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1. Changes with respect to the DoA

NA

2. Dissemination and uptake

NA

3. Short summary

The aim of this literature review is to set the stage for future prospective evaluation of COP21 implications for energy security in the European Union. First, we suggest the definition of energy security as a multidimensional form taking into account temporal and space effects. The definition is adapted to the European gas context and future large expansion of intermittent renewable sources. In the second part, we describe 46 energy security indicators issued from literature, 24-35 of which may be derived from POLES scenarios. We also explain how to build a composite indicator in order to compare the level of energy security between countries or scenarios if a high number of specific indicators are used. In the final section, we study the European background of energy security by recalling the commitments and targets of European climate and energy policies and by reviewing the existing literature of climate policy implications on energy security. These studies suggest that climate policy has generally a positive impact on energy availability and sustainability, but the impact on affordability may be both negative and positive. Moreover, the impact on three other dimensions (resilience, grid reliability and economic development) remains unknown. In addition, two case studies of energy security background are done for Poland and Bulgaria.

4. Evidence of accomplishment

Report (M3.1).

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Introduction

It is widely accepted that the implementation of climate policies through energy efficiency measures and an increased use of renewable sources in energy mix would enhance energy security. However, some induced effects have to be considered when talking about impacts of climate policies on energy security. For example, the closure of coal-fired power plants can lead to an insufficiently installed power capacity to cope with peak demand as is the case with repeated blackouts in South Australia, and the increased gas back-up capacity requirement with the penetration of intermittent renewable energy sources (I-RES) or a coal/gas substitution can lead to an increase of gas import dependency for countries that previously relied on domestic coal resources.

The objective of this milestone is to identify or elaborate energy security indicators that will help to evaluate the implications of COP21 on European energy security. We also propose a further analysis of energy security issues with respect to two elements of crucial importance in the European context. First, what is the future role of gas in European mix and the level of dependency on gas imports from Russia, especially in some Eastern European countries? Second, how does the high share of I-RES affect the stability of the electricity system?

Section 1 is an overview and a literature review of definitions of energy security in general and more particularly considering stakes related to gas and to I-RES. Section 2 describes energy security indicators and composite indicators. Section 3 is dedicated to the EU background, first on existing energy and climate policies in the EU and second on EU country specificities with case studies for Poland and Bulgaria. We conclude with emphasising trade-offs between climate policies and energy security.

1. What Definition of Energy Security Shall We Use?

The aim of this section is to give an overview of the definitions of energy security and to propose one definition that shall be well adapted to the European Union context. We focus on two energy sources that can prove to be of major importance when considering the implication of COP21 on energy security for the European Union. The first is gas security, and the second is electricity security and the possible negative spillovers on electricity system stability in the case of increasing use of intermittent renewable energy sources (I-RES).

1.1. Holistic Definition of Energy Security

Energy Security is a complex and multidimensional concept whose definition varies widely from one country or region to another, according to the purpose of analysis. Sovacool and Mukherjee (2011) identify 45 distinct definitions and 320 energy security indicators, Winzer (2012) quotes 36 definitions of energy supply security. Such a wide variety can be explained by the nature of the energy risk for each country/region, the level of the country's economic development, geographical aspects, domestic energy mix, domestic and foreign policies, scope of study, etc. For example, the large contribution of gas and oil export revenues to the GDP in OPEC countries make these economies highly sensitive to oil prices, the exchange rate of local currency to dollar or euro, or worldwide oil demand (Vivoda, 2009; Sovacool and Mukherjee, 2011). On the contrary, the European Union (EU) needs to decrease oil and gas dependency to deal with the risk of energy supply disruption through energy efficiency improvement, and through an increased diversification of suppliers[1]. The increase in energy supply is essential to economic growth of developing countries, where coal is usually the cheapest and the most secure way to increase energy security (Bazilian et al., 2011). These few examples demonstrate that the definition of energy security must be specific to each region. In this section, we review the existing definitions and propose one that seems the most appropriate to EU countries with regard to climate mitigation.

1.1.1. Review of Energy Security Definitions

The IEA's definition is the most cited and concise: energy security is the "*uninterrupted availability of energy sources at an affordable price*"[2]. IEA also points out the importance of a temporal dimension:

- From a long-term point of view, energy security depends on investments to maintain at the same level or to increase energy supply without jeopardising the sustainable growth of domestic economy.
- As for a short-term point of view, energy security is the ability of energy systems to deal with short-term disruption and its repercussions (IEA, 2014b).

However, this definition is far from exhaustive. Both Lefèvre (2010) and Narbel (2013) define energy security as an energy insecurity to overcome. Narula and Reddy (2015) suggest adding sustainable aspects of countries' development to a long-term sustainable energy security definition: energy services should be secure, support the economic growth and be environmentally benign. For Bang

[1] https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/energy-security-strategy
[2] https://www.iea.org/topics/energysecurity/subtopics/whatisenergysecurity/

(2010) energy security is the combination of available natural resources for energy consumption and national security. Von Hippel et al. (2011) suggest that the energy security concept should ensure survival of the nation, protection of national welfare and minimisation of energy supply and fuel use risks. Moreover, the authors encourage the incorporation of recent challenges into the definition: environment and climate change policies, potential transfer of technological risk between countries, new energy management technologies, social acceptance related to energy choices, and policy risk. Vivoda (2010) considers two more challenges that need to be added: human security and the existence of a clear and coherent energy security policy.

