and TIS. Finally, ignoring the original label (university, industry and government), we divided the 6 perhaps 7 categories into three: Academia, Market and Institutional Bodies. So we create a 3x2 matrix, where the lines present the categories and the columns the levels. With this matrix, it is possible to aggregate similar actors, considering their origin.

The third step, exemplification, requires a synthesis exercise. Basically, by the aggregation step, one should assemble those elements in each cell that are similar and express exclusively the property of similar elements that once were there. For instance, from 4 different firms, ”w”, ”x”, ”y”, ”z”, we see the similarities regarding the moment in the production cycle they are. Some of them could be firms that create energy plans, and some can be firms that produce material products. By understanding similarities, ”w”, ”x” and ”y” are together as firms that produce material products, and we select the ”w” as the example to summarize it. In contrast, ”z” rest alone as the one that creates energy plans and would be its self example. The same would happen for different aggregations, sometimes with larger, shorter or single examples. This step would be simpler if the other two were meticulously done.

Through these three steps, we identified the relevant actors within a network. Once again, the actors displayed in the matrix are examples of the large N, but that represents the probable universe. Also, they are both nodes that join the network and enablers that promote the evolution of the RETIS.

A.1.2 Policy mix, power and geopolitics analysis

For the analysis of the political interventions, the considerations over the policy mix as a method seems reasonable (Rogge et al., 2015; Flanagan et al., 2011). The theory itself requires the collection of data according to the development of the technology. In our case, collecting the programs and projects related to low carbon technologies from some Member States and from the EU, as a supranational entity, is necessary to understand the network's incentives and guidance. The evolution of the network depends on how the political elements interact with the innovation process, from knowledge production to the diffusion in the network.

The method for sure is content/text analysis (Bardin, 1977) by counting specific terms aligned to the international trend discussion and identifying on a time frame the policies that play in this manner. The effects caused on the network and the interests of the international actors are important facts to get to know. The reading of the projects requires an objective search for fundamental political efforts that support the development of the network and offers incentives to the nodes to keep, strengthen or weaken their relationship. We believe that this collected data provides some discussions that uncover the intention of the nodes vis-a-vis the TIS and that it helps the identification of the third step in this project, the analysis of the power relation in sustainable transitions.

One of the ways to understand the struggle of power in sustainable transitions is via the identification of the resources of power and how they are exercised in politics (Avelino & Rotmans, 2009; Köhler et al., 2019), in our case, world politics. A relevant insight from transitional studies is that technology changes affect and even facilitate political changes (Markard et al., 2016; Hoppmann et al., 2014; Schmidt & Sewerin, 2017). So the EU endeavour to shift to low carbon technologies to generate energy suggests a mobilization of the resources to modify the current energy regime, which still has high energy levels generated by fossil fuels and high dependence on Russian imports.

We mobilised the different power typology by the pattern of relations between the actors, previously described during the policy-mix and TIS analysis. We tried to identify which actors are involved in the transition and how their expression can be seen as innovative, transformative or reinforcive. The expression analysis is a qualitative and quantitative step. During the experts level network analysis, TIS, policy-mix and country-level network analysis, we identified which types of resources have been mobilized by the actors. Even though with different degrees in which steps are planned to achieve the transition, most of the actors' performances tend to address the energy transition somehow.

The next step was toward the type of power analysis. Between the three types Synergy, Antagonism or Neutrality, we consider the expressions of power and the mobilization of resources in each type. So we conduct another qualitative analysis to identify how this power dynamic can be interpreted. Only after considering the material, institutional, legal and ideational factors involved in the transition we were able to identify this. We mean that we understood the power relation regarding the energy transition after considering patents, publications, policies, plans, initiates, firms involved, and relationships between experts and countries.

The last step toward our qualitative methods would be the discussion about geopolitics. We begin with identifying the dependence and renewables installations, and the method is discussed later on in the Appendix in the Section A.2.5. To retrieve some data about the geopolitics of gas, which is a fundamental source in the energy transition, we retrieve data from Wettengel (2021); Stokes & Spinks (2017); Meyer (2017). So based on the map from Wettengel (2021), we provide a map to highlight some information crucial for our analysis.

Based on Criekemans (2018); Scholten et al. (2020); O'Sullivan et al. (2017), our second step, we did the geopolitical analysis on energy transition considering three steps:

1. The identification of the resources available and their potential use to be mobilized;
2. The industrial capacity to efficiently manufacture the resources;
3. The effort to promote sustainable use of the resources.

First, we map the European Union potentials for renewable energies according to the incidence of the sun and the wind speed blowing over the year. The maps were entirely collected on Global solar atlas (2021); Global Wind Atlas (2021) then edited to fit on our purposes of presentation. According to the potential, some countries would be benefited by the invest in some RET than others.

Second, we search for the most approximated documents mapping installations for on and offshore wind and solar parks in Europe. It worth notice that this is just an approximation based on some data found in some documents and sites. The maps were collected in Solar Energy Maps (2021); Wind Europe (2020); European Commission (2021b) and then edited to comprise the approximated number of parks around Europe that might or might be not presented. We read some documents and reports from Wind Europe (2020); Solar Power Europe (2019); European Commission (2021b) and manually add the missing dots to identify the missing parks. The of Transmission System Operators (2020) map and database had an important contribution to observing the electrical transport in energy and based on the complete infrastructure of the electric system in Europe.

For the third, considering the two other steps, we run a k-means algorithm described in Section A.2.5 of this Appendix. As a result, we find out the pattern of development of each country (or group of countries) based on their RET potentials and on the variables used to run the k-means.

This past section is dedicated to explaining our methodology. The following sections are responsible for dealing with some methods and techniques applied in this whole research process. Although not very enjoyable, it might serve as a helpful guide for further scholars from IR, or even other disciplines, that might be interested in methodologies and methods to study technological changes or sustainable transitions. Of course, we dedicate this Appendix to deeply discuss some methods used that might be covered during the reading. But also, the full reading contemplates some more superficial discussion about the techniques and methods.

A.1.3 Interviews

Interviews are a classic and relevant technique to grasp primary information, data and individual insights about a topic. We based our interviews on the study from Binz et al. (2016) where they interview 20 key stakeholders to identify their understanding regarding the political challenges on the legitimation of potable water reuse technologies in the US. In our case, the goal of the interview was in respect to the political challenges regarding the integration of the energy transition in the European Union and how to deal with the dependency. In total, we had 5-6 questions. Questions vary from personal opinion about the energy and climate challenges in Europe; to more technical, describing the impact of climate and energy policies and Member States' performances toward the infrastructure and conditions created for an energy transition. We adjusted our interest and consequently the question according to the institution of the representative.

We tried several times to contact different experts and representatives from key European Union and international institutions. We reached a total of 3 interviews performed with representatives from the Directorate-General for Energy (DG ENER), Directorate-General for Climate Action (DG CLIMA) and Directorate-General for Research and Innovation (DG RTD) of the European Commission that demanded to remain anonymous. Each interview had a different duration depending on the schedule of the representative. Notes were taken, and interventions were made when necessary during the interviews. After the interview, we manually transcripted the content and marked the relevant information to reaffirm or contradict some of the data found previously in the content analysis. We did not provide a discourse analysis.

A.2 Quantitative methodology

Here on, we provide a short description of the quantitative methods and techniques used.

A.2.1 Programming and computational power

This section is not properly a method or technique itself employed in the research. Instead, it can be described as a caution and awareness letter that every researcher with large data sets must have.

We are at a moment that we do researches via computer. It definitely does not matter what type of device it is. It can be a MAC or a PC, even Ipad or any other device with a certain operational system. We are used to not worrying, not even a bit, about computational power. Typing a text on a favourite text editor or creating a table on is not a demanding task for an average computer to perform. Precisely, we from IR are really not used to it because we deal with much texts analysis and some qualitative non demanding tasks. But when one engages in the idea to analyse international data on something, considering the time frame, the level of storage level of the data and the method, it can be tricky. If we use statistical methods such as patent analysis, bibliometric analysis or social network analysis. This development of such analysis can demand a lot of your computer, and sometimes it is really frustrating.

The method chosen to deal with this, besides simple, requires some maturation over time, a learning by doing process, and also deadlines. First, one has to understand the basics of such an app to perform statistics tasks. Second, play a little bit with columns, rows and functions to discover how one performs tasks faster and memorize those with which one feels comfortable. In these first two processes, one probably will get stuck often because the functions are not detailed enough to run or simply do not work this way. Remember, one can always search on the internet or ask someone you trust. Then you are going to start to perform simple tasks with large data sets, and you may find that your computational power is not enough.

