An Integrated Assessment of Energy Technology Dependence in the EU

Master Thesis Report

Perla Carolina Torres Vega
Student Number 5662214
p.c.torresvega@students.uu.nl

Sustainable Development; track Energy and Materials
Supervision by Dr Robert Harmsen
Supervision Trinomics by Onne Hoogland
ECTS 45
February 2017 – September 2017

Preface

This research was carried out as part of the master thesis of the programme Sustainable Development track Energy and Materials, at Utrecht University. It was carried out during six months at Trinomics, an economic policy consultancy firm specialized in topics related to energy, environment and climate change. Nevertheless, the conclusions of this research are my own, and they do not necessarily reflect those of Trinomics.

A number of people have contributed to this thesis. First, I would like to thank Dr. Robert Harmsen for his valuable guidance and support during the research process. Second, I would like to thank Onne Hoogland for his continuous interest in the topic, and the fruitful discussions that led to the proposed methodology used in the study. Finally, to Antoine and Marcela, for their support and soothing words that ultimately allowed the termination of the report.

This research would not have been possible without the support of an academic grant provided by Consejo Nacional de Ciencia y Tecnología (CONACYT).

Perla Carolina Torres Vega
August 2017

Summary

Renewable energy sources (RES) are considered to have a positive impact in European energy security by reducing its energy dependence. Typically, RES are portrayed as unlimited and locally available, and dependency-free in energy security indicators. However, being part of Global Value Chains (GV), energy technologies might present dependencies on foreign actors or regions. This research parts from the idea that energy technology dependence should also be considered when evaluating energy security. Previous studies have provided a methodology to assess the risk of supply bottlenecks on selected value chains, however they are focused on a specific activity within the value chain, or they do not offer a systematic approach that can be applied to other energy technologies. The objective of this research is to overcome these problems by outlining a methodology to identify and assess the risk of dependence along an energy technology's value chain. The question asked is *How can the risk of energy technology dependence be assessed in an integrated way, in the context of the EU's energy security?* Drawing from studies in energy security, GVC and Innovation Studies, this research introduces a conceptual framework to assess energy technology dependence by proposing three dimensions of dependence: product supply, tacit knowledge and codified knowledge. Based on desk research and a case study on the assessment of solar photovoltaics (PV) assessment in Europe, this study presents a value chain analysis with indicators on imports reliance, the EU's share of global market share and concentration of supply. The case study shows that Europe has relevant dependencies on the product supply dependence, and no major dependencies in the dimensions of tacit knowledge, nor the codified knowledge. Specifically, it has a high dependence in cells and module manufacturing and a medium dependence on two critical materials (Indium and Gallium). The main limitations of the methodology used were the lack of details about the physical locations of the production activities, inconclusive information on certain activities and the possibility of missing data if the methodology is used on incomplete or undefined value chains. The methodology could be improved by adding guided interviews to industry experts to the analysis. The integrated assessment of energy technology dependence in the EU confirmed the existence of dependencies along low-carbon energy technologies. Consequently, these risks should be included in the evaluation of the EU's energy security long-term strategies.

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1 Introduction

1.1 Background

The first oil crisis in 1973 initiated a growing concern about the vulnerability of the energy supply in the European Union (EU). Moreover, the interruptions in the European gas supplies caused by the 2009 Ukraine-Russia gas conflict has put energy security in the top of the discussions of the EU and its member states' energy policies (Umbach, 2010; IEA, 2017). The term "security of energy supply" or in its short version "energy security" is often labelled as difficult to define (Löschel et al., 2010). Perhaps the most common definition for energy security nowadays comes from the International Energy Agency (IEA), as "the uninterrupted availability of energy sources at an affordable price" (IEA, 2014, p. 13). The IEA also proposes a short-term and a long-term approach of energy security; the short-term approach focuses on the system's ability to meet the region's energy needs under drastic supply-demand imbalances. Whereas long-term energy security strives for the alignment of opportune investments on energy supply and economic developments and environmental needs.

Nowadays, the EU short-term strategies are mainly comprised by policy measures to prevent disruptions in energy supply by holding minimum emergency stocks of oil enough to cover for 90 days of net imports or 61 days of consumption (Council Directive 2009/119/EC) or less days in the case of gas (Regulation 994/2010). Additionally, as part of its long-term approach, the EU has a European Energy Security Strategy (2014), a plan to reduce its energy dependence by, amongst other actions, increasing energy production and developing energy technologies. These new energy technologies are needed to *"further reduce primary energy demand, diversify and consolidate supply options, and to optimise energy network infrastructure to fully benefit from this diversification"* (European Commission, 2014, p.14). The security strategy reinforces the EU's Renewable energy target set in the Renewable Energy Directive (2009) to achieve 20% share of energy from renewable sources in the EU's final consumption in 2020 (Directive 2009/28/EC, p. 28).

Delimiting all the factors comprising energy security, and how to fully assess has been widely disputed amongst scholars. Nonetheless, there is a consensus around the fact that energy dependency can be considered the most important indicator of energy security, since it is a direct threat to the energy security, and consequently to the country's' security (Radovanović et al., 2016). A recurring factor in the efforts to reduce energy dependence, is the focus on fossil fuels as the only element facing risk of external dependence. Common measures to reduce energy dependence include stocking enough commodities (e.g. oil, gas) to generate energy, while reducing the amount needed through energy efficiency. In this posture, only the "fuel" powering the energy sources are considered, and except for biomass, the renewable energy (RES) "fuels" (e.g. sunlight, wind, water) are portrayed as free, unlimited and locally available, with virtually no external dependence at all in energy security indicators (Löschel et al., 2010; Radovanović et al., 2016; Narula et al., 2017).

However, low-carbon energy technologies such as RES, energy storage linked to them and Carbon Capture and Storage (CCS) are part of global value chains (GVC). Therefore, their activities, as well as resources might be outsourced in countries outside the EU. GVC analysis is a suitable framework to identify energy technology dependencies since it goes beyond the Supply Chain (SC) and includes all the activities involved in a product since its conception to its end use, often covering wide geographic areas (Frederic, 2016).

1.2 Problem description

1.2.1 Energy technology dependence

The study of dependency in low-carbon energy technologies is rather recent, however there is already extensive literature focusing on the potential risks or bottlenecks of their deployment. To name a few, the European Commission's Joint Research Centre (JRC) conducted several studies showing potential bottlenecks on energy-technologies and assessing the EU resilience to supply of raw materials (Moss et al.,2013; Blagoeva et al., 2016). These studies communicate a growing concern regarding the availability of critical materials for low-carbon energy technologies, and special interest on early detection of potential interruptions for meeting European long-term demand. The concern over this risk is shared by the WWF International, which has stressed the latent risk of resource depletion (WWF, 2014).

Lehner et al. (2012) took an approach similar to GVC analysis technologies to identify risks that include not only the raw materials, but the rest of the activities involved in the production and installation of the energy technologies such as patents, intellectual ownership and skilled labour. However, these studies tend to focus only on one or two technologies (e.g. solar PV and wind energy). More importantly, the risk of dependence is discussed but it is not the focus, and there is not a shared methodology across energy technologies to evaluate it.

The objective of this research is to overcome these problems by outlining a methodology to identify and assess the risk of dependence along an energy technology's value chain. Additionally, such methodology should be replicable amongst different low-carbon energy technologies.

1.2.2 Research question

As based on the problem description, the main research question to be answered is:

How can the risk of energy technology dependence be assessed in an integrated way, in the context of the EU's energy security?

To answer this research question, this report is structured as follows. In chapter 2 a literature review is provided about energy security and energy dependence, the Global Value Chain framework and studies on Innovation Systems regarding the topic of energy technology dependence. The last section in this chapter comprises the conceptual framework proposed to assess energy technology dependence, including the final definition of energy technology dependency, the dimensions of dependency, and key literature findings on the factors influencing each dimension. Chapter 3 contains the explanation of the methodological framework used: the set of indicators to identify and evaluate energy technology dependence, and the data collection for the case study. The proposed method to assess energy technology dependence in Europe is tested on a case study on Photovoltaics (PV) technology in chapter 4. Chapter 5 comprises the overall discussion of the lessons learned regarding the state of European dependence in the PV value chain, the limitations of the research method, and provides insights for policy. Finally, chapter 6 contains the conclusion of the research, and recommendations for future research.

2 Theoretical Framework

2.1 Theory

This section gives a synthesis of the scientific literature about energy security and energy dependence, the Global Value Chain framework and Innovation Systems regarding energy technology dependence. Drawn from the overview of these studies, a conceptual framework to assess Energy Technology Dependence is introduced and explained.

2.1.1 Energy security and energy dependence

The idea of long-term security of energy supply has been widely discussed and studied in the policy and scholarly literature, yet there is a lack of consensus in the definition of energy security. The debate is mainly caused due to the diversity of risk types involved (Löschel et al., 2010; García-Gusano et al., 2017). Hughes (2009) presented the *"Four R's"* methodology to explain energy security and potential improvements to public in general. The steps consist in review (understanding the problem), reduce (using less energy), replace (shifting to secure sources), and restrict (limiting new demand to secure sources). Around the same time Kruyt et al. (2009), based on a report from the Asia Pacific Research Centre, underwent a literature review and classified the main elements in the security of energy supply in a *"Four A's"* model: Availability, Accessibility, Affordability and Acceptability. Elements related to geological existence are grouped under Availability, geopolitical elements under Accessibility, economical elements under Affordability and finally, Acceptability include the environmental and societal elements. The interconnections of these elements englobe the geopolitical aspects pertinent to energy dependence, as well as the economic, technical and environmental aspects (Kruyt et al., 2009). Sovacool and Mukherjee (2011) further developed this conceptual framework by interviewing experts and grouping in five dimensions the components of energy security. The key dimensions identified, their values and components are summarized in table 2-1. Moreover, the study grouped 320 simple indicators and 52 complex indicators into the 20 components.

Regardless the perspective with which scholars addressed energy security; either economic or policy oriented, there is complete agreement that energy dependency is a direct threat to energy security of supply and therefore it is the most important indicator of energy security (Radovanović et al., 2016). Several studies measuring and monitoring energy security centre their metrics on diversity and import dependence (Le Coq and Paltseva, 2009; Löschel et al., 2010; Frondel and Schmidt, 2014). Traditionally, these studies include only fossil-fuels imports (oil, gas, coal) in their assessment, while studies in new trends include electricity imports and fuels for low-carbon energy options (e.g. biomass, uranium). Sovacool and Mukherjee's (2011) indicators under the categories of dependence and diversification already include many metrics related to low-carbon energy options.

Amongst the latest initiatives for developing energy security index include the incorporation of low-carbon energy options in the energy system (Narula et al, 2017) or a focus in renewable power generation (García-Gusano et al., 2017). Narula et al (2017) distinguished between domestic supply and imports when assessing the energy supply subsystems. Under this distinction, renewable primary energy sources such as hydro, solar and wind as well as nuclear are classified as domestic in nature, therefore they are not assessed on their import dependence, but for their potential to supply electricity. On the other hand, García-Gusano et al. (2017) developed an energy security index for policy-makers with the focus on renewable power generation. The Renewable Energy Security Index (RESI) intends to analyse energy security through an integrated and practical indicator defined as the sum of the product of electricity demand satisfaction and the national renewability factor for every energy technology. RESI measures the *availability* dimension of energy technologies by its availability rate of the transmission grid. Both studies are based on techno-economic analysis of energy technologies and the only dependences mentioned are about fuel (biomass, uranium).

Table 2-1 Energy security dimensions, values, and components.

Dimension	Underlying values	Components
Availability	Self-sufficiency, resource availability, security of supply, independence, imports, variety, balance, disparity.	• Security of supply and production • Dependency • Diversification
Affordability	Cost, stability, predictability, equity, justice, reducing energy poverty.	• Price stability • Access and equity • Decentralization • Affordability
Technology Development and Efficiency	Investment, employment, technology development and diffusion, energy efficiency, stockholding, safety and quality	• Innovation and research • Safety and reliability • Resilience • Efficiency and energy intensity • Investment and employment
Environmental and Social Sustainability	Stewardship, aesthetics, natural habitat conservation, water quality and availability, human health, climate change mitigation, climate change adaptation.	• Land use • Water • Climate change • Pollution
Regulation and Governance	Transparency, accountability, legitimacy, integrity, stability, resource curse, geopolitics, free trade, competition, profitability, interconnectedness, security of demand, exports.	• Governance • Trade and regional Interconnectivity • Competition and markets • Knowledge and access to information

Source: Adapted from Sovacool and Mukherjee (2011).

2.1.2 Global Value Chain

Global Value Chain basic concepts

A Value Chain (VC) describes the full range of *activities* that are required to bring a product (a good or a service) from its conception to the different phases of production (involving a combination of physical transformation and the input of various producer services), delivery to final consumers, and final disposal after use (Kaplinski and Morris, 2000, p.4). Generally, a VC can be presented in the following sequence: (1) product (service) design, (2) supply with input material, (3) production, (4) marketing, (5) distribution, (6) post-sales services to consumers, and (7) disposal (or recycling) after use, the steps in the sequence are also called *"functions"*, *"core functions"* or *"core value chain"* (Todeva and Rakhmatullin, 2016; Nutz and Sievers, 2015).