Several studies define energy security as a combination of key words, each of which represents one energy security dimension. Each dimension can be considered as a distinct aspect of security or not. This approach is especially useful for empiric studies where many energy security indicators are used. APERC (2007) develops the 4 "A" concept: **A**vailability, **A**ccessibility, **A**ffordability and **A**cceptability of energy. With the same logic, Hughes (2009) proposes 4 "R"s: **R**eview the background of a problem, **R**educe energy usage, **R**eplace insecure sources with secure ones, and **R**estrict new demands to secure sources. We can also mention the Five "S"s of the U.S. Department of Defense: **S**urety (easy access to energy), **S**urvivability of a system in the face of damage, availability of **S**upply, **S**ufficiency and **S**ustainability (see Sovacool and Sanders, 2014). For Guivarch et al. (2015) there are four dimensions: Availability, Dependence, Affordability and Sustainability. However, Sovacool and Sanders (2014) consider that dependency is a part of availability dimension. They also suggest five dimensions of energy security: availability and access for each energy source, affordability and equity of energy costs, resilience, sustainability and safety of energy system, and the quality of governance. To summarise, we can cite a broad literature review among 83 studies of Ang et al. (2015a). The authors built the definition through seven dimensions: availability of energy, infrastructure, energy prices or affordability, societal effects, environment, governance, and energy efficiency.

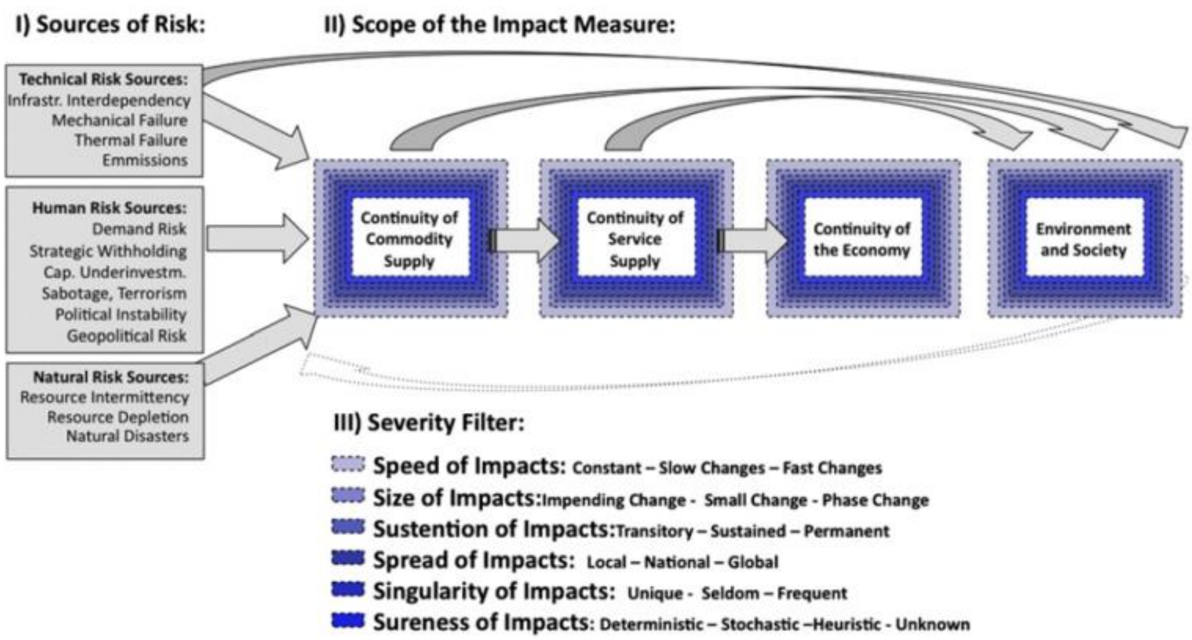
The energy security definition of Winzer (2012) is threefold. First, he takes into account the human, technical and natural risks that affect one or several dimensions. Then, he proposes to analyse four dimensions: continuity of commodity supply, continuity of service supply, continuity of the economy, environment and society (Figure 1). Finally, the author also describes the severity of impact: spread, speed, size, sustention, singularity and sureness.

Contrary to previous authors, Cherp and Jewell (2014) criticise the key word approach to define energy security. The authors state that the energy security definition must also answer three questions: "Security for whom?", "Security for which values?" and "Security from what threats?". The same kind of questions were asked in von Hippel et al. (2011) and Leung et al. (2014): "What to protect?", "From which risk?" and "By which means?".

Turton & Barreto (2006) neither establish a general definition of energy security, nor use the security indicators. They assume that the oil and gas importer countries take into account energy security in mitigation scenarios with two requirements to maintain:

- Vulnerable regions must produce at least 25% of domestic total consumption to reduce the risk of a disruption.
- Regional resources must be sufficient to supply the current level of regional consumption for at least the next 20 years.