The following procedures are basic, but they are just some hints to shortcut the process of dealing with it. Internet is a vast and underexplored space for newcomers who are programming, and many people, in general, have the same questions about the same problems as you do. There are lots of blogs and forums to exchange questions and lock-in problems when programming something, and you may end discovering that one or another function performs the task faster or more efficient without demand too much of your computer. For example, consider the original forum of the application and Stack Over Flow. The latter, we basically found over 90% of our problems written in the same way, and few or more than enough strategies to overcome a problem. We cannot count how many times we spent more time trying strategies found on the internet and talking to my colleagues about my problems than actually programming and get stuck in a loop or errors.

Social network analysis might have been the most difficult quantitative method we applied in this whole process because we had to run tables with thousands of rows and columns. In the beginning, we had ideas to separate the periods of time that right after 1 month, they presented to be inefficient. Overall, computational power plays a decisive role in large networks, which one should be aware of. We apply several modifications and change several times our strategy to retrieve a reliable and concise network. Sometimes, after running a line, it was possible to get stuck for over 2 hours with an error in the end, which is inefficient, unproductive and frustrating.

Reshaping the data for short periods of time and with a short data range solves some problems in most cases. But if it persists, it is relevant to be aware of a centre for computational support on your institution. Ask for a machine with a superior setting compared to the one currently used. You can apply for on-site access or remote access, the last one sometimes works with a time delay of minutes, and some restrictions of days and hours to work may apply, but at least you can unlock your workflow.

Finally, if the computational power is definitely blocking the progress of such a work, consider changing the research approach or even the type of raw data that is manipulated. Different sources can have different sizes even for similar information, and switching on time between them may apply no long computation power constraints on your workflow. Understand your deadlines for tasks and the whole project, and be aware of not putting the project into serious trouble just because of a method or tool.

A.2.2 Energy statistics

All statistics were collected in traditional and reliable database. We used Eurostat for major statistics about the European Union (Eurostat, 2020b). Eurostat is the statistic office responsible for collecting and publishing high-quality data from Europe-wide and indicators that compare selected countries. The database is organized by general themes such as Energy, Finances and STI. These themes are constituted of a tree with different sections broken down into variables and indicators. For the indicators, one can manipulate filters and other parameters to retrieve the desirable amount of data. In our case, we mobilize data for ”Energy statistics”, considering almost all the variables that present annual variation. We provide some examples of variables and their indicators down below. In parenthesis, the code to find it:

- Energy balances (nrg_bal): Data for “Completed Energy Balances (nrg_bal_c) and Energy Flow - Sankey diagram data (nrg_bal_sd)” where one can retrieve major statistics such as imports, exports, production and generation of specific energy sources vary from fossil fuels and renewables

- Energy indicators (nrg_ind): Data for energy intensity (nrg_ind_ei), energy efficiency (nrg_ind_eff), energy imports dependency (nrg_ind_id) and Gross and net production of electricity and derived heat by type of plant and operator (nrg_ind_peh).

- Electricity production capacities for renewables and wastes (nrg_inf_epcrw) for Installed Capacity.

- Prices of natural gas and electricity (nrg_price).

Also, in Eurostat, we mobilise data for Science, technology and digital society to retrieve data for ”Statistics of research and development (rd)” in STI.

- R&D expenditure at the national and regional level: Intramural R&D expenditure (GERD) by sectors of performance and socio-economic objectives according to NABS 1992 (rd_e_gerdsobj92) and Intramural R&D expenditure (GERD) by sectors of performance and socio-economic objectives according to NABS 2007 (rd_e_gerdsobj07) for complete data of Gross Domestic Expenditure on R&D (GERD) inside the countries filtered by ”Energy”.

- Business expenditure on R&D (BERD) by NACE Rev. 1.1 activity and source of funds (rd_e_berdfund) and Business expenditure on R&D (BERD) by NACE Rev. 2 activity and source of funds (rd_e_berdfundr2) for complete data regarding the contribution of the business sector on the R&D for ”Electricity generation”.

- Governmental budget appropriations or outlays on R&D: Total GBAORD by NABS 1992 socio-economic objectives (gba_nabsfin92) and Total GBAORD by NABS 2007 socio-economic objectives (gba_nabsfin07) for complete data of R&D investments provided by the State in or outland.

- General government expenditure by function (COFOG) (gov_10a_exp) also presents some complementary data.

For climate-related statistics such as emissions of GHG, we mobilize the Climate Watch database. Climate Watch is a reliable database that compiles data from different government offices and international organizations about climate. In addition, we mobilise data for Historical emissions of CO2, which is the most dangerous among the GHG broken down by nations and by economic sectors as sources of emissions (Climate Watch, 2018).

A.2.3 Knowledge production: patents and publications

This section describes the methods used to retrieve information from reliable databases related to knowledge production. We understand knowledge production as both Patents and Publications. According to our theoretical framework, both can identify and analyse the Renewable Energy Technological Innovation System - RETIS.

A.2.3.1 Patents for RET

The selection of patents in respect to any technology can be trick by itself. The development of IPC (International Patent Classification) classes by WIPO at the time of the formulation did not consider that new technologies dedicated to some societal challenges could emerge. That is why the Y class came into play inside the CPC (Cooperative Patent Classification) classes to address these types of technology. CPC is younger than IPC. It resulted from a partnership between the European Patent Office (EPO) and the US Patent Trademark Office (USPTO) since 2013 to harmonize the structure and hierarchy of the patent classes. Nowadays, researchers use CPC more often than IPC tracking technologies. The technique related to this type of research is called patent count. It is a traditional technique that could measure by cumulative data the amount of such a developed technology.

Before anything, the researcher interested in the patent count technique must be familiar with the discussion of innovation and technological change. Second, the person must understand the standardization of the IPC and CPC classes and be familiar with the destination of each class for each technology type. These two steps take some time to be mastered, but they are more than necessary to cut some chips. The patent count is one of the possible ways to visualize and measure technological change or even how such an industry or a research field evolved through time. For RET, it is considered to be one of the most accurate forms to perform analysis (Haščič & Migotto, 2015; Johnstone et al., 2010). To fulfil the patent count, we followed some steps that will be described ahead.

The first step was to track on the literature of innovation, the application of patent count for renewable energies or even climate technologies. This helps to understand the classification structure and how one can find the classes that must be in the study according to the objectives and research question. To find out what technologies related to RET someone is looking for, a supporting tool is the “WIPO - IPC Green inventory” that provides information dedicated to Environmentally Sound Technologies (ESTs) as listed by the UNFCCC (WIPO, 2020). It aggregates IPC and CPC classes that correspond with RET. Specifically, we were looking for solar power and wind energy technologies with electrical purposes, ignoring heating technologies, for example.

Wind energy seems very simple to grasp information. The classes related to probable technologies are more straightforward. For example, a “rotor” is a technology used for many purposes, but it certainly is inside a wind turbine, so it is possible to break it down into more subclasses and identify the specific one related to wind turbines. However, according to Bruns & Kalthaus (2020), solar technologies are more complicated. It is divided into two main technologies, Photovoltaics which uses PV cells for a direct conversion of sunlight into electricity, and Concentrated solar power (CSP) uses a thermodynamic cycle to collect and store thermal solar energy in an absorber to utilize the heat for residential heating or to use heat as an engine to convert heat into electricity. They are both different in terms of applicability, scalability and cost. A general problem with the patent count is the non-accurate rate of patents that definitely talks about the product. Some technologies can be used for more than one end, for example, the absorption of light into digital cameras or wind turbines for ship/boat motors. To minimize some problems, the amount of subclasses code was enhanced in order to grab the probable and more connected technologies regarding the production of electricity via renewable energies. The result was a large vector with lots of classes and subclasses, as displayed by the Table A.2.3.1.

Table A.1: Selected CPC classes for RET and their description

Technology description	**CPC Class**
Wind energy based technologies.	F03D
Structural aspects of wind turbines.	B63B 35/00 and F03D
Devices adapted for the conversion of radiation energy into electrical energy. Assemblies of plurarity of solar cells. Hybrid solar thermal-pv systems	B64G 1, C01B 33, C01B 33, C08G 61, C08K 3, C23C 14, C23C 16, C30B 15, C30B 29, F21L 4/00, F21S 9, G05F 1, H01B 1, H01G 9, H01L 25, H01L 27, H01L 29, H01L 31, H01L 51, H01M 10, H01M 14, H01R 13, H02J 7, H02K 7/18,H02M 7, H02S.
Generators in which light radiation is directly converted into electrical energy.	H02N 6, H02S
Aspects of roofing for energy collecting devices including solar panels.	E04D 13, E04H 12/00.