In this sequence, production itself is only one of many value-added links therefore it is important to mention that a VC differentiates from a Supply Chain (SC) since the latter explains a firm's relationship with suppliers and customers to deliver their products or services at lower cost. Hence, the VC includes the SC, but also considers the value created during the numerous backward and forward (or upstream and downstream) interactions between the entities as a source of competitive advantage (Hernández and Pedersen, 2017). These activities can be carried out by one or more firms, at a regional or a global scale; the latter is referred to as a Global Value Chain (GVC) (Gereffi and Fernandez-Stark, 2011).

Global Value Chain framework

The GVC framework was developed during the early 2000s to integrate different aspects of firms' organization frameworks such as commodity chains, supply chains, value networks and clusters (Frederic, 2016). As summarized by the OECD (2012), GVC are useful for policymakers to understand the following characteristics of the world economy:

- The interconnections of economies, particularly how the export competitiveness relies on the efficient sourcing of inputs and the access to final producers and consumers abroad.
- The specialisation of countries in tasks and functions of business, rather than specific products, since nowadays countries compete on economic roles within the value chain.
- The functions of networks, global buyers and global suppliers, since GVC analysis helps identify the entities that control and coordinate activities in production networks.

The GVC framework explores four basic dimensions: (1) an input-output structure, describing the transformation process from raw materials into final products; (2) a geographic scope; (3) a governance structure, that explains how the value chain is controlled; (4) and an institutional context in which the industry VC is embedded (Gereffi and Fernandez-Stark, 2011). The approach translates these four dimensions in two steps: VC mapping and analysis.

1. VC mapping is *"the process of identifying the geography and activities of stakeholders involved from taking a good or service from raw material to production and then to the consumer"* (Frederic, 2016, n.a.). A value chain map is a visual representation of the value chain system, it combines a map of the chain links (also called functions) and a map of supporting actors within the VC (GTZ, 2007).
2. VC analysis aims to identify the functions of external factors such as governance and institutions, who influence the location, development and competitiveness of a product or service. This step starts by quantifying and describing the VC in detail, adding numbers to the basic value chain map (e.g. the volume of produce or the market shares).

Both steps of the GVC methodology can "zoom-in" into any relevant aspect that wishes to be further understood. Therefore, the resulting value chain maps can vary greatly both in content and style depending on the scale of the analysis and the aspect of the chain structure they show (GTZ, 2007). One example of this variation is a comparison between Frederic (2014) and Nutz and Sievers (2015) conceptualisation and visual representation of value chains.

Frederic (2014) presented a value chain reference model with which the four parts of any industry's value chain can be represented visually. These four parts include value-adding activities, the SC, end-use markets, and the supporting environment.

On the other hand, the International Labour Organisation (ILO) published a "rough guide to Value Chain development" – partly based on a 2009 ILO guide on the "Value Chain Development for Decent Work" by Herr and Muzira (2009). In this new guide, Nutz and Sievers (2015) suggested a framework to represent how a value chain is embedded within a wider market system. The players in the market system can be in the "core" market (the transactions from producer to consumer that constitute the value chain, otherwise referred to as core functions), or in the wider “system” consisting of supporting functions and rules.

The manuals of value chain analysis for practitioners and researchers typically suggest that an initial step to value chain mapping can be the identification of the core transactions (or core functions) through a simple flow chart (i.e. the simple process from design/raw material to the end customer). Moreover, through this flow chart the flow of products (supplies and services), finance, information, and knowledge throughout the chain should be identified and explained (e.g. Kalpinski and Morris, 2000; GTZ, 2007; Herr and Muzira, 2009; Gereffi and Fernandez-Stark, 2011; UNIDO, 2011; Nutz and Sievers, 2015).

2.1.3 Innovation Systems

Background of Innovation Systems

Innovation is crucial for addressing most challenges related to energy security, since innovation in energy systems determines which systems are available, how efficiently energy services can be provided, at what costs, and with which associated externalities (Gallagher et al., 2012, p.139). Innovation in energy technologies have a direct impact on social and environmental outcomes, since energy technologies are the very technologies that *help exploit existing and new sources of energy (extraction and supply technologies), convert these to readily usable forms of energy (conversion technologies), and use these forms of energy to satisfy human and economic needs (end-use technologies)* (Sagar, 2004, p.27).

The innovation systems (IS) approach has been established as a conceptual basis for the study of the actors, networks and institutions that influence innovation processes. IS was developed as a policy concept in the context of discussions over industrial policy in Europe, in which a range of system approaches emerged, including national innovation systems (NIS) (Freman,1987; Freeman & Lundvall, 1988; Lundvall, 1992, 2007), sectoral innovation systems (SIS) (Brechi and Malerba, 1997; Malerba, 2004), technological innovation systems (TISs) (Carlsson and Stankiewicz,1991) and regional innovation systems (RISs) (Cooke, 1996). Even though these approaches vary in system boundaries, they share many features, particularly, they part from the notion that the innovation and diffusion process is both an individual and collective act (Jacobsson and Johnson, 2000; Jacobsson & Bergek, 2011).

From the range of IS approaches, the TIS approach is the most widely used by scholars to study the emergence and diffusion of low carbon energy technologies (e.g. Negro et al., 2008; Suurs et al., 2010; Huang et al., 2016, Andersson et al.,2017). A technological innovation system can be defined as a dynamic network of actors, institutions (rules) and material artefacts interacting in a specific technological field and contributing to the generation, diffusion, and utilization of a new technology or product (Carlsson & Stankiewicz, 1991; Hekkert et al., 2007; Markard & Truffler 2008). The aim of TIS analysis is threefold, (1) to understand the complexity of emergence and growth of new industries, (2) to identify system failures (also labelled as systemic problems, system weaknesses, and blocking mechanisms), and based on these, (3) to derive implications for policymakers and other actors to remedy them (Bergek et al.,2008; Wieczorek and Hekkert, 2012, Bergek et al., 2015). The “functions approach” was developed to handle this complexity by broadening the traditional analysis of the structure of the IS (the actors, institutions, interactions and infrastructures), and include a functional analysis focused on the key processes that can indicate if a TIS is functioning well, and measure the performance of it (Hekkert et al., 2007; Bergek et al., 2008; Wieczorek and Hekkert, 2012). The proposed seven functions of innovation systems are: entrepreneurial activities, knowledge development, knowledge diffusion, guidance of the search, market formation, resources mobilization and creation of legitimacy (Hekkert et al., 2007). Bergek et al. (2008) suggest a scheme of analysis in which mapping can be done through a historical event analysis, and furthermore, a comparison of different TIS can be used to detect patterns that can enhance the innovation process, or possible system failures.

More recently, in the Global Energy Assessment (GEA) of 2012 the term energy technology innovation systems (ETIS) was used to englobe the IS approach applied specifically to the energy system. The ETIS approach is largely based on concepts and metrics existing in the TIS literature, primarily the seven functions approach mentioned above, with the aim to integrate all the components of energy technology innovation systems, in terms of innovations, mechanisms of change and supporting policies, and energy technologies (supply and end-use), as well as in terms of geographical and actor network coverage (Grubler et al., 2012, p.1677). After the publication of the GEA 2012, some scholars have followed up the conceptualisation of ETIS (Gallagher et al., 2012; Grubler & Wilson, 2014) and provided examples of empirical case studies on energy technologies (e.g.; Wilson et al., 2012; Winskel et al.,2014;).

Knowledge and Learning

Amongst the set of functions in the IS approach, knowledge development and diffusion are normally placed at the core of an innovation system, since it is concerned with the knowledge base of the TIS and its evolution (Jacobsson & Bergek, 2011). After all, innovation deals with the digestion and conversion of *information* from diverse sources into useful *knowled*ge about designing, manufacturing and selling new products and processes (Freeman, 1991). What differentiates knowledge from information, is that knowledge development requires social interaction, observation and communication for its transmission (Audretsch & Feldman, 2004). Therefore, there is copious relevant literature of IS focused on the understanding of the types of knowledge and the (technological) learning mechanisms in the energy technology innovation systems (e.g. Lundvall and Johnson, 1994; Audretsch & Feldman, 2004; Jensen et al., 2007).

Lundvall and Johnson (1994) suggested a categorization of knowledge into four different groups, that can be defined both at an individual and at an organization level. The proposed categories are: “know-what”, “know-why”, “know-who” (when and where) and “know-how”. “Know-what” refers to knowledge about facts, “know-why” refers to knowledge about principles and laws of motion in nature, in the human mind and in society, “know-how” refers to skills (or the ability to do something), “know-who” involves information about who knows what and who knows what to do, and the ability to cooperate and communicate with different kinds of people and experts (Lundvall & Johnson, 1994; Jensen et al., 2007). Lundvall and Johnson (1994) also argue that the first two categories of knowledge; “know-what” and “know-why”, share features that differ greatly from the last two categories. The first two are backed up heavily by data and information, and, while these types of knowledge are broadly published, it can also be privatized (e.g. through property rights). Contrastingly, the latter two; “know-who” and “know-how” differ from them, since they are difficult to be translated into codes that are understandable for others (codified).

Moreover, the process by which knowledge evolves and spreads through the economy involves a change in nature between tacit and codified forms (Cowan & Foray, 1997, p.595). From the previous categorisation explained above, tacit knowledge is linked to the "*know-how*" and the "*know-who*", the knowledge and embodied skill that is difficult to formalise and communicate, is highly personal, and might not travel easily beyond the context in which it was generated (Audretsch & Feldman, 2004; Lena et al., 2017). Since tacit knowledge is rooted in people's skills and accumulation of experience, the mobilisation of people is a useful mechanism for transferring this type of knowledge (Freeman, 1991; Jensen et al., 2007). It is important to remark that tacit knowledge (human) resources not only refer to production or installation workers in the downstream of the value chain, but also in managers or scientist's use of skills and personnel (Johnson et al., 2002; Jensen et al, 2007).

Over time, some tacit knowledge can become codified in diverse ways, for example, in written or electronic form (e.g. in the form of instruction manuals, or publications), or it can become embedded in the technology as software, hardware, manufacturing or installing equipment (Cowan & Foray, 1997; Maskell & Malmberg, 1999; Gallagher, 2012, Lena et al., 2017). In the case of technological learning, scientific and technological knowledge can represent codified knowledge. The codification process, more than just a tool to transform knowledge, can become itself a tool for creating new knowledge (Maskell & Malmberg,1999). Therefore, tacit and codified knowledge are complimentary when it comes to the knowledge development and diffusion (Johnson et al., 2002).

Within the functions of the energy technology innovation system, a distinction is made between the learning mechanisms in knowledge development and knowledge diffusion. Knowledge development is associated to learning through the traditional forms of knowledge creation in (e.g. RD&D activities and experimentation), whereas knowledge diffusion occurs through networks from the information transfer between different technology application fields, innovation actors and countries, also known as "knowledge spillovers" (Gallagher et al.,2012, Grubler et al., 2012). Listed examples of spillover mechanisms are imitation, trade, licensing, foreign direct investment, and movement of people (Grubler et al., 2012, p. 1673).

2.2 Literature gap on Energy Technology Dependence

Security of energy supply has been the interest of numerous studies, whereas they focus on providing a definition, a model classifying the dimensions of energy security, or providing indicators to monitor the progress of regions and countries, however, low-carbon energy technology dependences are often neglected from these indicators, or measured only by their techno-economic potential.

Global Value Chain analysis proves to be useful on the study of the supply chain, and the value-added created by the complex interactions between the actors involved in it, on a wider geographical scope. Some studies regarding low-carbon energy technologies have a similar approach to GVC analysis and identified potential bottlenecks in specific energy-technologies (PV and wind). Moss et al. (2013) and Blagoeva et al. (2016) already demonstrated the risk of material dependence for key energy technologies, and found critical materials that could endanger their future deployment. Even though they consider the risks of dependence, there is not one methodology outlined to identify and assess such risks amongst the rest of the technologies' value chain.

This research intends to fill this gap in literature by providing a conceptual framework for energy technology dependence, that includes both the physical and non-physical aspects identified.

2.3 Conceptual framework to assess Energy Technology Dependence

The conceptual framework on energy technology dependence presented in this section builds on the synthesis of literature across global value chain, Innovation Systems (IS), and previous studies attempting to asses some type of energy technology dependence introduced and explained in the section above.

In a report for the IEA RETD, a definition for bottleneck was "*any constraint along the entire physical supply chain (of wind or PV technologies) that could significantly reduce the scale of development, deployment or operation of the technology in the absence of mitigating measures*" (Lehner et al., 2012, p.10). Taking this definition as a starting point, it can be noted that the concept focuses on the physical supply chain, but does not include non-physical aspects present in the energy technologies value chains. As the GVC framework highlights, the supply chain solely cannot describe all the value adding activities that take place in the deployment of a product (or service), and the potential constraints can therefore not be described as solely from a physical nature. As noted by GVC literature, the flow of products, finance, information and knowledge can all present bottlenecks in a value chain, and depending on their severity, they can become a risk for the development of the final product (or service) (e.g. Kalpinski and Morris, 2000; GTZ, 2007; UNIDO,2011).