Figure 1 : Dimensions of energy security (Winzer, 2012)



Finally, we quote the European Commission's report "*European Energy Security*"[3] in which energy security is presented through three elements:

- Risk of disruption or price spikes – depend on the number and diversity of suppliers, transport models, regulation framework, supply point and political stability in fossil fuel exporter countries.
- Resilience – how the system responds to any disruption (substitutions among suppliers, energy sources, fuel routes).
- Consumer profiles to take into account a country's specificities.

Considering existing definitions, it seems impossible to obtain a short one that reflects all important aspects of energy security. We propose to handle the problem in two steps:

1) Define the scope and purpose of energy security definition, as advised by Cherp and Jewell (2014), Hippel et al. (2011), Leung et al. (2014).
2) Choose keywords to describe energy security dimensions. Such an approach will lead to large flexibility as several indicators can be used to describe a specific dimension of energy security. The final choice of indicators will depend on data available in models.

[3] https://ec.europa.eu/energy/en/content/depth-study-european-energy-security-swd2014330

1.1.2. Context of Definition

Security for whom?
We identify three economical agents: government, companies and households.

First, for a government the aim is to optimise the energy policies, and ensure security, health and safety, and integrity of the country both in the short and long term. The aggregated effect for the whole EU can also be distinguished from the specific effect for each country, and considerations for developed countries are not the same as for developing countries given the growing context of energy demand for climate mitigation objectives in developing countries.

Second, industries and businesses – the energy prices must be affordable and competitive compared to foreign companies. Furthermore, the energy services must be adequate and sufficient to insure the proper running of companies. In the case of energy intensive industries, the energy expenditure may not only affect the competitiveness of the company, but also additional costs due to climate policies (e.g. carbon tax or deployment of renewable energies). More generally, energy is a vital need of any company or organisation, to ensure both working conditions (lighting, heating, cooling) as well as correct functioning of company equipment (e.g. medical scanners, servers in data centres).

Finally, for households' energy services must be provided at affordable prices, not fall in fuel poverty, and be safe in terms of decent and comfortable living conditions (pollution, GHG emissions, quality of services).

From which risks?
Short-term risks refer to energy supply disruption, energy accidents, exceptional events, price shocks, and the difficulty to forecast demand/supply (e.g. wind generation, electricity demand). Long-term risks concern the need for investment to ensure an adequate level of domestic energy system and the ability to deal with unpredictable change or long-term technologies adaptation. In the case of the EU, we have some specific risks.

First, the EU presents a high-energy import dependence[4]. The most critical dependency is the gas import traded by Russia due to the nature of contract (long-term contract indexed to oil prices), the high dependency in 13 countries[5] (more than 50% in 2013), and the political tensions with Russia. Second, the climate mitigation targets in EU countries stipulate the strong increase in the use of intermittent renewable energy (wind, solar) that increases the risk of instability of electricity systems. Finally, energy landscapes are specific to each country and therefore the implications on energy security of climate policies are different. These three points will be studied in detail in the next sections.

Security by which means?
Von Hippel et al. (2011) summarise well the means to improve energy security. First, the most important is to identify risks before accidents in order to prevent them, prepare backups and recovery solutions in case of energy supply disruption, eliminate the causes of risk and encourage friendly

[4] https://ec.europa.eu/energy/en/content/depth-study-european-energy-security-swd2014330
[5] Germany, Poland, Austria, Hungary, Greece, Estonia, Slovenia, Bulgaria, Finland, Czech Republic, Slovakia, Latvia, Lithuania (European Commission, 2014)

diplomatic relations with foreign suppliers (e.g. Saudi Arabia for the US or Norway for the EU). Second, the government must ensure a favourable legislative environment to encourage private energy security improvements. Apart from diplomatic and new regulatory framework dimensions, an effective improvement of the energetic efficiency of the economy remains undoubtedly the best solution to reduce energy dependency for households and for companies. The diversity of energy sources and suppliers enhances the availability of solutions to deal with energy shortage. In addition, the high number of independent energy suppliers may increase the competitiveness and make energy prices more affordable. The means of improvement are not limited. Such related energy security indicators are presented the Section 2.

In summary, energy security should be considered at the international and at the EU level, but more specifically also at national level both in the short and long term. Three types of parties (government, companies and households) are to be considered. In addition to the traditional approach to energy security, given the specific context of the European Union for climate policies we will also focus on the security of gas supply, the grid stability with high level of I-RES and the interaction between climate policies and different dimensions of energy security. The list of energy security indicators (cf. in annex) will allow to us to identify energy security measures.

1.1.3. Energy Security Dimensions

As can be seen in the first part of this section, in most definitions the authors use similar keywords to describe energy security: availability and/or access of energy resources (9 references), sustainability (8), risks (7), affordability (6), resilience (4), economic growth (4), and social acceptability of energy security measures (3).