Technology description	CPC Class
Photovoltaic (pv) energy	Y02E 10/5
Thermal-pv hybrids.	Y02E 10/6
Wind energy	Y02E 10/7
Efficient for regeneration, transmission or distribution.	Y02E 40
Monitored, controlled or operated power network elements.	Y02E 60/72
Photovoltaic (pv) onto buildings.	Y02B 10/1
Wind power	Y02B 10/30
Energy efficient lighting technologies.	Y02B 20
Technologies for an efficient end-user side electric power management and consumption.	Y02B 70
Systems characterised by the monitored, controlled or operated end-user elements or equipment.	Y02B 90/22
The energy generation units being or involving renewable energy sources	Y04S 10
Systems for electrical power generation, transmission, distribution or end-user application management characterised by the use of communication or information technologies or communication or information technology specific aspects supporting them.	Y04S 40
Energy trading, including energy flowing from end-user application to grid.	Y04S 50/10

Source: Based on WIPO (2020); Johnstone et al. (2010); Bruns & Kalthaus (2020)

A.2.3.2 Patents improving fossil fuel technologies

Same similar steps were taken for fossil fuel technologies. The intention was to track the pace of development of energy technologies and see how fast and how far they have gone. For the FFT is important to highlight that innovation in RET has been larger than in FTT in every period after 1990. This would be something unexpected, but some reasons explained by (Nesta et al., 2018) The first one is because ”fossil technologies included in the OECD REGPAT are only those relative to improving the efficiency of fossil fuel energy production, rather than the overall number of fossil technologies.”(Nesta et al., 2018, p. 12)

It is important to consider that the market for FFT is old, basically with its roots in XVIII Century with the Industrial Revolution, and even though an international institution such as WIPO did not exist at that time, improvements in the industry were made anyway. So new improvements by the end of the XX Century are quite shorter than renewables innovations because FFT are mature. In addition, RET ”are more likely to be protected by intellectual property rights because they are novel and less incremental. Second, there is a global upward trend in patenting in both renewable and fossil fuel technologies, but the latter grew at a significantly slower pace than the former.” (Nesta et al., 2018, p. 12)

Completed all the steps for FFT. Therefore, it resulted in the following CPC classes as displayed by Table A.2.3.2.

Table A.2: Selected CPC classes for FFT and their description

Technology description	**CPC Class**
Production of combustible gases containing carbon monoxide from solid carbonaceous fuels.	C10J 3
Combustion apparatus specially adapted for combustion of two or more kinds of fuel simultaneously or alternately, at least one kind of fuel being fluent.	F23C 1
Combustion apparatus characterized by the arrangement or mounting of burners; Disposition of burners to obtain a loop flame.	F23C 5/24
Combustion apparatus characterized by the combination of two or more combustion chambers (using fluent fuel).	F23C 6
Combustion apparatus characterized by the combination of two or more combustion chambers (using only solid fuel).	F23B 10
Combustion apparatus with driven means for agitating the burning fuel; Combustion apparatus with driven means for advancing the burning fuel through the combustion chamber.	F23B 30
Combustion apparatus characterized by means for returning solid combustion residues to the combustion chamber.	F23B 70

Technology description	CPC Class
Combustion apparatus characterized by means creating a distinct flow path for flue gases or for non-combusted gases given off by the fuel.	F23B 80
Burners for combustion of pulverulent fuel.	F23D 1
Burners in which drops of liquid fuel impinge on a surface.	F23D 7
Burners for combustion simultaneously or alternatively of gaseous or liquid or pulverulent fuel.	F23D 17
Chemical or physical processes (and apparatus) were conducted in the presence of fluidized particles, with liquid as a fluidising medium.	B01J 8/20-22
Chemical or physical processes (and apparatus, therefore) conducted in the presence of fluidized particles, according to "fluidised-bed" technique.	B01J 8/24-30
Fluidised-bed furnaces; Other furnaces using or treating finely-divided materials in dispersion.	F27B 15
Apparatus in which combustion takes place in a fluidised bed of fuel or other particles.	F23C 10
Modifications of boiler construction, or of tube systems, dependent on installation of combustion apparatus; Arrangements or dispositions of combustion apparatus.	F22B 31
Steam generation plants, e.g. comprising steam boilers of different types in mutual association; Combinations of low- and high-pressure boilers.	F22B 33/14-16
Plants characterised by the use of steam or heat accumulators, or intermediate steam heaters, therein.	F01K 3
Plants characterised by use of means for storing steam in an alkali to increase steam pressure, e.g. of Honigmann or Koenemann type.	F01K 5
Plants characterised by more than one engine delivering power external to the plant, the engines being driven by different fluids.	F01K 23
Superheating of steam.	F22G

Technology description	CPC Class
Gas turbine plants - Heating air supply before combustion, e.g. by exhaust gases.	F02C 7/08-105
Cooling of gas turbine plants.	F02C 7/12-143
Technologies for improved output efficiency (Combined heat and power, combined cycles, etc).	Y02E 20/10 – 185
Technologies for improved input efficiency (Efficient combustion or heat usage).	Y02E 20/30-336

Source: Based on Haščič & Migotto (2015); Lanzi et al. (2012)

A.2.3.3 Manipulation of CPC classes

After defining the right classes for both RET and FFT, we mobilized the OECD REGPAT Database. REGPAT is a traditional database that links patents to its inventors and applicants (Maraut et al., 2008). The database concentrates on OECD countries and a few Non-OECD. Among the OECD countries, we selected those Member States of the European Union (28) before 2020, including the United Kingdom (this was a minor problem because the BREXIT enters into force only in 2021, so the data is trust full). We began the collection in 1990 and ended up in the closest possible version, in this case, OECD REGPAT 2020. We consider the closest version because it can provide updated information. However, the lag of 4-5 years between the application of a patent and the grant for the EPO plays an important role here. To make the data reliable, we can disregard or not the actual data. In our case, we kept it to see if it would be possible to present some tendency.

The result was possible to reach because every patent has a unique application number that connects information regarding inventors, applicants, date, and geographic location regarding the Nomenclature of Territorial Units for Statistics (NUTS). Inventors are those individuals related to the invention of technology. Applicants are the institutions, perhaps private or public actors, that embodied the inventors and the innovation. The NUTS is a common tool for the codification of geographic location inside the EU. It consists of three levels: NUTS 1 for countries; NUTS 2 for governmental regions or equivalent and; NUTS 3 for districts. We used only the NUTS 1 and their alpha-2 codes with the two letters corresponding to each NUTS 1 region: Germany - DE or Italy - IT with NUTS 1 an alpha-2 code, respectively. After these previous manipulations, we reached a total number of patents of 231.605 distributed among all RET e FFT's CPC classes. Then, we divided into two groups: Renewable Energy Technologies - RET with 218.617 patents and; Fossil Fuel

Technologies - FFT with 12.988 patents, considering specific CPC classes. Then we plot the evolution in a time frame of the application of energy technologies.

It is also important to note that this data was also used to create our social network analysis by the co-authored patents registered under a unique application number. This is discussed in the Appendix section A.2.4.

A.2.3.4 Publications for RET

Working with publications requires learning on how to access and retrieve the desired content type. SCOPUS Elsevier is one of the greatest and most completed databases to conduct bibliometric researches. We tried several approaches, constantly changing the keywords. For example, to retrieve only renewable energy technology papers type, we excluded climate change or everything related to the environment. This was done because, according to the Y02 CPC class, the technologies for climate change involve adaptation and mitigation technologies in other dimensions such as civil constructions, pavimentation, water treatment, and waste treatment, as well as a combination of main keywords related to energy, at first sight, were selected.

We used the title, abstracts and keywords(TITLE-ABS-KEY) as our default search field, and a combination of Boolean operators[1] to refine and narrow the scope of the research. Table A.3, describes the development of the research with the basic commands, narrow and refinement procedures, and the results after each procedure.

After checking the 10 first papers with the highest relevance and citation, they seemed to be coherent with the objective of the research.

The retrieved data began in 1971 until 2020 because this is what SCOPUS provided. But the number of publications per year was from 0 until 4 from 1971-88. The publications grew after 1989 with 7 papers as a benchmark and reached 2019 with 1632. The numbers for 2020 are still growing, so it is difficult to see the real evolution (especially after the COVID-19 crisis, the path at the moment of this research (April 2020) was around 30% if compared with 2019).