Even though value chain dependencies are not the focus of the GVC framework, and therefore there is not a systematic analysis to detect them, some of them can be identified along VC studies. To name a few, Gereffi and Fernandez-Stark (2011) mention flows of financial, material and human resources within a chain. Nutz and Sievers (2015) are in line with this initial set, identifying value chain constraints on raw materials, working capital and access to finance, as well as market dependencies (e.g. dependence on a single buyer). Moreover, Todeva and Rakhmatullin (2016) pointed out that it is common practice for firms to use suppliers for raw materials, technology, and services, and managing these is a critical part of the firms' activities.

The existing literature in IS also emphasises the idea that a system-based analysis of innovation requires a focus on the various institutions engaged in the production, diffusion and use of knowledge relevant to technological development, as well as the links and resulting flows of knowledge, technology, financing and other resources (Sagar & Holdren, 2002). The IS approach proves to be useful for the study of energy technology dependence thanks to its focus on the identification of system failures, as well as its extensive literature on the functions of knowledge development and diffusion. The term "technology" in the context of GVC, as used by Todeva and Rakhmatullin (2016) and UNIDO (2011), often refers specifically to the production technologies that are employed in the production process. Whereas from IS literature, it is understood that knowledge can be tacit or codified, in which tacit knowledge is difficult to articulate and share since most of the time they are contained in people's knowledge and skills developed by experience. This study, in line with IS studies, includes the production technologies as one of the elements within the broader category of codified knowledge.

Measuring or monitoring the value-added by manufacturing and extractive industries based on goods (physical resources) is relatively simple, they can be tracked by determining the difference between the cost of the inputs and outputs at each stage of the chain. In contrast, measuring the value-added by offshore services can be complicated since there is a lack of reliable company-level data and statistics for services. To address this problem, Gereffi and Fernandez-Stark (2011) suggest relying on skill levels and work experience – human capital inputs of offshore services- to measure the value of different services in the offshore services value chain. The IS literature supports this idea, pointing out that firms can access tacit knowledge by directly hiring experts and taking over other firms, therefore relying on the labour market, whereas codified knowledge may be bought in the market and be protected by patents and other forms of intellectual property rights (Johnson et al., 2002).

This study aims to identify dependencies in energy technology value chains by merging the findings of both disciplines (GVC and IS), and proposes an initial set of dimensions in which energy technology can present external dependencies grouped as: product supply, tacit knowledge or codified knowledge. The description of each dimension, and its impact in the energy technology dependence is explained below.

Product supply

The flow of products along the VC can be in the form of materials or sub-components, that are added to the initial product in every step of the chain, to transform them into a final product (or service). Dependence in this dimension refers to the capability (or lack of capability) to supply or procure the raw materials needed for the specific energy technology, as well as the subcomponents added in the different steps of the transformation process. This aspect deals with the availability of the resource within the EU, or the EU's ability to import them.

Tacit knowledge

Covers aspects of the human resources needed for energy technology deployment. It includes the skilled labour for assembling, installing and maintaining the final product, and the supporting activities that facilitate its deployment. A dependence in this aspect will reflect the need of training, consulting, hiring external labour force or relying completely on an external service provider. These needs can impact the timing of the deployment of a given energy technology.

Codified knowledge

Refers to the capacity of accessing and developing the energy technology codified knowledge within the EU. This capacity is reflected in the Research & Development (R&D) activities in the region, as well as Intellectual Property (I.P.) registered (patents). It also includes the equipment or turn-key production lines for manufacturing and installing the technology. Independence in this dimension offers the freedom to design or redesign the products and adapt them to meet European specifications, finding substitutes of critical materials and their manufacturing process. Dependence on foreign codified knowledge can reduce the European flexibility in order meet demand side needs. Table 2-2 provides a summary of the proposed conceptual framework for the dimensions of energy technology dependence, and their potential impacts on energy (in)dependence.

Using the definition of bottleneck by Lehner et al. (2012) as a basis, and including the GVC perspective, as well as the dimensions identified in this study, a preliminary definition for energy technology dependence could be:

"Any reliance on external actors or external elements along the entire value chain, including product supply, tacit knowledge and codified knowledge, that could significantly reduce the scale of development, deployment or operation of the technology in the EU in the absence of mitigation measures"

Table 2-2 Conceptual framework for assessing the proposed dimensions of Energy Technology Dependence (ETD).

ETD dimensions	Description	Actors	Impact on energy (in)dependence
Product supply	The capability to manufacture or to obtain the physical resources throughout the SC.	Providers of raw materials, sub-components, and the final product.	Influences the availability of the resources within the EU, or the EU's need to import them.
Tacit Knowledge	The human capital with the skills and competences needed for energy technology deployment.	The skilled personnel required for assembling, installing and maintaining the final product. People, organizations and institutions performing the supporting activities in the VC.	Need of training, consulting or hiring external labour force. These needs can cause delays in the deployment of a given energy technology.
Codified Knowledge	The capacity of developing the energy technology within the EU.	Institutions and companies engaged in research and product development, register patents and own I.P. related to the technology. Companies providing the manufacturing or transportation equipment for the production and distribution of energy technologies.	Dependence on foreign codified knowledge can reduce the EU's flexibility to meet current and future demand side needs.

Source: Own elaboration.

3 Research Design

This chapter gives an overview of the research design used in this report, which consists mainly in a combination of desk research, a case study and data collection. It explains the GVC framework used to map the value chain of the technology selected for the case (Solar PV) and the indicators used during the analysis to find European dependencies on its value chain activities. Finally, it outlines the sources used for the data collection, and the assumptions taken during their analysis.

3.1 Research Method

This research was focused on the product supply, tacit knowledge and codified knowledge dependencies to determine the EU's energy technology dependence for the period of 2016-2030. The study was conducted under an exploratory approach since there were no existing theories that provided a format to determine the energy technology dependencies. The approach used a combination of methods based on a literature review, the GVC analysis framework, a case study and data collection to answer the research question.

During the literature review, the concept of energy technology dependence was revised across the study fields of energy security and energy dependence, Global Value Chain and Innovation Systems, to provide examples of historic or current cases that have dealt with the different dimensions of dependence, the factors influencing them and the methods used to assess them. The purpose of this review was threefold: to validate the dimensions proposed by the current study, to understand their potential implications, and to collect metrics used to successfully monitor the dependences in those cases. The research made use of published reports, scientific articles and books covering the topics of GVC, energy technology dependence and supply chain analysis.

Due to the maturity of the supply chain, and the extensive research on its deployment risks, the Solar Photovoltaics energy technology was selected for a case study to test the set of indicators found during the literature review. The case study allowed not only to test the clarity of the conceptual framework, but also to test the practicality of the set of indicators being proposed for the methodology.

As mentioned in the theory chapter, there was not a methodology specifically designed for assessing energy technology dependence. Therefore, this study drew from an adaptation of the GVC framework, with a focus on potential European dependencies. The stages in which the case study was conducted were aligned with the GVC analysis framework, adapted from Frederic (2014):

- First, the Global Value Chain of Solar PV was mapped, identifying the core activities of the PV value chain. Based on these activities, a desk research was conducted to identify the key actors participating in each activity, their country of origin, and when possible, an indication of their market share or capacity share.
- Second, a Value Chain analysis was carried out to determine the level of European dependence in the PV value chain based on the initial set of indicators proposed for each of the ETD dimensions: product supply, tacit knowledge and codified knowledge.

Regarding the availability of raw materials, studies focused on the assessment of bottlenecks for low carbon energy technologies have already identified critical materials in their value chains. This study drew from the findings of Blagoeva et al. (2016), WWF (2014), Moss et al. (2013) and Lehner et al. (2012), and considers only the critical materials identified for PV technology as raw materials dependence. See Appendix A for the details on the analysis.

The activities considered to be relevant for product supply dependence are those related to the manufacturing of products and sub-components of the energy technology, as well as of the critical materials present. The activities linked to tacit knowledge dependence are relative to the certified installers, and the management services contractors for the energy technology. As for codified knowledge, the activities identified are the No. of patents and the No. of publications about the energy technology, the national RD&D budgets for the energy technology (both public and private) and the supply of manufacturing equipment and tools.

The indicators for assessing the overall dependence in each dimension of the energy technology were:

EU's import reliance

Relative to how much is Europe relying on imports in each activity, which can be recorded as high (very reliant, medium (somehow reliant), and low (not reliant). For example, if the sub-component being assessed held the largest market share in the technology mix, then the import reliance was high. Another way it was assessed was if the activity was not reliant in imports due to the nature of this activity, for example the service had to be provided in the local language, or the sub-component had to meet with strict local specification that made it difficult for foreign actors to enter the local market.

EU's global market share (%)

This indicator reflected the EU's participation in the global shares of the supply in each activity. There was not a prescriptive limit for what was a high and a low share for the EU, but 15% was used as a baseline in this analysis. Therefore, if the EU's s share was below 15% it was also considered a low share and contributed to a high risk of dependence.

Concentration of supply

As opposed to diversification, a high concentration of supply implied that there were many suppliers offering a product or service. Nevertheless, the concentration of supply also included the participation of European companies. Therefore, a high concentration lead to a low risk of dependence if it was combined with a medium or high EU's share of global.

The combined scores of the indicators explained above were used to analyse the risk of dependence in each activity. The results were presented in a table listing the activities relevant to the dimension being examined in the first column, a column for each indicator, and the combined score of them in the last column. Table 3-1 shows the template of the results presentation.

Table 3-1 Template of the assessment of risk of dependence based on the indicators proposed.

Indicator / Activity	EU's import reliance	EU's global market share (%)	Concentration of supply	Dimension of energy technology dependence
				High
				Medium
				Low
				N.A.

For the validation of the results, an analysis using trade statistics was conducted, by first comparing the EU's imports and exports of the technology selected for the case study (PV) over time. And later completing the analysis with a closer look at their trade partners and their shares on the EU's imports over time. The results of this analysis were used to validate the findings of the case study, and to evaluate the advantages and disadvantages of the methodology proposed in the current study. The details of the trade statistics analysis can be found in Annex B.

The data collection for the case study is discussed in detail in the following section.

3.2 Data collection

The data for the case study on the assessment of Solar PV dependence in Europe was gathered through an extensive desktop study that made use of up-to date sources such as scientific articles, books, national statistics, newspaper and websites of the industries and organizations within the solar PV industry in Europe. The literature was searched using online search engines like Mendeley, Google Scholar, and Google, using various search strings (e.g. "solar PV value chain" or "solar PV supply chain", or "solar cell suppliers") adding the specification of "Europe" to delimit the search. Scientific journals (e.g. ScienceDirect) as well as industry magazine websites such as PV Magazine and PV-Tech were also consulted to validate the quantitative data.

The mapping of the PV value chain was based largely on previous studies by Hoogland et al. (2017), Jäger-Waldau (2017) and Jäger-Waldau (2016). When available, the regional share of global production of PV products and sub-components was presented, based on reports and peer reviewed articles (e.g. REN 21 report; Jäger-Waldau, 2016).

As a proxy for the country of origin of the companies leading the PV industry, a list of the top 10 companies and their market share for each activity of the value chain was presented. The top 10 companies' rankings on the manufacturing of PV components were based on industry analysis (mainly IHS and Bernreuters Research) and articles from industry magazines such as PV Magazine and PV Tech. The market share is expressed as production, production capacity and/or shipments (either in products or in currency). Data for calculating the companies' production capacity and capacity shares was complemented with individual companies' press releases and estimations from previous studies. The most recent year with complete data available was selected for each case, which in most of the cases date back to 2015 for production figures and 2016 for capacity estimations. Moreover, the sources and specifications relative to each analysed component are made explicit for each table or figure.

The data regarding PV critical materials was largely based in previous assessments of critical materials for low-carbon energy technologies (Blagoeva et al., 2016; WWF,2014; Moss et al., 2013; Lehner et al.,2012). After a detailed analysis on the factors considered by each study (the results of the analysis can be found in Annex A), the materials marked as presenting “high risk” of supply bottlenecks by Moss et al. (2013) were considered for this study. The analysis on PV European dependence draws from the findings of Rabe et al. (2017), which is focused specifically in European dependence on the materials previously selected by Moss et al (2013).

For the number of patents, data regarding the number of applications to the European Patent Office (EPO PATSTAT) was collected from Eurostat on the most recent data available (2013). A single patent can be divided in equal shares between the countries of the applicants. The number of publications per country or region was collected from Web of Knowledge through a word search of “photov* or “solar cell*” in the title, abstract, or topic of the articles in their repository. The records of the country are based on the address submitted by the author(s), hence, one article with several authors might be considered as a publication for several countries. Regarding R&D, the data on estimated public budgets per country on PV RD&D was collected from the OECD iLibrary. The dataset contained data until 2015 for 29 countries (most of which are European), however 2015 was not considered for the analysis due to missing data for many countries during that year.

For the trade statistics analysis of European PV products, data from Eurostat trade statistics was collected for product code 854140, which include “Photosensitive semiconductor devices, including photovoltaic cells whether or not assembled in modules or made up into panels; light emitting diodes” (Eurostat, n.d.). The imports and exports flow were obtained from the dataset DS-045409, which gives EU Trade Since 1988 by HS2, 4, 6 and CN8. The last 10 years were extracted to validate the past trends with the information found in literature.