Researchers have been interested in the availability dimension of energy security since the first oil crisis (Moe, 1979; Daly, 1979) while other dimensions were considered more recently. The level of sensitivity of each country to each dimension of energy security varies between the countries. For the availability dimension, the European Union is sensitive to energy import dependency related to exporting countries because most of them have an unstable political system or are considered to be unreliable. In particular, this concerns Russia, which uses gas exports as a means of political pressure on Former Soviet Union (FSU) countries (Dickel et al., 2014). In contrast, the United States (US) appears to be less concerned with the security of imports. Sovacool (2011) investigated the degree of support for seven dimensions of energy security among 427 American respondents issued from the private sector, governments, universities and non-profit organisations. The results show that energy research, mitigating climate change and reduction of pollution are the most supported axes, whereas the security of supply/trade and energy democracy are placed at the bottom of the ranking.

In order to better understand the multidimensional aspect of energy security, we analyse the results of the literature review of Ang et al. (2015a) in which 83 documents (research articles, official reports and other publications) were used. The authors look at how many studies mention each of the seven dimensions. The ***"energy availability"*** dimension is the most cited (99%) and has a common comprehensive definition taking into account diversity (energy sources, suppliers, technologies, and supply routes) and geopolitical factors (including dependence). The ***"energy price"*** dimension refers to the "affordability" dimension, but only includes price risks. This dimension is used in 71% studies.

The five other dimensions are different from the studies cited above. The ***"infrastructure"*** dimension, in 72% studies, is described as a capacity of energy systems to provide a stable and uninterrupted supply: the quality of transformation and transmission infrastructure, reliability of electricity systems, storage facilities, capability of systems to handle fast force major situations. In our opinion, this dimension pools many different aspects of energy security that would be better to separate. The quality of infrastructure belongs to the long-term resilience of an energy system. The reliability of electricity systems (stability of grid) is an important aspect of energy security, particularly in recent years because of the increase of electricity generation from I-RES.

The ***"social effect"*** dimension, as defined by authors, is similar to the affordability dimension and is listed in 34% documents. The authors include also the acceptability aspect, but only in terms of the increasing risk of living environment damage. While the acceptability of environmental or other actions without any damage is also important, e.g. the change of household behaviour and lifestyle (von Hippel et al., 2011; Vivoda, 2010), the next one, the ***"environment"*** dimension (37% of citations) is associated with sustainability and environmental issues, as well as environmental risk and damage. The ***"governance"*** dimension reflects the ability of a system to support the energy security policies and to propose an appropriate legislative environment in view of climate mitigation objectives. Finally, the authors propose an ***"energy efficiency"*** dimension (22% studies) – the energy intensity of economy. However, this indicator more describes the energy dependence of the economy as suggested by Guivarch et al. (2015).

Ang et al. (2015a) also performed group studies in three categories by year of publication (2001-2005, 2006-2009 and 2010-2013). They highlight that the number of studies using environment, energy, governance and energy efficiency dimensions has been increasing since 2001.

Considering the literature review, we suggest using 6 dimensions throughout this report, defined as follows:

1) ***Availability*** – the availability of energy resources, diversification and the energy (in)dependency. At the beginning of the study, we wanted to use both availability and dependence dimensions. However, there are many interactions and causality between two dimensions and it is difficult to separate energy dependence indicators from availability indicators. For example, the high percentage of fossil fuel imports makes countries vulnerable and dependent, as well as leads to weak availability of energy in the case of break in supply.
2) ***Affordability*** – "*the capacity to produce energy services at the lowest cost, to have predictable energy prices and to enable equitable access to energy services*" (Sovacool and Mukherjee, 2011).
3) ***Sustainability*** – the search for improved energy security must not lead to increased pollution, to more GHG emissions, deforestation, environmental degradation, etc. In addition, the effects of these measures must persist over time.
4) ***Electricity grid reliability*** – the capacity of a power system to maintain the supply-demand equilibrium at any time. This implies the appropriate network, number and capacities of interconnections for better flexibility; the sufficient level of installed power capacities to cover peak demand; the ability of the electricity system to manage risks and limit outages. Given the EU commitments about climate mitigation targets and the important role of I-RES in the reduction of GHG emissions, it is also important to verify if the power system is able to

integrate the high percentage of intermittent renewables without deteriorating the grid reliability and the quality of services.

5) ***Resilience*** – *"how the energy services can survive unexpected events that disrupt efficient and effective operation"* (Sovacool and Sanders, 2014). There are two goals. First, it is important to evaluate and forecast possible future risks. The second goal is to ensure the stability of services throughout force major situations and disruptions. The second goal is close to reliability dimension.
6) ***Economic development*** – the ability of a domestic economy to maintain or raise the standards of living, as well as to change behavior of energy users. This dimension is more relevant for developing countries and quit difficult to assess.

Four dimensions cannot be ignored: availability, affordability, sustainability and electricity grid reliability. The first three are very common in contrast to the stability of electricity systems. There are only a few studies investigating how the high level of I-RES impacts the stability of grids. Studies focus mainly on the security of energy imports to fuel the power plants, or use the I-RES as a means of the energy supply diversification, or address the electricity security problem by only technical means. In section 1.3 we will explain the specificity of ensuring electricity security in the context of I-RES increase in the energy generation mix.