After these procedures, we retrieved 13,338 papers with high confidence to represent the pool of references to our discussion. Then, we exported to RStudio and applied lots of treatments to reduce the number of doubles and unnecessary information. As some manipulation necessary in order to make the data visualization clean and reliable.

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[1] Boolean operators are a set of commands that can be used to refine the research in some databases. They are commonly known as AND, OR and NOT, but there may exist variations and some additional commands. For example, in SCOPUS, one can find the following: AND, OR, ANd NOT, PRE/ and W/. Please visit https://www.scopus.com to find more and a complete explanation of the use and the research engine.

Table A.3: KEYWORDS FOR SCOPUS

Final Strategy	
KEYWORDS (TITLE-ABS-KEY)	RESULTS
QUERY 1 - ”innovat*” OR ”technolog*”	4,032,019
QUERY 2 - ”energ*” OR ”renewable power” OR ”renewable energ*” OR ”low carbon” OR ”carbon free energ*” AND NOT ”transport*” AND NOT ”heat*”	6,346,664
- COMBO 1 (Last two queries combined)	561,930
Narrowing	
Limiting the EU countries: AND (LIMIT-TO (AFFILCOUNTRY , ”United Kingdom”) OR LIMIT-TO (AFFILCOUNTRY , ”Germany”) OR LIMIT-TO (AFFILCOUNTRY , ”Italy”) OR LIMIT-TO (AFFILCOUNTRY , ”Spain”) OR LIMIT-TO (AFFILCOUNTRY , ”France”) OR LIMIT-TO (AFFILCOUNTRY , ”Netherlands”) OR LIMIT-TO (AFFILCOUNTRY , ”Denmark”) OR LIMIT-TO (AFFILCOUNTRY , ”Sweden”) OR LIMIT-TO (AFFILCOUNTRY , ”Poland”) OR LIMIT-TO (AFFILCOUNTRY , ”Switzerland”) OR LIMIT-TO (AFFILCOUNTRY , ”Portugal”) OR LIMIT-TO (AFFILCOUNTRY , ”Austria”) OR LIMIT-TO (AFFILCOUNTRY , ”Finland”) OR LIMIT-TO (AFFILCOUNTRY , ”Belgium”) OR LIMIT-TO (AFFILCOUNTRY , ”Romania”) OR LIMIT-TO (AFFILCOUNTRY , ”Norway”) OR LIMIT-TO (AFFILCOUNTRY , ”Ireland”) OR LIMIT-TO (AFFILCOUNTRY , ”Czech Republic”) OR LIMIT-TO (AFFILCOUNTRY , ”Croatia”) OR LIMIT-TO (AFFILCOUNTRY , ”Hungary”) OR LIMIT-TO (AFFILCOUNTRY , ”Slovakia”) OR LIMIT-TO (AFFILCOUNTRY , ”Latvia”) OR LIMIT-TO (AFFILCOUNTRY , ”Lithuania”) OR LIMIT-TO (AFFILCOUNTRY , ”Slovenia”) OR LIMIT-TO (AFFILCOUNTRY , ”Cyprus”) OR LIMIT-TO (AFFILCOUNTRY , ”Bulgaria”) OR LIMIT-TO (AFFILCOUNTRY , ”Estonia”) OR LIMIT-TO (AFFILCOUNTRY , ”Luxembourg”) OR LIMIT-TO (AFFILCOUNTRY , ”Malta”)) AND last query result	99,313
Refinements	
WEIRD KEYWORDS REMOVAL: AND NOT ”animal*” AND NOT ”female*” AND NOT ”male*” AND NOT ”adult*”	95,859
The removal of ”energ*” as the main keyword was necessary because energy is a physics property, and lots of papers use this keyword to describe the process of transference of energy among entities, nor by the meaning of generation of energy in our terms.	13,509
The exact keyword was also excluded: AND (EXCLUDE (EXACT KEYWORD, ”Anaerobic Digestion”))	13,338

A.2.4 Social network analysis

The studies of technological changes, precisely those that deal with sustainable transitions, sometimes requires more than just one single track of methodology. The complexity of a change is difficult to access since lots of social forces happen together at the same but in different or even opposite directions. In the current state of the art, the study of transitions, since it has roots in innovation theory, scholars search for the analysis of the knowledge creation and diffusion. Our interest is certainly in the diffusion process because by communicating a technology, the science itself advances from that point, and new contributions can be made. Also, since it is embedded in society, the market has to deal with it and reshape itself based on public or private incentives (Nelson & Nelson, 2002; Freeman, 1989; Mazzucato, 2013). To understand this first step on identifying the actors from the diffusion, one theoretical approach that seems to help create a social network that could help us understand the relation between inventors in a single issue area. (Hekkert & Negro, 2009; Graf & Kalthaus, 2018; Cantner et al., 2016).

Naturally, network analysis is a quantitative method that can reach statistical analysis and provide correlations. The research design requires more than just the identification of the nodes but further analysing their relationship. The nodes are those elements that connect with other elements, and they are always mutually dependent. The ties are the connections between nodes that can be channels for transmitting material and non-material products. The patterns of association or who stands for who creates a structure that can define, enable or restrict the actions of the nodes (Scott, 2013; Wasserman et al., 1994). So that, the collaboration among scientists, research institutes and political institutions are the probable elements that we can identify like elements in this discovery process. So that, the functions of a TIS help us identify within the meaning of knowledge diffusion what are the important data to collect, focusing on the renewable energies specifically for wind and solar power generation. According to IEA (2019) these are the main types of energy that receive more investments and have a high number of installed capacity worldwide.

As well as for international relations purposes, networks are quite familiar. Understanding world politics by this method elicits the mapping of an organization, regime or structure, which may constrain and enable agents because the ontology behind emphasizes how material and social relationships become the real world. The mapping of such a network allows analysis of power relations. It can embody a new actor in the international dynamics that create economic, political and social causes, effects, or processes. Those are intended to be empirically studied, so the network has actually meaning for its own existence (Hafner-Burton et al., 2009; Kahler, 2011). Within this project, the network defines the build of resources in academic or non-academic forms that are enabled or enabling policies that deal with the innovation of renewable technologies. It is also possible to identify more examples of TIS functions. The presence of certain countries and their connectivity with other nodes reveals their economic interests in such a technology and their political attitudes or endeavours in relation to the main subject of the network.

Finally, the characteristics of the network such as the number of nodes, degree, closeness, eigenvector (centrality), betweenness and information of their ties can be calculated from the observations, for example, of the co-authoring publications (in a micro-level) and international cooperation (in a macro level) by correlation. But one should be aware of the inflation of the proposed network. Since the world leaves in a permanent international interaction or course, non-expected nodes can arrive, and also obvious nodes can do not make much sense. This is also related to the historical growth or shrink of a network, and one should seek a structural balance and equivalence (Wasserman et al., 1994; Hafner-Burton et al., 2009).

To conduct the social network analysis (sna), we started by mobilizing the previous patents and publications selected and the data already treated as bibliometric and patent analysis. Both raw data received treatment and parsing procedures to reduces redundancies, a task important to clean and make the data easier to work (Graf, 2017). Raffo & Lhuillery (2009) advise us about the difficulties of the "Names Games" which can bring complexity and fallacious results if one does not parse nam character strings within this process. So we reduced doubles of names for same items, different spelling for character strings and sometimes empty and useless data, using some parsing methods. We also followed some adjustment of the data retrieved from SCOPUS (Albort-Morant et al., 2017) to transform it into data with the characteristics necessary to run it on the package "Igraph", a complement and powerful package to network statistics in RStudio. The complete code sequence is not available in this study but can certainly be privately shared if it is necessary.