4 Results

4.1 Introduction into the case study

The analysis in this section provides a summary of the results on the assessment of European technology dependence in Solar PV in terms of product supply, tacit knowledge and codified knowledge. First, the Solar PV technology is described, followed by the current state in terms of the global installed capacity and projections for future installations. Second, it presents the Value Chain Mapping of Solar PV, listing the core activities (from downstream to upstream) and their key players within the global context. Third, a Value Chain Analysis of Solar PV is presented with a special focus on European technology dependence in the context of the EU's energy security.

4.1.1 Technology description

There are two main types of solar PV production technologies today: Crystalline silicon and thin-film cells. Even though silicon still has the largest share of the market, over 90% according to Jäger-Waldau (2016), the desire to reduce the cost of cells led to the research and development of thin-film cells (Andrews & Jelley, 2013).

Crystalline silicon cells

Crystalline silicon (c-Si) cells can be produced either as single crystal (monocrystalline) or polycrystalline (multicrystalline) cells. In the first case, silicon crystal ingots are sawn into thin wafers[1] of ~200-400 µm thick. A cheaper, but less efficient option to reduce the wafers'costs is to use ingots of polycrystalline silicon made from casting or to make polycrystalline silicon in the form of a ribbon (Andrews & Jelley, 2013). For either monocrystalline or polycrystalline modules, polysilicon feedstock is shaped into ingots and then sliced to wafers used for solar cell production. These wafer-based c-Si cells are the initial structure of a PV module, which entails many cells assembled in arrays (Fu et al., 2015).

Thin-film

Thin-film technology makes use of other materials that have a good solar light absorption: GaAs, CdTe, $CuInGaSe_2$ (CIGS) and amorphous hydrogenated silicon (a-Si:H). These films only need to be ~1 µm thick, requiring less material than crystalline silicon cells (Andrews & Jelley, 2013). For thin-film production technology, the semiconducting material is deposited directly on a substrate (glass, plastic or metal), therefore the process is cheaper and less costly. Nevertheless, thin-film technology still has lower efficiency rates when compared to c-Si modules. The challenge for thin-film solar cells is to develop fast deposition of films that do not compromise the film quality. According to a PV Status Report carried out by the JRC, the market share for thin-films modules peaked in 2009, when it reached almost 20% and ever since it has declined to less than 10% today (Jäger-Waldau, 2016). See figure 4-1 for a comparison of module costs between the two technologies.

[1] Wafers are thin slices of semiconductor material.

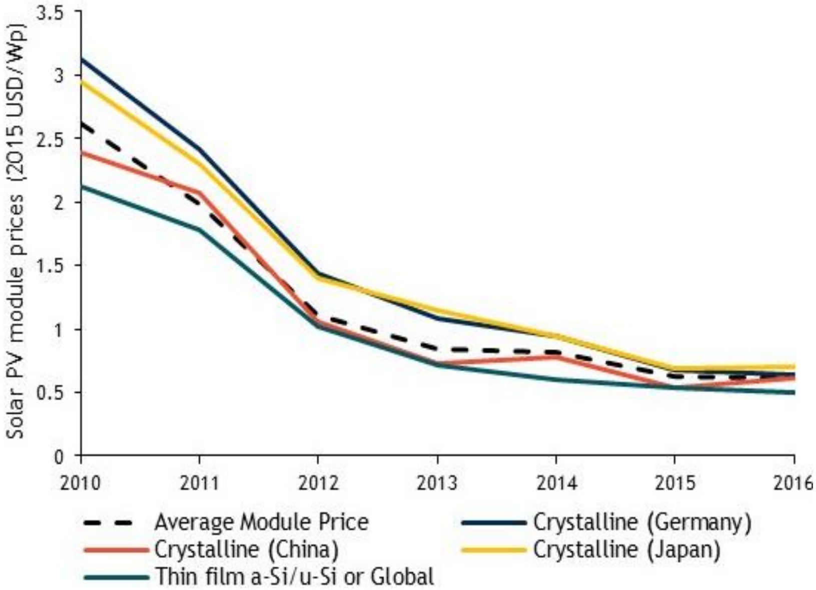

Figure 4-1 Overview of Solar PV module prices from 2010-2016.

Source: Own elaboration based on data from IRENA (2017)[2].

4.1.2 Global installed capacity

2016 closed with more than 70 GW of additional PV capacity installed worldwide, almost double the 2015 additions and raising the global installed capacity to almost 300 GW (IRENA, 2017). The last ten years have seen a shift in the regions dominating the PV market in terms of their annual installed capacity (see figure 4-2). From 2006 to 2012 the largest market was in Europe (e.g. in 2012 70% of the new installations in the world were in Europe). The European market slowed down its demand of new PV after that period, nevertheless, in 2016 it reached a milestone becoming the first region to pass 100 GW installed, more than 30 times its size in 2006 (SolarPower Europe,2016; IRENA, 2017).

The largest markets now reside in Asia, which has steadily increased its capacity since 2012, growing by a factor of ~7 from 16.5 to 139 GW between 2012 and 2016. At a country level, China continues to be the largest market in 2016 with 48% of the additional installed capacity. Followed by USA and Japan, these three countries accounted for three quarters of the new capacity during 2016.

[2] The module prices are expressed in 2015 USD, and the values are the price recorded in January of each year, except for 2016, in which data from December 2015 was used due to availability.

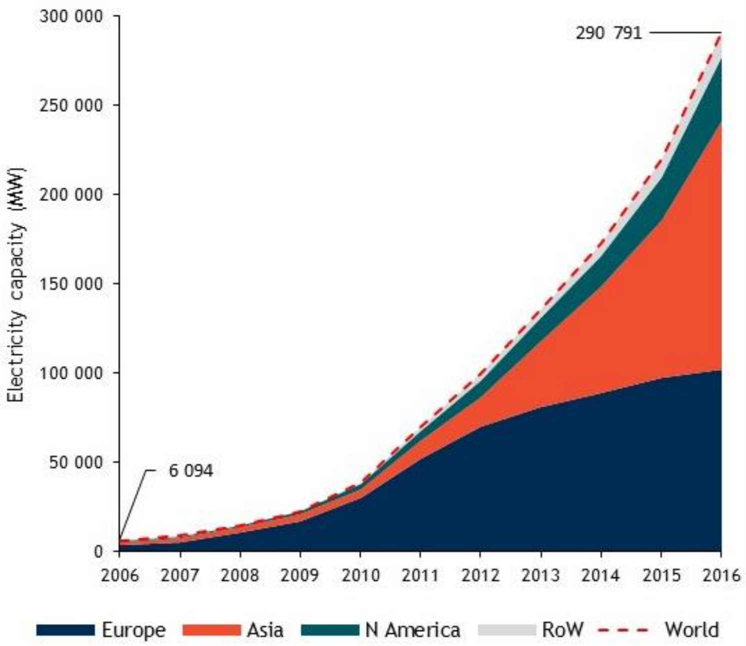

Figure 4-2 Overview of Global solar PV installed capacity from 2006-2016.

Source: Own elaboration based on data from IRENA (2017)[3].

4.1.3 Projections for PV installed capacity

Solar PV capacity is projected to continue growing at a high rate in future years. Industry associations and worldwide energy associations such as IRENA and the IEA, as well as Greenpeace, have developed energy scenarios for the future growth of PV electricity capacity. Figure 4-3 shows the SolarPower Europe Global Market Outlook (2016) IRENA Roadmap 2016, the IEA World Energy Outlook (WEO) 2015, and the Greenpeace study 2015 scenarios.

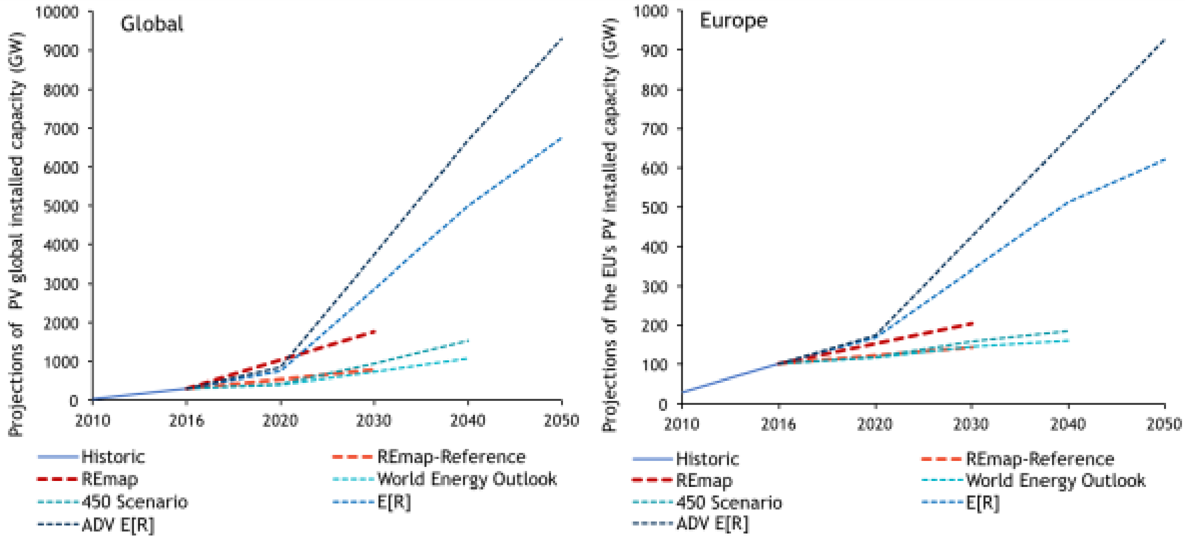

Figure 4-3 Evolution of PV Electricity Capacity (GW) according to different sources.

Source: SolarPower Europe (2016) IRENA (2016), IEA (2015) and Greenpeace (2015).

[3] Europe includes: EU 28 and Albania; Andorra; Belarus; Bosnia Herzegovina; Faroe Islands; FYR Macedonia; Holy See; Iceland; Kosovo; Liechtenstein; Moldova Rep; Monaco; Montenegro; Norway; San Marino; Serbia; Switzerland; Ukraine.

The expected additional capacity varies greatly depending on the assumptions made in each of the scenarios, it ranges between 437 GW in the lowest scenario (IEA's WEO) and 6387 GW in the highest (Greenpeace's ADV[E]R) for the 2016-2030 period. Nevertheless, even the high value scenarios for the IEA projections for an energy trajectory consistent with keeping the global increase in temperature below 2° have fell short compared to the actual deployment of PV (Haegel et al.,2017). Also, with industry forecasts predicting more than 80 GW global PV installations in 2017, even the higher scenarios predicting Terawatt-scale deployments by 2030 are not unlikely to be achieved (GTM Research, 2017; Haegel et al., 2017; Jäger-Waldau, 2016). These projections also show that there are big opportunities for PV systems in the future European market, with projected additions ranging from 44 to 323 GW in the coming 15 years.

4.2 Value Chain Mapping of Solar PV technology

4.2.1 The extended PV value chain

The solar cell and module manufacturing are the central part of a PV value chain, but the extended PV value chain consists of other core activities that range from raw materials to the PV system installation, maintenance and ultimately, its recycling. Figure 4-4 shows a visual representation of the extended PV value chain, including the core activities and supporting actions.

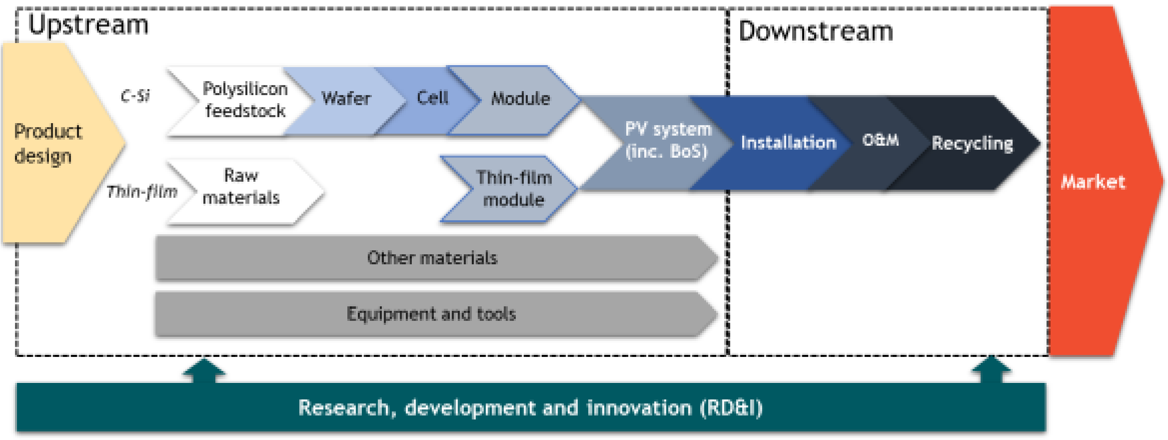

Figure 4-4 The extended PV value chain.