The two additional dimensions are resilience and economic development. The additional dimensions are as important as the four dimensions that can be considered mandatory, but the characteristics of the prospective models may make it difficult or impossible to compute some energy security indicators related to these dimensions. In the resilience dimension, it is important to quantify and evaluate risks, which are usually exogenous to the model and unpredictable. To our knowledge, there is only one study taking into account future risks. In the "SECURE" project[6] (2008-2011) the risks were evaluated using the database ENSAD (Energy-related Severe Accident Database) that gathered 24,152 energy accidents between 1970 and 2008. The future risks were estimated using the existing relationship between frequency of accidents and its consequences.

1.2. Intermittent Renewable Energies and Security of Electricity Supply

Among energy security studies, only a few articles investigate empirically the security of electricity supply. There are 2,626 academic journal articles indexed by Scopus[7] on energy security, but only approximately 100-200[8] articles investigating electricity security (security of electricity supply, grid reliability, etc.), and only three articles in Scopus related to empirical energy security studies. The reason for such a small quantity of articles on this issue is that until now the security related to electricity supply was studied mostly from a technical point of view. However, the current and the expected penetrations of intermittent renewable sources (I-RES) induced by new energy and climate policies force us to rethink the network and market architectures. Currently, the share of I-RES is higher than 15% in 12 countries, reaching 42% and 49% in South Australia and Denmark, respectively (Figure

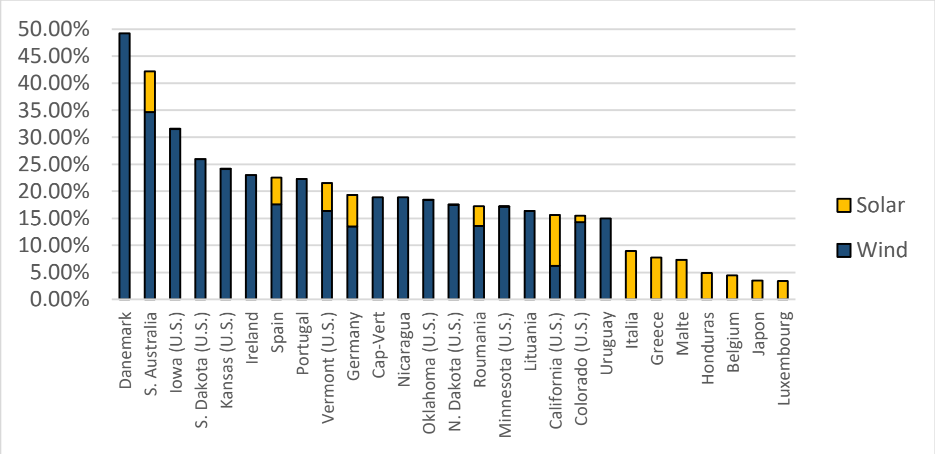
[6] Security of Energy Considering its Uncertainty, Risks and Economic Implications : http://www.feem-project.net/secure/

[7] Research articles published in English between 2005 and 2017 using the key word "energy security" in title, abstract or article's key words.

[8] Research articles published in English between 2005 and 2017 using the several combinations of key words in title, abstract or article's key words: "energy security", "intermittent renewable", "grid reliability", "electricity security", security, etc.

7). It is generally considered that a high share of I-RES is likely to cause blackouts, but we have not found any evidence. For example, since 2016 South Australia, 46% of I-RES, has suffered several major blackouts and outages. I-RES did not cause these blackouts, but amplified them. When the main cause was a violent storm, the insufficient power capacity was due to the phasing out of coal power and the overloading of interconnections between the state of Victoria and South Australia (Global Electrification, 2017).

Figure 2: Electricity generation shares from intermittent renewable energies in 2015 (ENERDATA, Australian Energy Market Office, U.S. Energy Information Administration[9])

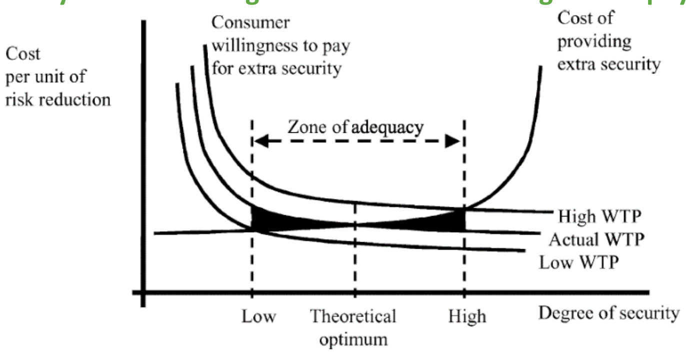


As noted at the beginning of the report, there is a range of energy security definitions. However, in the case of electricity security (or stability of the power system), the authors seem to be unanimous: security is related to the equality between supply and demand at any moment in time (Newbery, 2015; Belderbos and Delarue, 2015;) or, at its simplest, "keeping the lights on" (IEA, 2014a). Lieb-Dóczy et al. (2003) represent the security of electricity supply as a compromise between cost of risk reduction and degree of security (Figure 6) assuming that it is impossible to ensure electricity security at any time due to prohibitive costs. The cost of risk reduction is presented by the consumer willingness-to-pay (WTP) for additional levels of security. The higher a consumer is WTP, the larger the investment level in electricity security is.