We follow the definition provided by (Wasserman et al., 1994, p. 20) for the network as: "A social network consists of a finite set or sets of actors and the relation or relations defined on them. The presence of relational information is a critical and defining feature of a social network". The intention was to observe the development of a scientific collaboration network for renewable energy technologies beginning around 1990, following the most recent and reliable data. We reconstructed the networks for Patents from 1990 until the most reliable data, respecting the 4-5 years lag, which comprehends 2014[2] For Publications, we start in 1989, the oldest data, until 2020. Since publication has a continuous flow, we did not have to respect some lag rule. Then, we were able to identify 9 different periods for

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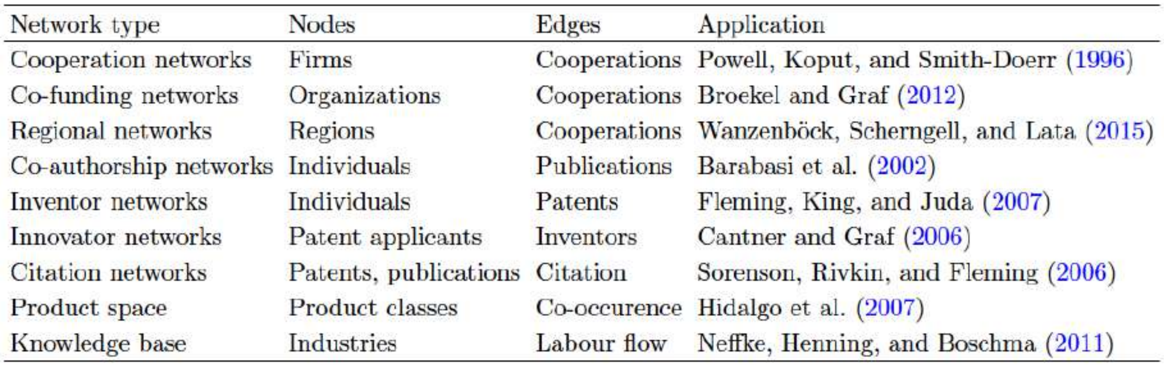
[2] We also plotted, to check if the trend were right the tendencies for 2015 - 2019, which reveal a continuation of expansion and elevation of density.

each category. According to Graf (2017), there are several possibilities to conduct sna for innovation studies purposes. Figure A.1 summarises some possibilities.

Figure A.1: Examples of network in innovation studies



Network type	Nodes	Edges	Application
Cooperation networks	Firms	Cooperations	Powell, Koput, and Smith-Doerr (1996)
Co-funding networks	Organizations	Cooperations	Broekel and Graf (2012)
Regional networks	Regions	Cooperations	Wanzenböck, Scherngell, and Lata (2015)
Co-authorship networks	Individuals	Publications	Barabasi et al. (2002)
Inventor networks	Individuals	Patents	Fleming, King, and Juda (2007)
Innovator networks	Patent applicants	Inventors	Cantner and Graf (2006)
Citation networks	Patents, publications	Citation	Sorenson, Rivkin, and Fleming (2006)
Product space	Product classes	Co-occurence	Hidalgo et al. (2007)
Knowledge base	Industries	Labour flow	Neffke, Henning, and Boschma (2011)

Source: Graf (2017)

There are several concepts present in sna. So we present them, as it reveals necessary. Beginning with a simple but fundamental one, *nodes* are social entities in a network, also referred to as vertices or actors. *Edges* are the social ties, links between two nodes. They can be existent or absent, directed or undirected, weighted or unweighted. *Existent* means a link between two nodes, and *absent* means no link between two nodes. *Directed* means that the links have just one direction from 'A' to 'B', and the opposite is not true, while *undirected*, the opposite direction exists. *An unweighted* network means that all connections disregarding their importance are presented, while in *weighted* networks, we attach some weight to the importance of some links avoiding loops and "infinite" numbers. The *type* of network is defined by what the research intends to observe, the research design. It can be of whatever type or topic enabling a connection between nodes.

Considering our data and objectives, we found it appropriate to analyse a network that may be composed of:

1. Type: International scientific collaboration
2. Nodes: Individuals/Institutions/States
3. Edges: Knowledge production

The nodes are separated into 3 different categories following the probable types of relevant actors defined in Table 2.2.3. In addition, by following the experiences by selecting individuals from Barabâsi et al. (2002); Fleming et al. (2007), institutions, organizations, educational and research institutes, and firms from Broekel & Graf (2012); Cantner & Graf

(2006), and states from Graf & Kalthaus (2018); Wagner et al. (2017). The first level analyses the growth in terms of quantity of each element, consider as knowledge production. The second level analyses the co-funding but also the cooperation between institutions. The third level analyses the embeddedness of such a country in this historical process and its centrality and influence overall the European Union. Unfortunately, we were not able to provide an analysis of the network for the second level, but the influence of some elements comprising this level are presented on both other analyses.

Beyond this point, we were able to perform two different levels of analysis, the experts and the countries. The basic data remains the same, but different treatments were done to achieve different objectives.

A.2.4.1 Experts network

Knowledge production breaks down into two categories: Patents and Publications. We adopted this strategy for some reasons. Procedurally, aggregating them would overcharge the computer, and the analyses would not be completed. For methodological manners, we understand the TIS approach with a possibility to grab the production of knowledge related to the development of such technologies, and this last one is not restricted to material artefacts but also as ideational, institutional and all possible biases that it can apply in the process of sustainable transition (Markard & Truffer, 2008).

We reconstructed the networks for Patents from 1990 until the most reliable data, respecting the 4-5 years lag, which comprehends 2014[3]. For Publications, we start in 1989, the oldest data, until 2020. Since publication has a continuous flow, we did not have to respect some lag rule, which also explains the difference between the duration of each period. Patents time frame led to 28 overlaps and 9 periods (considering the years lag, 23 overlaps and 8 periods), corresponding to: 1990-1992, 1993-1996, 1997-1999, 2000-2002, 2003-2005, 2006-2008, 2009-2011, 2012-2014 and 2015-2019. Publications time frame led to 30 overlaps and 9 periods, corresponding to: 1989-1992, 1993-1996, 1997-2000, 2001-2004, 2005-2008, 2009-2011, 2012-2014, 2015-2017 and 2018-2020.

We transformed our data into a 2-mode matrix (incidence matrix), then in a one-mode matrix (adjacency matrix). When i and j have a connection, the sell is higher or equal to 1; otherwise, 0. Our sociograms are undirected because we are dealing with cooperation between the nodes. We set the diagonal to zero creating a bipartite network which means nodes cannot be connected to themselves. Moreover, we produced a weighted matrix that prevents large ”infinity” numbers from appearing and making the calculation difficult or impossible. This weighting process occurs by avoiding recounting repeated connections between i and j, which

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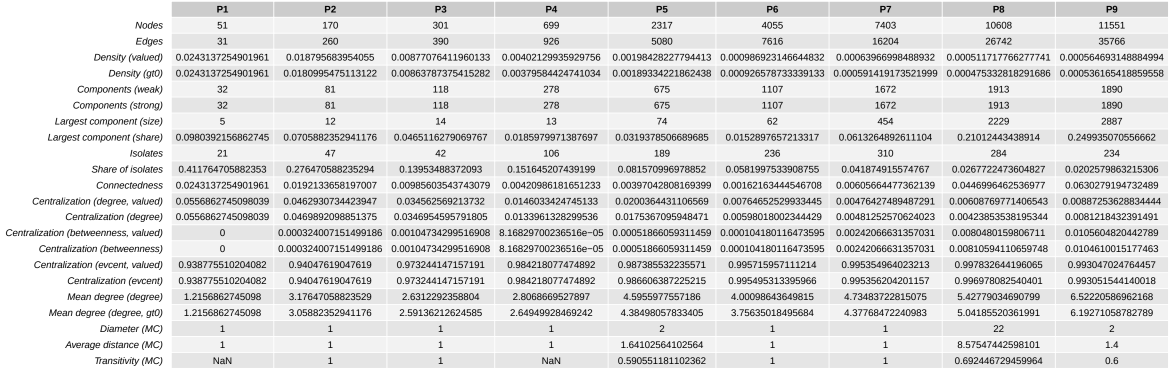
[3] We also plotted, to check if the pattern was right, the tendencies for 2015 - 2019.