Source: Adapted from Hoogland et al. (2017).

The PV value chain can be divided in upstream and downstream activities. The activities are drawn up mainly from the studies by Hoogland et al. (2017), Jäger-Waldau (2017) and Jäger-Waldau (2016), amongst others. The so-called upstream value chain ranges from the development to the production of the PV technology, it includes raw materials (e.g. polysilicon feedstock), wafer, cell, module and balance of system (BoS) component manufacturing. This part of the VC also extends to the providers of manufacturing equipment and tools necessary for the PV system manufacturing process. The downstream VC is usually associated with service activities such as installation of a PV system, its operation and maintenance, and finally, recycling of the PV system components to recover raw materials for reutilisation. Research, development and innovation (RD&I), is an integral horizontal process that enhances the added value in every step of the value chain in manufacturing and service activities.

4.2.2 *Key players of the PV Global Value Chain*

Global PV market per application type

The end market for Solar PV systems can be divided in distributed or utility-scale installations depending on their size and location. Distributed installations refer to PV systems with relatively small capacity (e.g.<1 megawatt [MW]) and are often integrated into the built environment for self-consumption (REN21, 2017). While utility-scale PV systems have a higher capacity (e.g. >1MW), and they are concentrated in the land of solar parks created by project developers and utilities (Roland Berger, 2015). Globally, new installations in utility-scale PV systems dominate the market, accounting for almost 65% of the share of new installations in 2015, an increase from the previous year in which the shares were almost even: 52% were utility-scale and 48% were distributed (SolarPower Europe, 2016). This increasing trend might be due to a mix of lower costs of economies of scale, feed-in tariff policies, tax incentives and national standards in renewable portfolios (SolarPower Europe, 2016; Jäger-Waldau, 2016). Unlike the rest of the world Europe has a low share of utility-scale capacity, and in 2016 European PV solar parks accounted only for 21% of the world total utility-scale installations (figure 4-5).

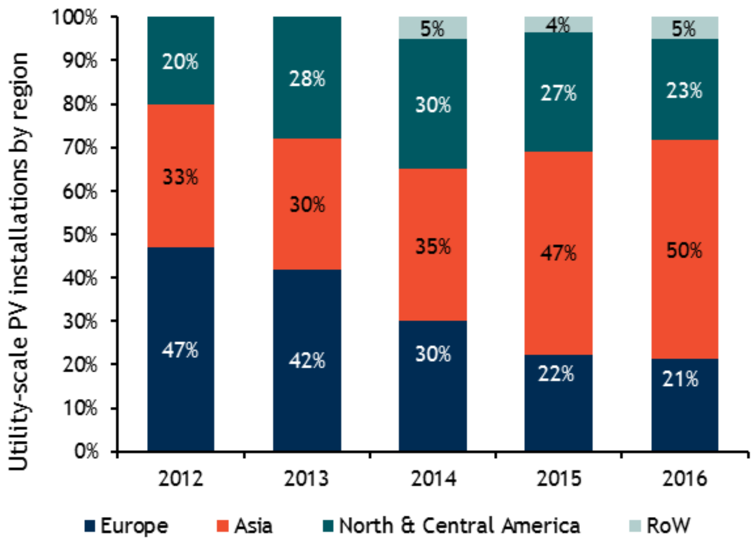

Figure 4-5 Overview of global utility-scale PV installations from 2012-2016.

Source: Roland Berger (2015) and Wiki-Solar (2016) [4].

Projections for 2018 show that utility-scale is expected to represent only 28% of the total PV installations in Europe, the lowest share compared to the other regions in the world (Roland Berger, 2015). This differentiation might be due to lower irradiation factors in Europe, and a limitation of volume and size by implementing tenders in certain European countries (Roland Berger, 2015; SolarPower Europe, 2016). Even if new large-scale projects are announced, the industry expects the European utility-scale market over the coming years to be driven primarily by replacement and repowering of existing sites (PV Magazine, 2016a). In this context, distributed PV systems will dominate the European market in terms of future installations.

[4] The installations consider only the operating utility scale solar power plants of 4MW $_{AC}$ and over.

Installation and O&M

In distributed PV systems, the installation and O&M is a service that can be provided by individual contractors, installation firms, PV manufacturers or suppliers. Moreover, there is limited data regarding the activities of each actor, and the available databases are not exhaustive[5]. Therefore, there is not enough information available to list the names of the key players in these activities. Nevertheless, literature suggests that downstream activities for distributed PV systems seem to be done locally (Neij et al., 2017; Strupeit, 2017). At the European level, it is assumed that countries with large deployments of rooftop PV, such as Germany, have a large pool of available installers of residential PV systems (ibid).

For utility-scale PV systems the downstream activities of the VC are performed mainly by the project developers, the Engineering, Procurement and Construction (EPC) contractors and the O&M contractors. Typically, the project developer is the owner during the initial stages of a project, and appoints the EPC contractor (Wiki-solar, 2017). The EPC contractor is the one responsible for the selecting the suppliers of the PV system components (e.g. modules, inverters) and installing the systems. Very often, after finishing the construction of the power plant, the EPC contractor takes the role of O&M and becomes responsible for its technical operation (ibid). Therefore, for this study EPC contractors are considered the responsible party for the installation and O&M of utility-scale PV systems. Table 4-1 shows the Top 10 EPC contractors ranked by their cumulative installed capacity, as well as their country of origin. The No. 1 contractor is by great length First Solar (US) since it has 3 times more installed capacity than the second ranked company. However, considering only the participation in the Top 10 ranking, European companies have the lead with half of the places (5), followed by the US (4) and finally India with one company.

Table 4-1 Top 10 EPC contractors by cumulative installed capacity of utility-scale power plants in 2016.

Rank	EPC contractor	Country	No. of Projects	Capacity MW_{AC}
1.	First Solar	US	45	3,497
2.	Juwi Solar	Germany	72	980
3.	Swinterton Renewable Energy	US	51	967
4.	Belectric	Germany	90	959
5.	Sterling & Wilson	India	40	839
6.	Enerpac	Germany	92	825
7.	Sun Edison (including Enfinity)	US	46	746
8.	Q-Cells (now Hanwha Q. Cells)	Germany	30	558
9.	SunPower Corporation	US	26	474
10.	Activ Solar	Austria	11	466

Source: Wiki-Solar (2017)[6].

Manufacturing of components

Balance of systems (BoS)

While BoS elements such as cables and switches are elements found in other products, solar inverters are specific to PV technology. Following the largest PV market, the manufacturing of inverters and

[5] For example, a quick search in the company directory of ENF Solar Database gives almost 35 thousand residential solar panel installers; from which almost 11 thousand are located across 15 European countries, whereas in China only 310 are listed (ENF Solar, 2017)

[6] The installations consider only the operating utility scale solar power plants of 4MW_{AC} and over.

module level power electronics (MLPE) is moving to Asia or Asia-based companies (REN 21, 2017). Global PV inverter shipments increased from 59 GW in 2015 to 80 GW in 2016, and 79% of these shipments were supplied by the top 10 vendors (GTM Research, 2017a). Huawei (China) is leading the shipment's ranking, however, SMA Solar (German) lead the global ranking in terms of revenue, accounting for 14% of total revenue shares in 2016 (PV Magazine; 2017a). ABB and Schneider Electric, the other European companies in the top 10 of shipments, have also expanded outside their local region into the Indian solar market.

Table 4-2 Top 10 PV inverter suppliers by global shipments in 2016.

Rank	Company	Country
1.	Huawei	China
2.	Sungrow	China
3.	SMA Solar Technology	Germany
4.	TMEIC	Japan
5.	ABB	Switzerland
6.	Sineng	China
7.	TBEA Sunoasis	China
8.	Schneider Electric	France
9.	General Electric	USA
10.	SolarEdge	Israel

Source: IHS[7].

Cells and modules

Production statistics about PV cells and modules manufacturing are often difficult to separate. For example, a recent analysis on global cell production by Jäger-Waldau (2017) considers only the cells productions for wafer-based cells, and the complete module for thin-films. Based on market reports and expert assessments, the study estimates around 77 GW were produced worldwide during 2016, and expects between 80 to 85 GW in 2017 (see figure 4-6). Nevertheless, other studies providing earlier estimations on production shares separated for cells and for modules, confirm the production of both is highly concentrated in China (Fraunhofer Institute for Solar Energy Systems [ISE], 2016; IEA PVPS, 2015).

[7] Web references: https://www.pv-magazine.com/2017/05/08/sma-holds-firm-as-inverter-revenue-leader-with-huawei-topping-shipment-charts-says-ihs-markit/

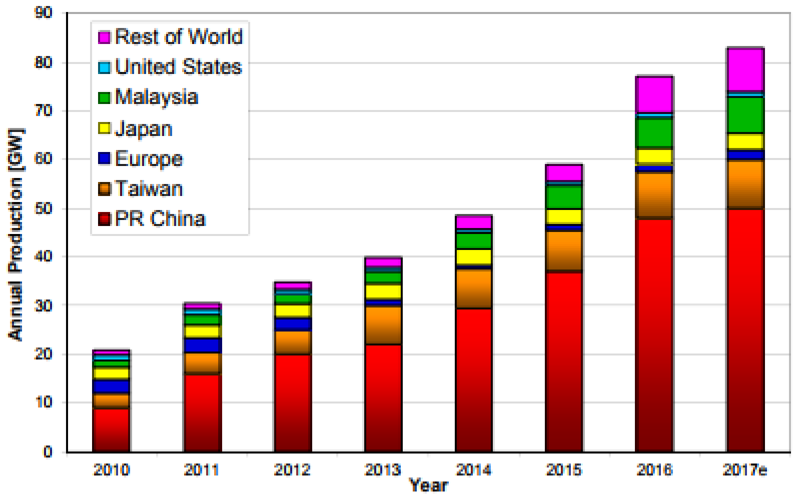

Figure 4-6 World PV Cell/Module Production from 2005 to 2017.

Source: Jäger-Waldau (2017).

In 2016, 90% of the global module production was concentrated in Asia, with China accounting for the largest part of it (figure 4-7). Europe's module production output declined to 2.7 GW, and its global share was reduced to 5% (REN 21, 2017). The USA's capacity grew but compared to the global production its share was stable at 2% (Fraunhofer ISE, 2016; BNEF; 2016).

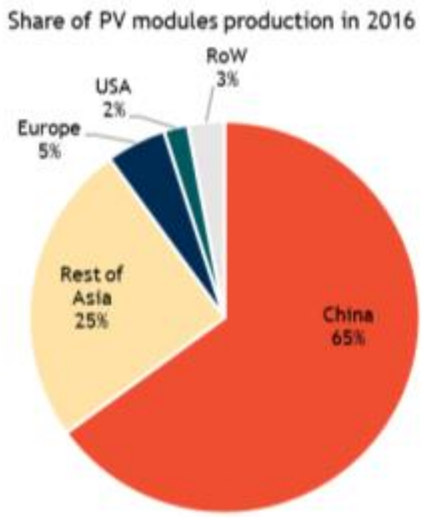

Figure 4-7 Share of PV modules production in 2016.

Source: REN 21 (2017).

Tracking the source of module and cell production might be obscured due to the presence of Original Equipment Manufacturers (OEMs), referring to OEMs selling their products to a company that then sells them under their own brand. In this sense, the top 10 rankings of companies manufacturing modules might show only a partial picture of the industry. Table 4-3 also shows that the shipments of assembled modules reported by the top 10 suppliers in 2016 exceeds their estimated in-house capacity at the end of the year, indicating that inventory might also play a role. This 10 companies represent around 50% of all the shipments during 2016, however, over one third of cells used in the shipped modules of the top 10 were made by OEMs (PV Tech, 2017). Considering First Solar is the only company that is 100% supplied by in-house capacity (a thin-film producer), this share increases for the rest of the companies.

Table 4-3: Top PV module suppliers ranked by their 2015 shipments.

Rank	Company	Country	Module shipments 2016 (MW)	In-house capacity 2016 (MW/year)
1.	JinkoSolar	China	~6,600	6,300
2.	Trina Solar	China	~6,300	5,600
3.	Canadian Solar	Canada	~5,073	5,000
4.	JA Solar	China	~4,900	4,000
5.	Hanwha Q-Cells	South Korea	~4,800	4,800
6.	GCL-Poly Energy Holdings	China	~4,000	6,000
7.	First Solar	USA	2,800	3,140
8.	Yingli Green ("Yingli Solar")	China	2,200	---
9.	Talesun	China	1,503	2,800
10.	Risen Energy	China	---	3,100

Source: Bloomberg New Energy Finance (BNEF) (2016), PV-Tech (2017), PV-Tech (2016) and own elaboration based on annual reports of the companies.

The estimates of 2016 global production capacity are ~80 GW for cells and 83 GW for modules (REN 21, 2017). Industry analysis foresees an increase of overcapacity in these two activities, mixed with a shift to competitive low-price markets like China and emerging markets to further increase the competition amongst cell and module manufacturers (Jäger-Waldau, 2017).