Along the same lines, Rutherford et al. (2007) define electricity security as "*a low business risk related to energy with ready access to a stable supply of electricity at a predicable price without threat of disruption from major price spikes, brown-outs or externally imposed limits*".

[9] For U.S. – only data from Solar Photovoltaic

Figure 3: Optimal security level according to the consumer willingness to pay (Dóczy et al., 2003)



If we ask the same questions as in Section 1.1.2, we can see that there are a few differences. First, in the case of electricity security the role of the system operator is decisive. To avoid electricity disruption, the operator should ensure the balance between demand and supply at any time[10], but electricity is not storable. In the past, the main challenge was to find a missing supply. Now, an oversupply due to a high share of I-RES is becoming a rising issue.

Second, the risks are not strictly identical. According to Nepal and Jamas (2013), there are two types of electricity security risks that can be distinguished from the energy security definition: economic and technical. The economic risks concern particularly the possible lack of investment in power capacities (especially in back-up capacity) and in an appropriate electrical network. As these investments are not always profitable for companies, the government has to implement incentive policies and develop relevant regulation framework. Other economic risks are related to the increasing electricity demand or changes in use that are difficult to predict. In the case of electricity supply, it is vital to anticipate all possible risks and the amount of storage, reserves, back-up capacities and possible curtailment well in advance, that, in turn, create additional risk. The second type of risk is related to the use of new technologies. Power generation is more and more decentralised in EU countries due to market liberalization, need for flexibility and cost optimisation. However, it is not necessarily suitable considering that the current network was built for managing a centralised generation. Distributed generation may also affect system frequency increasing the risk of shortage/blackout. Authors also consider the integration of I-RES is a technical risk, especially in the case of large share of I-RES. On the one hand, the high share of I-RES diversifies the energy sources and increase the availability of electricity, but on the other hand, the electricity generation from I-RES is less predictable. Another large technical risk relates to the use of Smart Grid technology that is sensitive to cyber-attacks.

Finally, means to ensure electricity security are different. The International Energy Agency (2014a) and more recently the Council of European Energy Regulators (CEER, 2016) have provided extensive analysis of the current situation and suggest several solutions to address electricity security. First, the IEA report suggests ensuring adequate generation, energy markets (e.g. Local Marginal Pricing), standards and procedures (new criteria, better forecast). They recommend offering targeted contracts and proposing market-wide capacity mechanisms. There is also a need to improve climate and low-carbon policies (credibility, design, new instruments). In addition to investment, the networks need better coordination between network services and electricity markets. The Demand Response has good potential to secure electricity supply, but this measure needs to introduce dynamic pricing, build

[10] From electricity point of view, a short-term is between few seconds and 5 minutes.

competitive dynamic retail markets, inform consumers, and minimise transactions costs. The regional markets should be consolidated and need better coordination. Moreover, a single operator for several regions may be a good solution. Finally, the IEA recommends rethinking emergency solutions. CEER (2016) makes approximately the same suggestions. Their report also emphasises the real need for common electricity supply regulation and harmonisation of electricity security indicators through EU countries.

To sum up, electricity security presents quite the same dimensions as energy security apart from the specificity of the need to ensure the stability of the grid at any time. Electricity supply must be available to respond to demand, be affordable for households and companies, support economic development of a country, and be sustainable. In our opinion, if we want to assess grid stability, the best way to do it is to create a separate dimension, named "electricity grid reliability", which would include all the particularities of electricity security.

1.3. Which Aspects of Climate Policy May Affect Energy Security?

Even though the energy security usually takes into account the GHG emissions and share of renewables, this is not enough to describe the impact of energy security policy on the climate change. The climate and energy security policies do not have the same objectives. Is it possible to combine the two objectives so that they are compatible or is there some trade-offs?

Sovacool and Saunders (2014) give an overall analysis of trade-offs between policy packages to improve energy security. They open a discussion by defining the concept of energy security through five dimensions: availability, affordability, resilience, sustainability and governance. Then, the authors describe five energy security packages: energy self-sufficiency, energy affordability (price reduction), energy access, climate change mitigation and water availability. The last package aims to reduce water uses in energy sector. Each package is split in 14 measure types (54 measures in total): supply of 6 energy sources; electricity and gas networks; optimisation (transportation, efficiency, substitution); government measures (taxes, subsidies, research). According to authors, the most common measure is a greater spending for research (energy self-sufficiency, climate change and water availability). The most contradictory measures concern gas network and subsidies: each package has a different objective. Only 14/54 measures are common for two packages, the rest of measures (72%) are conflicting. Concerning climate change, the half of climate mitigation measures are completely opposite to objectives from other packages (for example, the promotion of domestic production of fossil fuel to improve availability).

Using the MERGE model to produce eight scenarios, Bollen et al. (2010) investigate how the combination of energy security, climate and pollution policies affects the GHG emissions, the level of pollution and the oil consumption in OECD countries until 2100. The concept of energy security is based on overall region dependency, energy imports, consumption, energy intensity and disutility, associated with a low level of energy security. Their results show that CO2 emissions decrease only in the case of global climate change policy, combined or not with other policies. The same conclusions can be drawn for pollution: a climate change policy does not necessarily lead to a reduction of pollution. In the case of a single energy security policy or combined with air pollution policy, the peak of oil consumption is simply delayed from 2050 to 2070.