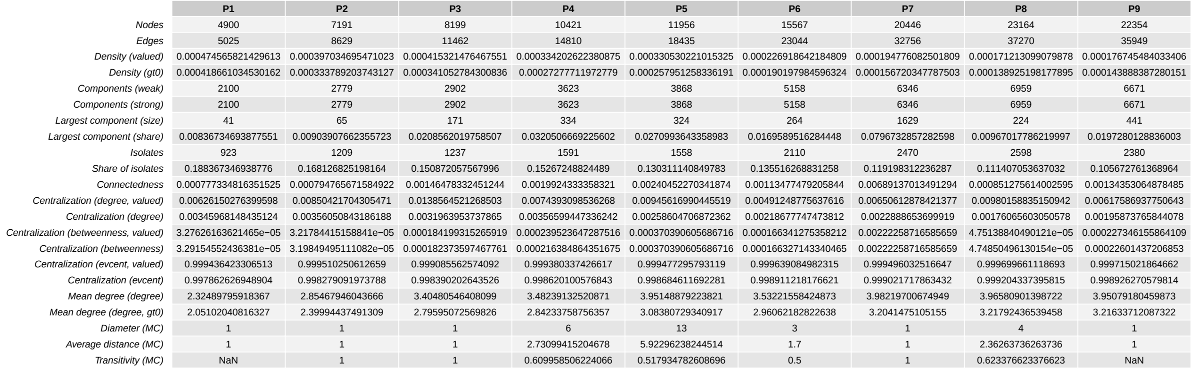
Figure A.2: Result of network statistics for individual level (co-patenting and co-publishing)

(a) Co-authoring publication stats



	P1	P2	P3	P4	P5	P6	P7	P8	P9
Nodes	51	170	301	699	2317	4055	7403	10608	11551
Edges	31	260	390	926	5080	7616	16204	26742	35766
Density (valued)	0.0243137254901961	0.018795683954055	0.00877076411960133	0.00402129935929756	0.00198428227794413	0.000986923146644832	0.000639669984889932	0.000511717766277741	0.000564693148884994
Density (gt0)	0.0243137254901961	0.0180995475113122	0.00863787375415282	0.00379584424741034	0.00189334221862438	0.000926578733339133	0.000591419173521999	0.000475332818291686	0.000536165418859558
Components (weak)	32	81	118	278	675	1107	1672	1913	1890
Components (strong)	32	81	118	278	675	1107	1672	1913	1890
Largest component (size)	5	12	14	13	74	62	454	2229	2887
Largest component (share)	0.0980392156862745	0.0705882352941176	0.0465116279069767	0.0185979971387697	0.0319378506689685	0.0152897657213317	0.0613264892611104	0.21012443438914	0.249935070556662
Isolates	21	47	42	106	189	236	310	284	234
Share of isolates	0.411764705882353	0.276470588235294	0.13953488372093	0.151645207439199	0.081570996978852	0.0581997533908755	0.041874915574767	0.0267722473604827	0.0202579863215306
Connectedness	0.0243137254901961	0.0192133658197007	0.00985603543743079	0.00420986181651233	0.00397042808169399	0.00162163444546708	0.00605664477362139	0.0446996462536977	0.0630279194732489
Centralization (degree, valued)	0.0556862745098039	0.0462930734423947	0.034562569213732	0.0146033424745133	0.0200364431106569	0.00764652529933445	0.00476427489487291	0.00608769771406543	0.00887253628834444
Centralization (degree)	0.0556862745098039	0.0469892098851375	0.0346954595791805	0.0133961328299536	0.0175367095948471	0.00598018002344429	0.00481252570624023	0.00423853538195344	0.0081218432391491
Centralization (betweenness, valued)	0	0.000324007151499186	0.00104734299516908	8.16829700236516e−05	0.00051866059311459	0.000104180116473595	0.00242066631357031	0.0080480159806711	0.0105604820442789
Centralization (betweenness)	0	0.000324007151499186	0.00104734299516908	8.16829700236516e−05	0.00051866059311459	0.000104180116473595	0.00242066631357031	0.00810594110659748	0.0104610015177463
Centralization (evcent, valued)	0.938775510204082	0.94047619047619	0.973244147157191	0.984218077474892	0.987385532235571	0.995715957111214	0.995354964023213	0.997832644196065	0.993047024764457
Centralization (evcent)	0.938775510204082	0.94047619047619	0.973244147157191	0.984218077474892	0.986606387225215	0.995495313395966	0.995356204201157	0.996978082540401	0.993051544140018
Mean degree (degree)	1.2156862745098	3.17647058823529	2.6312292358804	2.8068669527897	4.5955977557186	4.00098643649815	4.73483722815075	5.42779034690799	6.52220586962168
Mean degree (degree, gt0)	1.2156862745098	3.05882352941176	2.59136212624585	2.64949928469242	4.38498057833405	3.75635018495684	4.37768472240983	5.04185520361991	6.19271058782789
Diameter (MC)	1	1	1	1	2	1	1	22	2
Average distance (MC)	1	1	1	1	1.64102564102564	1	1	8.57547442598101	1.4
Transitivity (MC)	NaN	1	1	NaN	0.590551181102362	1	1	0.692446729459964	0.6

(b) Co-inventing patents stats



	P1	P2	P3	P4	P5	P6	P7	P8	P9
Nodes	4900	7191	8199	10421	11956	15567	20446	23164	22354
Edges	5025	8629	11462	14810	18435	23044	32756	37270	35949
Density (valued)	0.000474565821429613	0.000397034695471023	0.000415321476467551	0.000334202622380875	0.000330530221015325	0.000226918642184809	0.000194776082501809	0.000171213099079878	0.000176745484033406
Density (gt0)	0.000418661034530162	0.000333789203743127	0.000341052784300836	0.000272777119727779	0.000257951258336191	0.000190197984596324	0.000156720347787503	0.000138925198177895	0.000143888387280151
Components (weak)	2100	2779	2902	3623	3868	5158	6346	6959	6671
Components (strong)	2100	2779	2902	3623	3868	5158	6346	6959	6671
Largest component (size)	41	65	171	334	324	264	1629	224	441
Largest component (share)	0.00836734693877551	0.00903907662355723	0.0208562019758507	0.0320506669225602	0.0270993643358983	0.0169589516284448	0.0796732857282598	0.00967017786219997	0.0197280128836003
Isolates	923	1209	1237	1591	1558	2110	2470	2598	2380
Share of isolates	0.188367346938776	0.168126825198164	0.150872057567996	0.15267248824489	0.130311140849783	0.135516268831258	0.119198312236287	0.111407053637032	0.105672761368964
Connectedness	0.000777334816351525	0.000794765671584922	0.00146478332451244	0.0019924333358321	0.00240452270341874	0.00113477479205844	0.00689137013491294	0.000851275614002595	0.00134353064878485
Centralization (degree, valued)	0.00626150276399598	0.00850421704305471	0.0138564521268503	0.00743930985362688	0.00945616990445519	0.00491248775637616	0.00650612878421377	0.00980158835150942	0.00617586937750643
Centralization (degree)	0.00345968148435124	0.00356050843186188	0.0031963953737865	0.00356599447336242	0.00258604706872362	0.00218677747473812	0.0022888653699919	0.00176065603050578	0.00195873765844078
Centralization (betweenness, valued)	3.27626163621465e−05	3.21784415158841e−05	0.000184199315265919	0.000239523647287516	0.000370390605686716	0.000166341275358212	0.00222258716585659	4.75138840490121e−05	0.000227346155864109
Centralization (betweenness)	3.29154552436381e−05	3.19849495111082e−05	0.000182373597467761	0.000216384864351675	0.000370390605686716	0.000166327143340465	0.00222258716585659	4.74850496130154e−05	0.00022601437206853
Centralization (evcent, valued)	0.999436423306513	0.999510250612659	0.999085562574092	0.99938033742617	0.999477295793119	0.999639084982315	0.999496032516647	0.999699661118693	0.999715021864662
Centralization (evcent)	0.997862626948904	0.998279091973788	0.998390202643526	0.998620100576843	0.998684611692281	0.998911218176621	0.999021717863432	0.999204337395815	0.998926270579814
Mean degree (degree)	2.32489795918367	2.85467946043666	3.40480546408099	3.48239132520871	3.95148879223821	3.53221558424873	3.98219700674949	3.96580901398722	3.95079180459873
Mean degree (degree, gt0)	2.05102040816327	2.39994437491309	2.79595072569826	2.8423375875 6357	3.08380729340917	2.96062182822638	3.2041475105155	3.21792436539458	3.21633712087322
Diameter (MC)	1	1	1	6	13	3	1	4	1
Average distance (MC)	1	1	1	2.73099415204678	5.92296238244514	1.7	1	2.36263736263736	1
Transitivity (MC)	NaN	1	1	0.609958506224066	0.517934782608696	0.5	1	0.623376623376623	NaN

means we can attribute the magnitude of such a relationship between nodes. Finally, we took the knowledge production as edges on every network constructed in this study, an element that connects two nodes.

We performed some network statistic procedures and retrieved the Table ?? presented as follow. Important to mention that we selected some of these measurements to incorporate our argument in the text, and some of them just remain here for statistical purposes.