Wafer manufacturing

Contrary to cell and module manufacturing, wafer and polysilicon manufacturing are closing the excess capacity gap, a trend that is expected to continue in coming years (Jäger-Waldau, 2017; PV Magazine, 2017b). Chinese manufacturers also dominate the global market in this activity, both by production and capacity share (see Table XX). Total wafer production in 2015 was estimated to be 61.9 GW, hence the Top 10 manufacturers represent 54% of the total production (IHS, 2016).

Table 4-4: Top 10 wafer manufacturers market and capacity share.

Rank	Company	Country	Production 2015 (MW)	Market share 2015[8] (%)	Capacity 2016 (MW)	Capacity share 2016[9] (%)
1.	GCL-Poly Energy	China	14,968	24%	17,755	36%
2.	Xi'An LONGi Silicon	China	2,757	4%	7,300	15%
3.	LDK Solar	China	2,672	4%	4,800	10%
4.	Jinko Solar	China	2,440	4%	4,500	9%
5.	Yingli Green Energy	China	2,280	4%	2,452	5%
6.	Green Energy Technology	China	1,978	3%	2,625	5%
7.	ReneSola	China	1,826	3%	2,900	6%
8.	Sornid Hi-Tech	China	1,680	3%	3,200	7%
9.	Trina Solar	China	1,675	3%	1,800	4%
10.	Huantai Silicon Sci. & Tech	China	1,314	2%	1,600	3%

Source: based on data from IHS[10].

[8] Total wafer production in 2015 was estimated to be 61.9 GW.
[9] Capacity share considering only the top 10 companies.
[10] Web references:

https://www.pv-magazine.com/magazine-archive/polysilicon-wafer-rankings-2016/

https://www.pv-magazine.com/magazine-archive/2015-poly-and-wafer-rankings_100023726/

Polysilicon feedstock

Polysilicon is the main feedstock material in PV manufacturing. Until 2000, the semiconductor industry consumed over 80% of global polysilicon production, but nowadays the PV industry is the main consumer and uses about ~80% of the polysilicon production (Fu et al.,2015). Supply-demand imbalances and drastic price fluctuations during 2004-2014 have led to overcapacity in polysilicon manufacturing (Fu et al.; PV Magazine, 2017b). Current trends point to a reduction in the oversupply of polysilicon production, with an estimated global production capacity of ~415 metric tonne (MT) to ~ 475 MT in 2016 (Jäger-Waldau, 2016).

The latest news on 2016 polysilicon manufacturers place Wacker Chemie (Germany) in the lead with over 70,000 MT shipped and a capacity of 80,000 MT (Benreuter Research, 2017). According to Bernreuter Research (2017), this change in positions is attributed to a delayed expansion project by GCL- Poly (China) reducing its capacity to 70,000 MT which placed the company in the second place with 69,345 MT produced in 2016. China has become the largest polysilicon market and the German company is currently their only western supplier (PV Magazine, 2017c). South Korean manufacturers (lead by OCI Company) have also benefited from the rise of Chinese demand since 50% of the imports into China came from this country (ibid). Wacker and OCI have a competitive advantage of superior polysilicon quality, which differentiates them from their Chinese counterparts (PV Magazine, 2017b). Conversely, US manufacturers lost market share. Chinese duties of 53% and 57% of US providers seem to be having impact in the country's top manufacturers; Hemlock (US) came on the number four spot in 2016 after leading the world rankings from 1994 to 2011, while REC Silicon, the remaining large US-based company is no longer in the top 10 and SunEdison filed for bankruptcy (SunEdison, 2016).

Table 4-5 shows an overview of the Top 10 polysilicon manufacturers' market share and capacity share based on market analysis. The top two companies' positions and market share have changed since 2015, and the top 5 five producers were responsible for ~55% of market share in 2016 (PV Magazine, 2017b).

Table 4-5: Top 10 polysilicon manufacturers market and capacity share[11].

Rank	Company	Country	Production 2015 (MT)	Market share 2015 (%)	Capacity 2016 (MT)	Capacity share 2016 (%)
1.	GCL-Poly	China	74,358	27%	70,000	20%
2.	Wacker Chemie AG	Germany	51,050	18%	80,000	23%
3.	OCI Company	South Korea	44,209	16%	52,000	15%
4.	Hemlock	US	26,000	9%	36,000	10%
5.	Xinte Energy	China	19,205	7%	26,000	7%
6.	REC Silicon ASA	US	16,882	6%	16,000	5%
7.	Tokuyama	Japan	16,344	6%	23,800	7%
8.	China Silicon	China	10,091	4%	14,250	4%
9.	Daqo New Energy	China	9,019	3%	18,150	5%
10.	SunEdison[12]	US	10,055	4%	13,500	4%

Source: based on data from IHS[13] and Bernreuter Research (2017).

https://technology.ihs.com/571152/ihs-confirms-solar-wafer-supply-shortage-in-2016

[11] Market share and capacity share considering only the top 10 manufacturers on the list.
[12] SunEdison filed for bankruptcy in 2016.
[13] Web references:

Critical materials

Previous studies on critical materials have pointed at five materials that are considered potential bottlenecks in the Global PV value chain (Blagoeva et al., 2016; WWF,2014; Moss et al., 2013; Lehner et al., 2012) (see appendix A for the detailed review of these studies). Studies on the EU's import dependence on critical materials, signal that while c-Si modules do not contain critical materials with potential supply bottlenecks, thin-film production require three: tellurium, indium and gallium (Rabe et al., 2017; Moss et al., 2013). The latter two are sourced mainly from China, which might pose a risk in the future since the Chinese state has already started to implement export duties and quotas on resource materials, including indium (Rabe et al., 2017).

The production of tellurium is somehow diversified, with only 20% of the global production located in China (Rabe et al.,2017; Moss et al., 2013). In the case of indium, its production might seem more diversified – with European facilities in Belgium, Germany, Italy, the Netherlands and the United Kingdom- however, however the production quantities of these are small compared to China's (Rabe et al.,2017). Gallium production is also concentrated in China, with 70% of the global market (ibid.).

Suppliers of manufacturing equipment

The supply of PV manufacturing equipment, characterized by using turn-key production lines, has long been dominated by western countries (Huang et al., 2016). Companies from Germany, along with the US have played a significant role in the industry, however new entrants mainly from Asia are increasing the competition during the last years (Huang et al., 2016; VDMA, 2016). According to the German manufacturing association VDMA (2017), German PV manufacturers still hold over 50% of global market share, most of which is sold to China. The shares of the sales given by country and by type of production (figure 4-8) consist of records from the last quarter of 2016, which are consistent with the sales of previous periods and years (VDMA, 2016).

Figure 4-8 Share of German PV Equipment sales by country in the fourth quarter of 2016.

Source: VDMA (2017)[14].

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https://www.pv-magazine.com/magazine-archive/polysilicon-wafer-rankings-2016/

https://www.pv-magazine.com/magazine-archive/2015-poly-and-wafer-rankings_100023726/

[14] The sum of total shares might not add to 100% due to roundups. The sales records are accounted per revenue, not per number of products.

R&D

R&D activities in the PV value chain can be tracked by the number of patents filed for the technology, the scientific publications on the topic, and the budgets dedicated to RD&D activities. The key actors identified for each are presented below.

Patents

Data from Eurostat on the number of applications to the European Patent Office (EPO PATSTAT) shows that from 2006 to 2009 there was a rapid increase in the number of patent applications for PV energy, peaking in 2010 with 1,756 applications filed (figure 4-9). European countries have been active participators, filling around 50% of the applications during the 2003-2013 period, while Japan and the USA have also been key players with 19% and 18% shares respectively. In the last three years, the total number of patent applications seem to decrease, which could be caused due to delays between the processing of the applications and the reporting.

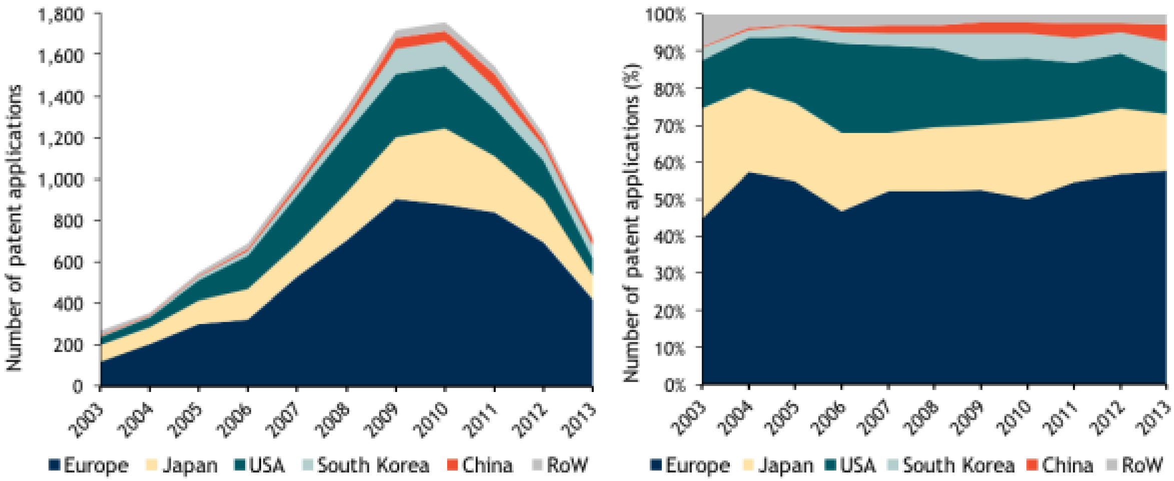

Figure 4-9 Number of patent applications per country/region for the 2003-2013 period (left) and their share of total (right).

Source: data from Eurostat.

Publications

Based on a keyword search in Web of Science, the analysis shows that from 2007 to 2016 the number of global publications about PV has increased more than six times, with Europe and China being the main countries of residence of the authors[15] (figure 4-10). During this period Europe has been leading the publications on the field, and last year accounted for 26% of the publications about PV, while China has steadily increased their share up to 24%. The USA and Canada follow with 14% between both, as well as South Korea, India and Japan with 7%,6% and 4% respectively. An observed trend is also the increased participation of authors from the rest of the world, accounting for 19% in 2016.

[15] The search used keywords photov* OR solar cell* in title or abstract of the publications, and the country recorded is the one filed by each author in the field Address. For papers with multiple authors of different addresses, several countries can be recorded.

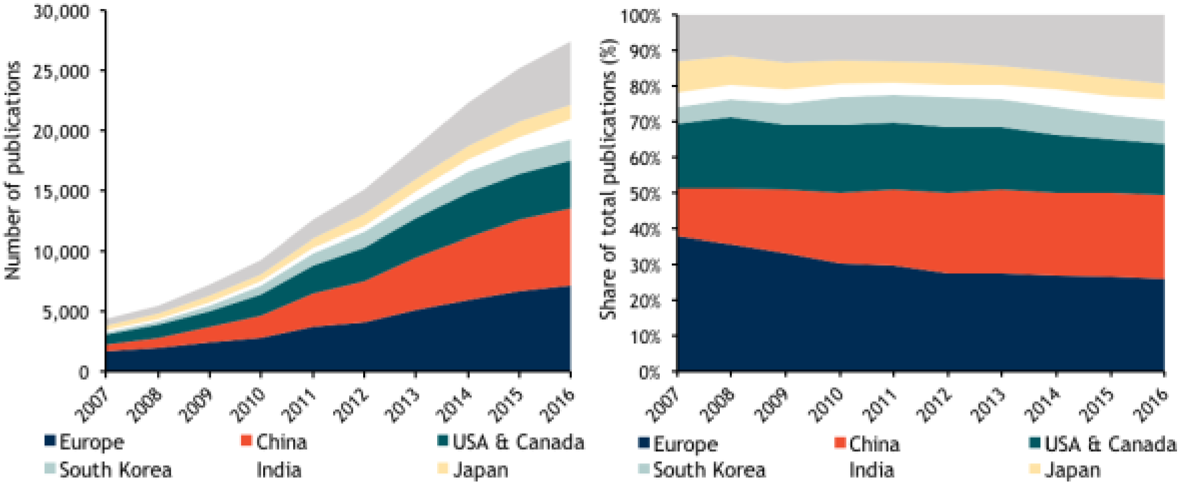

Figure 4-10 Number of publications about PV per country/region on the 2007-2016 period (left) and their share of the total number of publications (right).

Source: data from Web of Science.

RD&D Budgets

There is limited data regarding public or private RD&D Budgets specific for Solar PV. The most extensive source found was the OECD iLibrary, which includes information for only 29 countries (most of which are European) and considers only public budgets (figure 4-11 for the analysis on the available countries). Data on relevant countries identified in the previous sections (e.g. China, India, South Korea) is missing, therefore any analysis on key actors for RD&I Budgets based on this source would be inconclusive.