According to Brown and Huntington (2008) and Aslani et al. (2013), the optimal policy at cheapest costs is to use the combination of the technologies that could improve more than one objective instead of focusing only on technology(ies) with very high performance in one field. In the same way, Pfenninger and Keirstead (2015) studied highly renewable electricity mix in United Kingdom and found that 60% penetration of RES is feasible with a little cost increase. Many combinations of RES are possible and lead to the same RES penetration rate and CO2 reduction. The authors use the Shannon index of electricity mix as indicator of electricity security. In order to test the reliability of the system, they compute for each scenario the additional cost to satisfy 5% of unmet demand.

Victor et al. (2014) investigate the long-term impact of shale gas and the climate policy on the American energy security using MARKAL model. The energy security is defined as a diversity of energy mix and energy sources using the Shannon Diversity Index (SDI). Five long-term scenarios were tested: BAU (1), high performance standards in power sector (2), implementation of carbon taxes from 2015 (3), high level of oil and gas domestic production (4), and low level of oil and gas domestic production (5). The SDI shows the best energy security performance is observed in the fifth scenario (for primary energy) and in the third scenario (for electricity generation).

Using WITCH and REMIND models to evaluate the availability of energy supply by 2050 and 2100, Cherp and al. (2016) find that climate policies have a positive impact on diversity and availability of energy supply. Moreover, the sovereign risk decreases. Criqui and Mima (2012) investigate the impact of climate mitigation scenarios on energy imports. The energy import dependency decreases, but the effect depends on how countries coordinate climate policies. The authors shows that the level of EU energy imports is lowest in the case of worldwide coordinated climate policy, followed by the situation in which only EU carry out a strong climate policy.

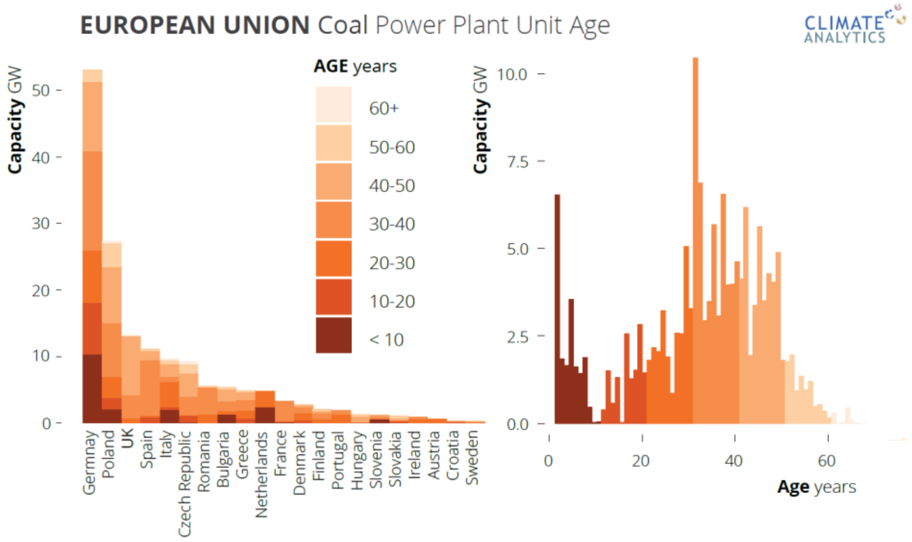
Jewell et al. (2014) analyse the availability dimension of energy security in 42 climate policy and BAU scenarios up to 2050. All low carbon scenarios have a better performance than in the BAU scenario. There are two exceptions: large gas and hydrogen trade, and low diversity of electricity generation options. To overcome this problem, the authors suggest implementing both energy efficiency policy and limitation of solar energy.

Guivarch et al. (2015) evaluate the level of security through 8 indicators and 4 dimensions (availability, dependence, affordability, sustainability) at short-term (2025), medium-term (2050) and long-term (2075) using Imaclim-R model. The energy security in Europe became slightly worse in 2025 (increasing energy dependence on imports and higher household energy budget). At 2050, all indicators improve, especially carbon content of TPES and expenditure on energy imports. This enhancement is also noted in 2075, but the nuclear capacity increases. The only indicator that remains the same is the oil market concentration.

Thus, most studies show that climate mitigation measures improve the diversity and availability of energy supply, but the effect on energy dependency and energy prices can be positive or negative. Moreover, according to Bazilian et al. (2011), the climate change and energy security policies could be conflicting in developing countries. On the one hand, climate policy argues for the limitation of fossil fuel consumption. On the other hand, the increase in energy supply is essential to economic growth of those countries, with the coal plants as cheaper and more energy secured solution. According to

Endcoal.org statistics, in 2016 there were 932 GW of planned capacity of coal plants and 350 GW under construction. Only 2.7% and 1.7% respectively are located in developed countries[11,12].