The tables as composed of several structural properties and their values for the 9 periods. We base our definitions on Graf (2017); Wasserman et al. (1994); Scott (2013) explaining the properties. This explanation also serves for the next network level related to countries. Nodes and edges were already explained. *Density* measures the share of all present connections in all possible connections. Close to 0 means a network not so dense with few connections in respect to what it could be; close to 1 means a network fully connected where the knowledge finds no limitations to reach all nodes. Values can be different for a weighted and unweighted network.

Components are the sub-networks. It might be a group or a clique that can expand or shrink depending on the number of nodes and the degree of relation between them. The more components, the less connected the network. Isolated nodes count as components as well.

Isolates are nodes without connection to any other node. the higher the number, the less connected a network.

Connectedness "is the proportion of pairs that can reach each other, i.e. which are members of the same component" (Graf, 2017, p. 15). When it is equal to 1 when the network is fully connected, but the number is shorter than 1 when it presents components. The R-code for the connectedness measurement is provided by Graf (2017).

Centralization can be measured in several different ways. We explained the centralization measurements in Section 4.1of Chapter 4. Degree, betweenness, closeness and k-core are different types of centrality but all related to the number of links and not just the number of nodes.

Degree is the simple count of links according to their intensity, or how many connections a unique node has.

Betweenness is the number of shortest paths through the network of which the nodes part, or how often the information of the network goes through a node to reach other nodes.

Closeness is the inverse of the average length of the shortest path to/from all the other nodes in the network, or how important a node is for the whole network. The

K-core is the maximal subgraph in which every node has at least degree k, or if a node is more central or peripheral.

Eigenvector measures the influence of a node related to the network, the degree of quality of the connection between nodes.

Mean degree is simply the average number of connections per node. The highest the mean, the more links nodes have.

Walk is the sequence of vertices and nodes between two nodes.

Path is the distance between two nodes in any position of the network. In a path, the same node is not repeated (A-B-D-G, not A-B-A-D).

Diameter of the main component (MC) is the shortest distance (Path) between the two most distant nodes. 1 means that the two nodes are neighbours; larger than 1 means that a number represents how many distinct nodes exist between the two most distant ones.

Average distance of the main component (MC) is the average shortest path between two nodes.

Transitivity measures the likelihood that adjacent nodes of a node are connected to the main component. When equals 1, the main component has nodes fully connected.

A.2.4.2 Countries network

We move to the representation of countries in the network. To perform it, first, we aggregated the data for patents and publications, accounting for 491.942 observations (207.107 from patents and 284.835 from academic publications). We distributed the years in nine periods P1 (1989-1992), P2 (1993-1996), P3 (1997-1999), P4 (2000-2002), P5 (2003-2005), P6 (2006-2008), P7 (2009-2011), P8 (2012-2014) and P9(2015-2020). We opted for a long last period because of the 3-4 years lag for patents. It was possible to aggregate them because we set both data with the same number of columns dedicated for specific variables and making internal modifications necessary to merge them. We similarly proceeded like for the experts level on the preparation and calculation of some indicators. But we decided to move for the Newman-Girvan method, a community detection analysis based on edge betweenness.

Removing edges does not show centrality, but it focuses on edges that are most likely ”between” groups of nodes. After applying this algorithm, it revealed how often a country is embedded in a cluster or not, if the country collaborates with another outside its own group, and other issues discussed below. The algorithm does not provide a component measurement, which is a traditional SNA indicator, but the final stats can be similar or not. For example, after running the Newman-Girvan method, we noticed that the number of communities in some periods is near to the number of components (P1, P2 and P9) but completely different in others. Since then, the benefits of applying the algorithm and do not follow the traditional indicator lie in the possibility of simplifying, even more, the pattern of links between nodes, calculating a particular edge as the number of times it appears in the shortest path matrix of the graph. As a result, the method provides a network with each edge value as 1 (without weighting the relationship), revealing the links between Member States that detect a scientific community (This paragraph is the same provided in the Section 4.1.2 from Chapter 4).

Moreover, we calculated 4 centrality measurements and the most intensive relationship between countries in the 9 periods, trying to retrieve the influence or importance some countries have depending on how one might look at the network.

A.2.5 K-means for energy transition

In order to retrieve more valuable information from the energy statistics, and based on the studies from Pacesila et al. (2016) regarding energy transition in the European Union, we mobilize the K-means algorithm. K-means is a clustering algorithm that consists of partitioning the data set into groups of points with high similarity (Galluccio et al. 2012 apud Pacesila et al. (2016)). It has been used for a long time for different purposes and is

Table A.4: Energy transition variables

Variable	Acronym	Unit	Year of reference
Renewable energy technology consumption	RET.cons	GW/h	2018
Renewable energy production	RET.prod	MW	2018
Greenhouse gas emissions	GHG.ems	k t of GHG	2020
Energy import dependence share	nrg.dep	% 2019	
Renewable energy technology maximum installed capacity share	RET.mx.capac	%	2019
Energy investments	nrg.inv	Million euros	2020
Knowledge production	knw.prod	units of	2018

one of the most popular and effective methods to cluster observations. Advantages to using K-means are that it is a relatively simple algorithm to perform. It is good for large data sets and can create clusters based on their identification of similarities. Unfortunately, the disadvantages are related to depending on the number of cycles selected when coding, and it is possible to retrieve a not precise clusterization of the units. Moreover, it is manually dependent on controlling the number of clusters, creating a biased number of clusters.

To overcome these problems, first, we run the algorithm to identify the best number of clusters based on the number of variables and their values. This results in 4 clusters with observations with similar characteristics. Second, we adjusted the number of cycles to optimize the result based on standardized parameters, which means 20 cycles to reduce overlapping data while calculating and informing the k-means algorithm that, if it sees this value with the same characteristics once again, discard it. This results in 4 clusters with maximum approximation.

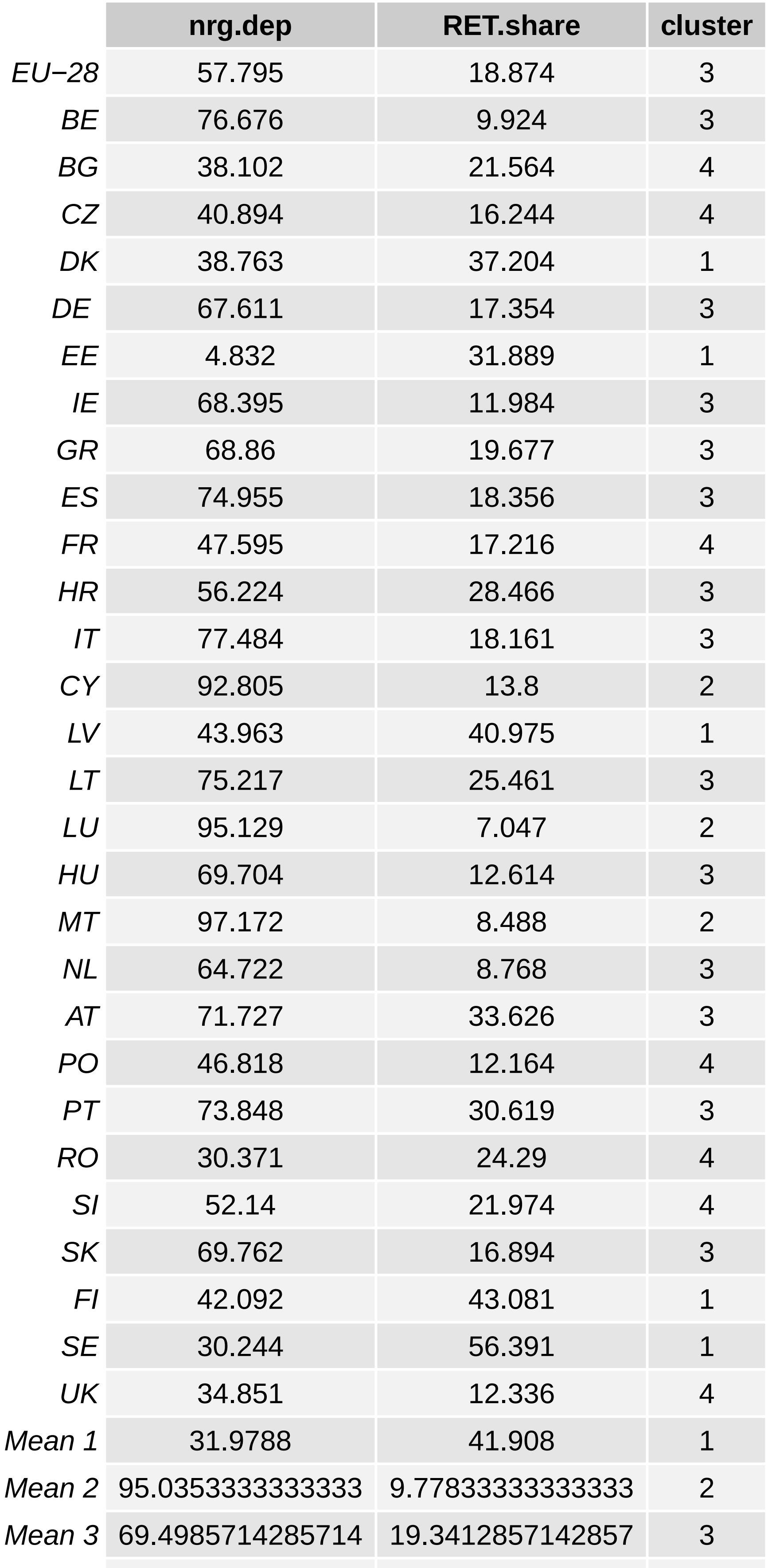
We had two purposes, or objectives, for this method. First, recalculate, based on the same factors, the updated result for energy transition and Pacesila. Second, advance on the calculation adding important variables for our study.