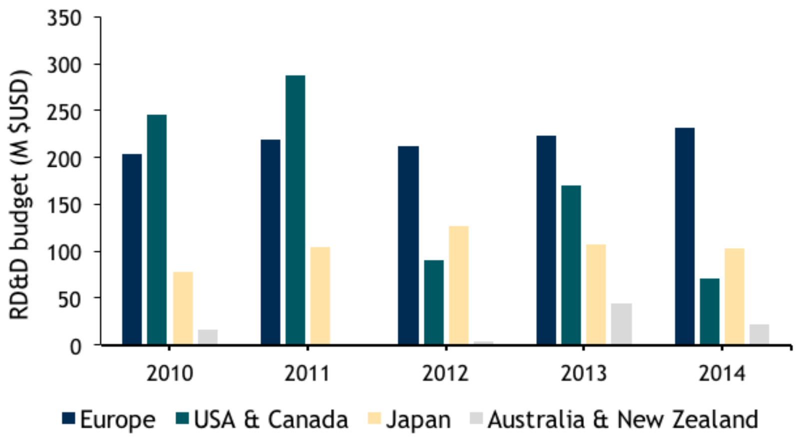

Figure 4-11 Total PV RD&D budgets in Million USD (2015 prices) for available countries from 2010 to 2014.

Source: data from OECD iLibrary[16].

4.3 Value Chain Analysis: assessment of European dependence in the PV Value Chain

[16] Data was missing for several countries in 2015.

Based on the information presented above, the three dimensions introduced in the conceptual framework (product supply, tacit knowledge and codified knowledge) can be evaluated to provide an integrated assessment of the European dependence in the PV value chain.

4.3.1 Results Products supply dependence

As mentioned previously, the inverter is the most relevant element amongst the balance of systems (BoS) components for PV systems. The inverter market is mostly local due to AC/DC local specifications, and Europe does not present a dependence in this item, since the top 10 of supplier's companies show a high participation of European companies (5 out of 10 are European). There is a high concentration of supply since the top 10 companies accounted for 79% of the total shipments, and besides from Europe, the rest of the companies were from the USA and India.

Contrary to inverters, cell and module manufacturing is dominated by Asian companies. 90% of module production was located in Asia, with China accounting for 65% of the total. Europe plays a minor role in the global production, with only 5% of the total share. The top 10 ranking of module suppliers is also dominated by Chinese companies, with minor participation of companies from Canada, South Korea and the USA. This leads to a high European dependence in cell and modules.

The top 10 of wafer manufacturing is also dominated completely by Chinese companies, accounting for 54% of the total shipments. Nevertheless, there was no information found regarding the European import dependence nor European global production shares. Therefore, this activity of the PV value chain could not be assessed.

There are no signs of European dependence in polysilicon feedstock, since Wacker, a European company is one of the leading companies. Wacker is one of the few western suppliers with access to the Chinese market (which is currently the largest), and part of its leading position relies on offering higher quality than their Chinese competitors. The top 10 is somehow concentrated, since the top 5 companies were responsible for 55% of market share in 2016. However, the top 10 shows some regional diversification, with companies from China, Germany, USA, Japan and South Korea.

Regarding critical materials, the analysis study conducted by Rabe et al. (2017) signals that Europe has a low dependence in tellurium, and a medium dependence for indium and gallium (table 4-6).

Table 4-6 European dependence on critical materials used for PV.

Material	Dependency on China	Percentage from China	Other main possible supply sources
Tellurium	Low	20*	Japan, Belgium, Sweden
Indium	Medium	58	Belgium, Germany, Italy, Netherlands, UK
Gallium	Medium	69	France

Source : Rabe et al (2017, p. 694).

Tellurium is considered to have a low risk of supply bottlenecks for the EU, since the EU's demand for tellurium is very small (less than 1%) compared to the global supply, and there is low concentration of supply (Blagoeva et al., 2016; Rabe et al.,2017). For Indium and Gallium, the EU relies heavily on

Chinese imports. These two materials might pose a risk of a rising PV costs in the future if their main world producer (namely China) decides to tighten its control of the resources needed by its growing industry. However, the risk of dependence is classified as medium for Europe, since these two materials are only used for thin-film modules, which represent less than 10% of the PV production technology mix.

Table 4-7 Assessment of European risk of dependence on the PV product supply dimension.

Indicator / Activity	EU's import reliance	EU's global market share (%)	Concentration of supply	Product supply dependence
BoS/Inverter manufacturing	Low	~30%	Medium	Low
Cell and module manufacturing	High	~5%	High	High
Wafer manufacturing	N.A.	N.A.	High	N.A.
Polysilicon feedstock	Low	18%	Medium	Low
Critical materials (Indium & Gallium)	Medium	Low	High	Medium

Overall, Europe presents a high dependence in cells and module manufacturing, and medium dependence regarding the critical materials Indium and Gallium. Also, there is low dependence for inverters and polysilicon feedstock, and wafer manufacturing could not be assessed.

4.3.2 Results PV Tacit knowledge dependence

Demand of installation services for distributed PV systems is met by local suppliers, and in Europe there seems to be an available pool of trained installers in the countries with existing PV deployments. Also, as mentioned in the previous section, European EPC companies play a key role handling large-scale PV systems worldwide. Even though utility-scale PV is not the main market in Europe, the European EPC companies have the skills and experience to develop utility-scale PV systems domestically if needed. From the top 10 EPC and O&M contractors, 5 are European companies, and together they account for 59% of the projects, and 37% of the installed capacity. Hence, there is low dependence for both distributed PV installers and large-scale EPC and O&M contractors.

Table 4-8 Assessment of European risk of dependence on the PV tacit knowledge dimension.

Indicator / Activity	EU's Import reliance	EU's global market share (%)	Concentration of supply	Tacit knowledge dependence

Indicator / Activity	EU's Import reliance	EU's global market share (%)	Concentration of supply	Tacit knowledge dependence
Certified installers	Low	N.A.	-	Low
EPC and O&M contractors	Low	>50%	Low	Low

In general, Europe has no dependencies in tacit knowledge. Neither for certified installers, nor for EPC and O&M contractor.

4.3.3 *Results PV Codified knowledge dependence*

Europe holds a strong position regarding codified knowledge along the PV value chain. It historically holds the leadership with more than 50% of the share of patent applications to EPO PATSTAT, followed only by Japan, USA, South Korea and China. Regarding scientific publications, Europe accounts for around 26% of the global share. Publications are diversified more evenly amongst other countries, therefore there is low dependence in this aspect. RD&D budgets could not be assessed due to the lack of data availability for countries outside the EU.

Germany is a leader in a leader in manufacturing equipment for PV production, holding more than 50% of the market and exporting the clear majority of their products outside Europe. Therefore, there is low or no dependence observed for Europe.

Table 4-9 Assessment of European risk of dependence on the PV codified knowledge dimension.

Indicator / Activity	EU's Import reliance	EU's global market share (%)	Concentration of supply	Codified knowledge dependence
Patents	N.A.	>50%	Medium	Low
Publications	-	~26%	Low	Low
RD&D Budgets	-	N.A.	N.A.	N.A.
Manufacturing equipment	Low	>50%	High	Low

In summary, Europe has low risk of dependencies in PV codified knowledge, since patents, publications and manufacturing equipment were considered to have low risks of dependence, while RD&D budgets were not assessed.

5 Discussion

5.1 Limitations of the research method

The GVC framework by itself has a strong focus on companies, but in the case of energy technology dependence what is being tracked is the dependence in foreign actors or regions. Therefore, the GVC had to be adapted to include an analysis not only of the individual companies, but their country or region of origin. The impacts of some of the assumptions taken along the adaptation process should be addressed when considering the main limitations of the research method used.

First, the top 10 of suppliers in each activity provided information about both the company and the country of origin, but it did not specify the offshored locations of the companies. The companies listed were assumed to be entities of their country of origin, disregarding the country in which they had production activities. Doing this the methodology allowed to focus on the issue of ownership of the entities involved in the energy sector, however the detail of the physical locations was lost. Due to the diverse pool of companies, the location of their production plants was not assessed. This information might have played an important role in the risk assessments, since suppliers with production located in regions prompt to extreme climate events, or under political, economic or social instability have higher risks of supply disruptions.

Second, in cases when the top 10 suppliers are dominated by a single country the methodology did not provide conclusive results. For example, the top 10 of wafer suppliers was dominated by Chinese companies, however it could be argued that their production could be for China's own consumption, not for exports. In these cases the top 10 market shares do not reflect the European dependence on them, and they do not provide information about whether Europe has their own manufacturers or not. Therefore, the current study could not conclude whether Europe is dependent or not in this activity. It would be ideal to find the main companies supplying wafer to European companies, or the total number of wafers produced in Europe. Nonetheless this data was not available on the reports explored, which gives an indication of the scarcity on this type of statistics. An approach suggested to overcome this limitation is to complement the methodology with a more focused assessment. By including structured interviews to experts in the industry, information could be obtained about the country of origin of the main suppliers of inconclusive activities (e.g. wafers) and their concentration (or diversification). In this way, a conclusion could be reached about the risk of dependence in such activities.

Third, the present methodology parted from the assumption that top 10 rankings are available for the different activities in the value chain of a technology. This proved to be right for the PV value chain, and probably the same could be said about technologies with high penetrations levels such as wind energy. For cases of less defined or incomplete value chains, such as CCS, this might not be the case. To have meaningful results in these types of value chains, the information about the EU's share of global, and concentration of supply, a similar method to the one proposed previously could be followed. In this case, the interviews to industry experts could be used for each of the activities identified in the technology's value chain, and supported with statistics when available.

In general, the methodology followed was consistent along the PV value chain. In the case of activities involved in R&D (patents and publications), the focus was solely on the country of origin instead of naming companies. The reason for this variation, was because statistics could be obtained from a centralised data source that proved to be extensive, both relative to the coverage of countries and energy technologies. Moreover, these statistics have been published since several years, so availability is expected to continue in the future.

Furthermore, one of the main benefits of the present methodology is that it provides details about the degree of dependence in each activity of the value chain, which can lead to focused strategies for the identified dependencies. Simpler methods such as trade statistics lack this in-depth analysis, since data is not granulated per finished product, components or sub-components. While using trade statistics to validate the results of this study, it was observed that trade statistics alone can lead to deceptive or incomplete results, since trade statistics present the country of origin of the given product, but it does not deal with the ownership of the companies behind these products. Besides, trade statistics focus solely on the products supply dimension of dependence, and leaves out the dimensions of tacit knowledge and codified knowledge.

See Appendix B for the details on the trade statistics analysis of European PV products.

5.2 Contribution to literature

The research introduces a conceptual model to assess the risks of energy technology dependence in an integrated way. It proposes a definition for energy technology dependence. It proposes three dimensions of dependence: product supply, tacit knowledge and codified knowledge, to cover not only the physical but also non-physical elements on a value chain, and it also elaborates on how these dimensions can impact energy security. Moreover, the conceptual framework on energy technology dependence can also be used for evaluating the risks of dependence in other countries or regions, specially in countries with ambitious RES targets, or developing countries that want to strengthen their industry with a strategy involving low-carbon energy technologies.

The systematic approach used for assessing the risks of energy technology dependence in the case study is a replicable model that can be used to evaluate other energy technologies. It presents the steps to be taken, a set of indicators and their scoring system, and to some extent, suggestions of sources for data collectionThe methodology used proved to be suitable on the assessment of the EU's energy technology dependence in the PV value chain. Specifically, it was useful to set the scene for the analysis by giving a structure to follow: first the value chain mapping with the key actors, followed by an analysis focused on the EU's dependence. This allowed to have a wider view of the activities involved in the realisation of the product and service, while providing detail of the actors involved in the process.

The case study provided insights about the situation of the EU regarding the dependency along the PV value chain, an update on the current state of the EU PV industry and lessons learned from the EU´s independent activities in the value chain. These results of this case study are a starting point for a discussion on what is considered a high risk of energy technology dependence, and appropriate strategies to mitigate the identified risks.

As learned from the results of the case study about European dependence along the PV value chain, Europe is very dependent on cell and module manufacturing for both c-Si and thin-film based modules, and it is somehow dependent on the materials used for thin-film PV: Indium and Gallium. In both activities, the country on which the EU is consistently relying for imports is China.

In the short term, dependency in cell and module manufacturing does not necessarily represent a risk for European energy supply because of two main reasons: (1) the industry is experiencing excess capacity in these activities, which is expected to increase in the coming years, and (2) the average selling price of modules remains low (Jäger-Waldau, 2017).

In the case of critical materials, the EU is to some extent dependent on Indium and Gallium, but it is not a big risk for Europe because these are used in thin-film modules. This production technology currently represents only 10% of the technology mix, and demand projections for these materials expect only a slight increase in 2030 (Rabe et al., 2017). After that period, the global demand is expected to decrease due to mitigation strategies that include efficiencies in the material use, substitution and recycling.

As observed in the case study, Europe is benefiting from low prices offered by Chinese imports, making PV technology competitive along other energy technologies. Nevertheless, the greatest disadvantage of cheap imports is the downfall of the European PV industry, which in turn has increased the dependency on China even further. Being the main source of supply on the mentioned activities, any export restrictions implemented by the Chinese government can reduce the availability of PV systems in the EU. Likewise, an increase in the costs of PV systems can affect directly their affordability. These dependence risks are expected to increase in the long-term unless the EU diversifies its suppliers with actors that can offer the same, or similar benefits.

Strengthening the domestic cell and module manufacturing can also have positive impacts reducing the EU's dependence in the PV value chain. Some positive lessons can be learned from European suppliers of inverters and polysilicon feedstock. Surprisingly, the EU is not dependent in these two activities. In both cases, the European players (SMA Solar and Wacker) lead the rankings based on revenue, rather than by shipments. This could be due to the existence of local specifications in the case of inverters, and the fact that quality in polysilicon influences greatly the efficiency of the modules. Hence, the quality offered by the main European players is valued over the lower price of Chinese competitors.

The case study results also reflect that Europe is in a comfortable position regarding PV codified knowledge. The constant participation in R&D activities such as patents and publications, added to the leading position in manufacturing equipment provide a head start to strengthen the domestic PV industry if the right strategy is in place.

5.3 Recommendations for future research

The conceptual framework proposed by this study to assess energy technology dependence needs to be developed further. A number of topics were identified by this assessment for future research. First, a comparative assessments of other low carbon energy technologies would provide information about the presence of shared dependencies, either geographically or on patterns in the technologies' value chains. Studies assessing multiples energy technologies, will need to develop a method to prioritise the identified dependencies, by either risk assessment or based on the technology's participation in the European energy mix.

Second, this research analysis was limited to the dimensions of product supply, tacit knowledge and codified knowledge, further research could extend the conceptual framework of energy technology dependence even broader by including a fourth dimension of access to finance.

Third, research on mitigation strategies for the detected high risk dependencies is also needed. Policy advisers can draw from historic cases in the space and food industries, since both have dealt with dependencies posing strategic or security risks.

Finally, the design of numeric indicators for energy technology dependence, compatible with the overall energy imports assessment would allow its inclusion in the energy security matrix, and facilitate its tracking over time.

6 Conclusions

6.1 Conclusions and insights for policy

This research attempts to outline a methodology to identify and assess the European risk of dependence along an energy technology's value chain. As an answer to the research question *How can the risk of energy technology dependence be assessed in an integrated way, in the context of the EU's energy security?* A conceptual framework was introduced to assess energy technology dependence by three dimensions of dependence: product supply, tacit knowledge and codified knowledge. Based on desk research and data collection, these dimensions were evaluated using indicators on imports reliance, the EU's global market share and concentration of supply in a case study on PV. The results showed that Europe has relevant risks of dependence on the product supply dependence. Specifically, it has a high risk of dependence in cells and module manufacturing and a medium risk of dependence on two critical materials (Indium and Gallium). The results of the study confirmed the existence of dependencies along low-carbon energy technologies, and stress the need to monitor these risks to implement suitable measures that can reduce the EU's vulnerability.

As pointed out by Radovanović et al. (2016) energy dependency is the most important indicator of energy security. The increase of low-carbon energy technologies in the energy mix is an effective way to reduce energy dependency, however their existing dependencies should not be ignored. The results from the assessment of European dependencies in the PV value chain show that low carbon energy technologies also have dependencies on their own. These should no longer be portrayed as dependency-free elements in the energy security matrix, instead, dependencies in the energy technologies value chains should be assessed and monitored just like import dependencies in commodities are constantly monitored.

The detection of these dependencies can allow policy-makers to take opportune mitigation measures to reduce or eliminate them before they possess a risk for the long-term energy security. In this study only one technology was evaluated, and yet it already showed an existing dependency on China. As noted by Rabe et al (2017), the Chinese government is already tightening the measures over the supply of critical materials, and introducing exporting quotas that will probably increase prices for European consumers. The EU needs to monitor the dependencies not only for PV, but for all the relevant low-carbon energy technologies, and based on the assessment's findings pursue the strengthening of its domestic industry on specific activities, promote the diversification of suppliers in the value chains and guide research efforts on substitution for sub-components or materials that are considered with higher risk of dependence.

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APPENDIX A – Review on critical materials in the PV Value Chain

This section presents a detailed analysis on the factors considered in previous studies on critical materials present in low-carbon energy technologies. The objective of the analysis was to identify the causes of variation between the different risks assessments studies, for a better interpretation of their results.

Earlier studies assessing the supply bottlenecks in the PV value chain, have pointed out at Silver (for c-Si modules), Gallium, Indium, Tellurium and Selenium (for thin-film modules) as the critical materials present in PV technology. After their individual analysis, each study has given a classification of the material's vulnerability regarding supply disruptions, however these rankings differ substantially (see table 7-1). Therefore, a closer look at the risk factors that each study considered is required.

Table A-1 Overview of supply bottlenecks risk assessments of critical materials in the PV value chain.

Study	JRC (Blagoeva et al., 2016)	WWF (2014)	Moss et al. (2013)	RE-SUPPLY (Lehner et al., 2012)
Silver (Ag)	Medium	Low	Low	High
Gallium (Ga)	Low	Medium	High	Low
Indium (In)	Medium	Medium	High	High
Tellurium (Te)	Low	Medium	High	High
Selenium (Se)	Low	NA	Medium	Low

Source : Blagoeva et al., (2016), WWF (2014), Moss et al., (2013) and Lehner et al (2012).

The most recent study on critical materials is focused on the EU resilience to overcome supply disruptions of raw materials in the medium term (Blagoeva et al., 2016). It considers geological availability, geopolitical and economic risks (including concentration of supply, investment potential and purchasing potential), as well as market factors like supply and demand imbalances and lead time to expand production (especially important because of the materials' by-product character). An earlier study, also focused in the EU's import dependence of these materials, was also conducted for the JRC (Moss et al.;2013).

In contrast, the WWF (2014) and RE-SUPPLY (Lehner et al., 2012) reports share a global perspective on the assessments. The WWF looks at absolute bottlenecks (if there is enough material available in the world to meet future supply) in the long term (up to 2050), assuming cooperation amongst countries and thus ignoring geopolitical and economic risks. The RE-SUPPLY report does consider geopolitical and economic risks, but the assessment is mostly done at a medium-term time frame (up to 2025).

In general, other than time frame and geographical focus, what seems to be the causing most of the variation in the risk classification for the materials among the studies is whether they include the mitigation measures before or after the risk assessment. However, what they all have in common, is that after proposing the following mitigating measures: (1) increasing the by-product production, (2) encouraging the reuse, recycling and waste reduction, and (3) pursue research in finding substituting materials, all the studies conclude that these material supply bottlenecks can be overcome in the medium and long term (table 7-2).

Table A-2 Overview of the factors considered in the earlier studies assessing critical materials in the PV value chain.

Study	JRC (Blagoeva et al., 2016)	WWF (2014)	JRC (Moss et al., 2013)	RE-SUPPLY (Lehner et al., 2012)
Geographic focus	EU	World	EU	World
Time frame	Medium term (2030)	Long term (2050)	Medium term (2030)	Medium term (2025)
Risk factors considered	-Geological availability -Geopolitical and economic risks -Supply and demand mismatch -Lead times to expand production -EU import dependence	-Geological availability -Supply and demand mismatch -Competing demand	-Geological availability -Supply and demand mismatch -Lead times to expand production -Geopolitical Risks -EU import dependence	-Geological availability -Geopolitical and economic risks -Supply and demand mismatch -Competing demand
Mitigation strategies proposed	-Increasing the EU's production -Recycling potential in the EU -Substitution potential	-Recycling -Substitution	-Increasing the by-product production in the EU -Re-use, recycling and waste reduction potentials in the EU -Substitution potential	-Securing primary (silver) and increasing secondary supply -Recycling -Substitution potential
Mitigation measures before or after risk assessment?	Before	Before	After	Before
Conclusion	If mitigation measures are implemented, the EU's resilience on Silver and Indium can be maintained as medium.	-For c-Si no real bottleneck exists. -Expected global supply bottlenecks, but not critical.	-For c-Si no bottleneck exists. -For thin-film, Gallium, Indium and Tellurium are considered high risk, however proposed mitigation measures can overcome the supply risks.	Supply disruptions can be reduced, or resolved by the mitigating activities.

Source : Blagoeva et al., (2016), WWF (2014), Moss et al., (2013) and Lehner et al (2012).

APPENDIX B – Trade statistics analysis of European PV products

In the current section a trade statistics analysis of European PV products is presented to compare and validate the conclusions drawn from it, with the ones obtained with the methodology used in the present study.

The European reliance on imports of PV products goes back to 2008, when the local production capacity was not enough to meet the rise in demand driven by subsidy regimes (Hoogland et al., 2017; Huang et al.,2016). The boost in installations attracted Chinese manufacturers, which benefited from lower production costs and financial support by their central and local government to increase production capacity (ibid). The downfall of the European PV production industry prompted the EU to initiate anti-dumping and anti-subsidies investigations in 2012 (Huang et al.,2016). This led to duties imposed on Chinese solar cells and solar panels since 2013, and later extended to Taiwan and Malaysia to avoid transhipments through these countries (Council Implemented Regulation No. 1238/2013 and No 1239/2013). Even though these measures are still in place, trade statistics of last year show that EU imports of PV products were almost 3 times bigger than its exports, and more than half of them came from China and Taiwan (Eurostat, 2017).

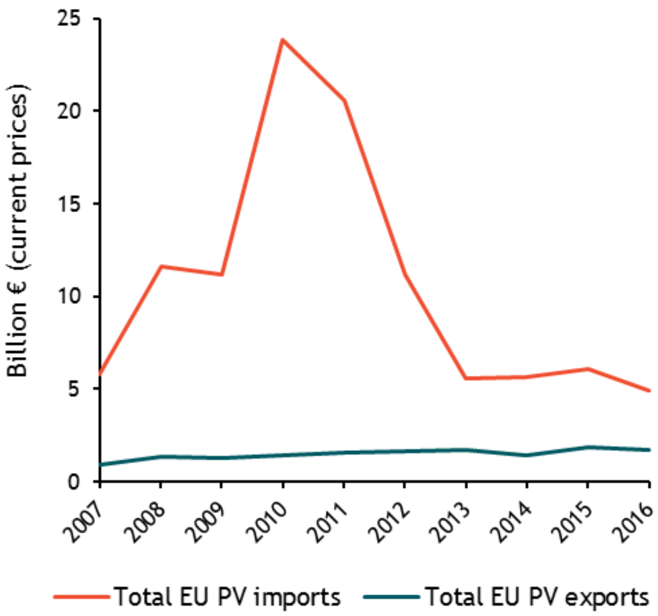

Figure B-1 Overview of the EU PV products imports from 2007 to 2016.

Source: data from Eurostat [17].

China and Taiwan accounted for 50% of the EU PV imports in 2016, while Japan, providing almost one-quarter of the EU's imports in 2007 went down to 9% last year. Meanwhile Malaysia increased its share from 4% to 12% during the same period. Alongside Malaysia; South Korea and Vietnam are now part of the main countries supplying the EU of PV products.

17 HS 854140 Photosensitive semiconductor devices, including photovoltaic cells whether assembled in modules or made up into panels; light emitting diodes. Data provided by EU28 Member States to Eurostat are in current prices, which are prices relevant to the reference period concerned, covering from the month of January to December of the displayer year.

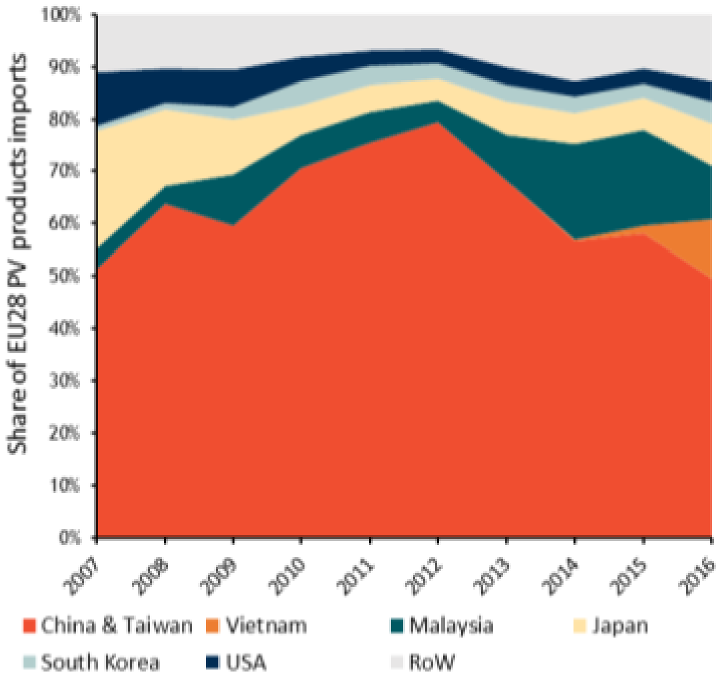

Figure B-2 Overview of the share of EU imports of PV products per country from 2007 to 2016.

Source: data from Eurostat.

Based solely on the results of the trade statistics analysis, it could be assumed that European dependence on Chinese PV products have decreased since 2012, and the suppliers have somehow diversified. However, when complementing trade statistics with the results of the value chain analysis performed in the current study, it's noted that dependence on Chinese companies have not been reduced. As noted by Jäger-Waldau (2016), Chinese companies are behind the largest portion of investments to increase production capacities of solar cell production in other Asian countries (namely India, Malaysia, Thailand, the Philippines or Vietnam). It seems that Chinese companies relocated their production plants to other countries to avoid the European (and US) duties imposed them.