For the first, we calculated only the correlation between energy dependence and renewable energy share. Both are percentages, which makes the calculation easier. Table A.3 presents the values used to calculate the clusters. The data is from 2019.

For the second, we calculated the correlation between seven variables important for the study to discuss the geopolitics of energy transition within the European Union. Table A.4 presents them and some valuable information.

We based this on the IEA (2020) category 'Energy transition indicators' for the first 3 variables; variables 4 and 5 are based on Pacesila et al. (2016), and; 6 and 7 are important

Figure A.3: Renewable production and energy dependence share for EU-28 2019



	nrg.dep	RET.share	cluster
EU−28	57.795	18.874	3
BE	76.676	9.924	3
BG	38.102	21.564	4
CZ	40.894	16.244	4
DK	38.763	37.204	1
DE	67.611	17.354	3
EE	4.832	31.889	1
IE	68.395	11.984	3
GR	68.86	19.677	3
ES	74.955	18.356	3
FR	47.595	17.216	4
HR	56.224	28.466	3
IT	77.484	18.161	3
CY	92.805	13.8	2
LV	43.963	40.975	1
LT	75.217	25.461	3
LU	95.129	7.047	2
HU	69.704	12.614	3
MT	97.172	8.488	2
NL	64.722	8.768	3
AT	71.727	33.626	3
PO	46.818	12.164	4
PT	73.848	30.619	3
RO	30.371	24.29	4
SI	52.14	21.974	4
SK	69.762	16.894	3
FI	42.092	43.081	1
SE	30.244	56.391	1
UK	34.851	12.336	4
Mean 1	31.9788	41.908	1
Mean 2	95.0353333333333	9.77833333333333	2
Mean 3	69.4985714285714	19.3412857142857	3

for this study. Since there are different units of measurement, a standardizing process was used. Table A.4 presents the values. The result is based on the standard deviation.

Figure A.4: Energy transition indicators for EU-28

	RET.cons	RET.mx.capac	nrg.dep	RET.prod	GHG.ems	nrg.inv	knw.prod	clus
BE	−0.435116190670691	−0.276568380608818	0.802171413122943	−1.00714270752768	−0.190819895014044	−0.292743615987722	−1.3907156629977	1
BG	−0.554636630392362	−0.472340356529463	−0.944707206062259	−0.0379877119197687	−0.45909727790928	−0.425091812667654	0.0235899217146806	2
CZ	−0.140043607523692	−0.473370343235268	−0.818267503030033	−0.480934840496578	−0.122389121105475	−0.266430103828484	0.104724392619975	2
DK	−0.497416191803793	−0.334791126339724	−0.914772878087939	1.26421023750529	−0.504323344381255	−0.19817262011047	0.45908092794139	2
DE	2.91101309184397	3.84902610147203	0.391649956107496	−0.388515420812319	3.64758744235389	4.24262414196876	1.82623143554642	3
EE	−0.778629681150842	−0.639677016485367	−2.4513866186275	0.82167941262075	−0.60185821179466	−0.425857241358859	−1.49924168604623	2
IE	−0.768402085340366	−0.488085578801067	0.427154514552075	−0.835625586311843	−0.487001876548109	−0.398636366711372	0.126221560124797	1
GR	−0.491619991270465	−0.298922361044405	0.44821270291525	−0.195100725383009	−0.301199728724859	−0.347464163812605	0.318655882143765	1
ES	0.763250412369585	1.46862528469506	0.724233472965901	−0.305088160881123	0.824073890350863	−0.00087196955799165	0.931325156031182	4
FR	2.50467937181058	1.33910976612588	−0.514803158467373	−0.400005402719011	1.17836397500233	2.17545216570113	0.939299911718454	4
HR	−0.616893128786969	−0.551261051712701	−0.124026583444065	0.536677904891724	−0.60879478144984	−0.422341845349915	0.000705840177289786	2
IT	1.60948584425953	1.39031800135415	0.838762845805621	−0.321324004879709	1.37404582412375	0.328282643916853	1.27527983610833	4
CY	−0.83464853801333	−0.651260959492517	1.5325961875523	−0.684424085278857	−0.669039660548863	−0.426245024768642	−1.49577440096481	1
LV	−0.642917985039706	−0.597485384978833	−0.679283459833077	1.57818648221641	−0.661684613229313	−0.421954061940132	−1.4850258172124	2
LT	−0.714657786223858	−0.604424396366291	0.736098516731819	0.28647938583659	−0.636227564664188	−0.412715692471781	0.0430067181706485	1
LU	−0.842916333493235	−0.601316226335088	1.63784184294159	−1.24668385206066	−0.653127107834861	−0.424508870286935	−1.54605003464544	1
HU	−0.45852074243525	−0.5829640314363	0.486434446955077	−0.783171321085642	−0.432962743032892	−0.396223492161614	0.0294843063530994	1
MT	−0.872377298068678	−0.656997008461662	1.7303620124598	−1.12670512794803	−0.698928460148043	−0.426234886640281	−1.54847713420244	1
NL	−0.426030826141442	−0.222016206830671	0.260817469696284	−1.10339212118083	0.231102167090981	0.0598351430636664	1.01211289842833	1
AT	0.0579721497146254	0.0885371034406743	0.578048887941537	0.966303315315847	−0.377481010574968	−0.267481934645869	0.732649720865653	2
PL	0.584432739213389	−0.274639828846814	−0.54999071192584	−0.820638653390072	1.36049664216138	−0.4099251726406	0.161934596463452	4
PT	−0.217230881247281	−0.145377993214531	0.674101398733568	0.715938274783805	−0.41511987138151	−0.390378861161883	0.263179320840999	2
RO	−0.00563881762273172	−0.247490398741466	−1.29481657001002	0.188981061106619	−0.242548511748543	−0.398649039371823	0.098483279473414	2
SI	−0.733343055788078	−0.601584684049909	−0.308976349627306	−0.00385080915351085	−0.622648508718254	−0.393721908988702	−0.00588200147741362	2
SK	−0.597563418519977	−0.542296455209243	0.489061059697151	−0.426815360501292	−0.530987991281611	−0.418033140796774	−1.51553792592892	1
FI	0.663087887124986	−0.376708131661655	−0.76401436397824	1.75353359740114	−0.45340374414877	−0.259744008174847	0.275314818625979	2
SE	1.00005715748626	0.434020869798532	−1.30056794618663	2.8617340262277	−0.488097900997391	−0.0507186121736458	0.318309153635622	2
UK	0.534624535709814	1.06994079349547	−1.09193337889814	−0.806317806375934	1.54207198415354	1.06795035095819	1.54711498649188	4
ean 1	−0.644185321017729	−0.492485160458606	0.855075016662429	−0.712258150144125	−0.436919286070649	−0.348297011057406	−0.596707379351867	1
ean 2	−0.205469398752465	−0.326460709475809	−0.69572243268433	0.847039245874952	−0.463120574786605	−0.326711837481024	−0.059509344070087	2
ean 3	2.91101309184397	3.84902610147203	0.391649956107496	−0.388515420812319	3.64758744235389	4.24262414196876	1.82623143554642	3
ean 4	1.19929458067258	0.998670803364749	−0.118746186103966	−0.53067480564917	1.25581046315837	0.632177603675517	0.970990897362659	4