Figure 4: Age structure and capacity by country (at left) and total age structure (at right) of the EU's coal power plant unit fleet (Climate Analytics, 2017)



In the same way, Climate Analytics (2017) debates the European coal phase out strategy, COP21 implications and its impacts on the economy of EU countries. The electricity generation from coal still accounts for a quarter in EU energy mix. Germany and Poland represent the half of coal generation. Coal plants in five EU countries are responsible for more than a quarter of domestic GHG emissions: Germany (28%), Poland (33%), Czech Republic (33%), Greece (34%) and Bulgaria (44%). Figure 10 shows the age distribution of coal plants. Using MESSAGE model, authors shows the need to close earlier the coal plants (before the end of the lifetime) in order to achieve EU COP21 targets.

As Germany and Poland have the biggest contribution to CO2 emissions from coal plants, Climate Analytics (2017) analyses the implications of coal plant phase-out on their economies. Our concern here is to understand if the impact in Poland is more negative (or positive) than in Germany. In Germany, the use of coal plants is driven by low coal and carbon prices, and by the phase out of nuclear plants after Fukushima disaster. The authors also mention the coal lobby. In spite of current climate policies, there are still 2020 MW capacity of coal plants that is planned or under construction in Germany. The early phase out of German coal plants may lead to an increase in electricity prices in Germany and to financial losses for owner of German coal plants. Therefore, the only energy security dimension affected by this phase out in Germany may be the affordability dimension.

The Polish context is different. First, the influence of Polish economy is not large enough to be a "price maker" during international negotiations. The coal plant phase out will lead to higher policy risk (resilience dimension), because of increasing gas imports from Russia. Second, the use of Polish coal ensures a certain level of electricity security: coal share in electricity mix accounts for 85% (availability dimension). Finally, Poland is the largest hard coal producer in EU. In one hand, the high production

[11] Japan, Germany, Australia, United States, United Kingdom, Greece, Italy and Czech Republic.
[12] http://endcoal.org/global-coal-plant-tracker/summary-statistics/

costs are uncompetitive and the coal plants are unprofitable. In other hand, the coal mining and coal plant employ a significant number of people. An unsuitable phase out policy will have negative impact.

These studies lead to the conclusion that climates policies have in general positive impact on two energy security dimensions: availability and sustainability. However, the impact on grid reliability, affordability and economic development cannot be considered as unequivocal and more research are needed on these issues.

2. Review of Indicators

A literature review allows us to identify around 50 specific indicators, which can be estimated from prospective models. Obviously, too many indicators cannot be analysed one by one. Therefore, we present first the indicators for each energy security dimension, and then we overview the methodology for the elaboration of composite indicators.

2.1. Review of Indicators by Energy Security Dimension

A number of studies suggest a wide range of indicators, up to 320 indicators in Sovacool and Mukherjee (2011). However, many of them reflect the same calculations in a different manner (e.g. several diversity indexes) or are split in several indicators (e.g. 11 GHG emission intensity, one for each greenhouse gas). We found 58 distinct indicators, additional useful measures and energy security components; they are listed in the annex of this document. In this section, we present the most important indicators (46). The goal of this milestone is to prepare a list of indicator for the energy security analysis of mitigation scenarios issued from POLES model. Given the structure of POLES model and the nature of prospective scenarios, it is impossible to use all indicators. Some of them need the detailed data at national level, especially the indicators form grid reliability dimension. Some other indicator need data that cannot be obtained from POLES model. The POLES model will allow us to compute directly up to 18 indicators and to use 6 proxy. It is also important to note that only 5 indicators can be calculated with templates used to gather national 2°C and 1.5°C scenarios in task 2.1 of RIPPLES project. This scenarios' database cannot be used to analyse energy security.

2.1.1. Availability

The availability dimension is the oldest and the most studied one. We identified 11 generic indicators to describe the availability of supply (Table 2) corresponding to the three measures to improve it. We also indicate if it is possible to calculate the indicator using the template from DDPP scenarios or using the POLES model.

The first measure is the diversification of energy suppliers, energy sources used by economy and origins of the imports. Diversification allows a country to cope more easily with disruption of supply by switching from one supplier or energy source to another. Note that not all suppliers and energy sources are substitutable. The Shannon Diversity Index (SDI) measures the diversity of types and species. The best performance of the SDI is the equal distribution of species. The SDI gives a more important weight to the rare spaces/types. On the contrary, the Herfindahl-Hirschman Index (HHI) is interested in the quantity supplied, i.e. market shares. The HHI is widely used to measure the degree of competitiveness of a market and it relies on economic theory. A high number of sellers is one of the conditions to approach perfect competition, considered as the most efficient market situation. However, the HHI is not applicable for all energy sources. In the case of electricity generation, the quantity of electricity supplied does not necessarily reflect the market power of sellers. The seller with the fastest response during peak hours has more power than a large utility company supplying the base load electricity.

Both diversity indicators are widespread in energy security studies. Instead of the HHI and the SDI, research can also measure directly the market shares of suppliers and energy sources, as well as the geographic diversity of supply. For example, Jewell (2011) proposes an indicator based simultaneously on the HHI of suppliers and the number of entry points (interconnections, pipelines, ports, LNG ports, railways). The next diversity indicator is the number of interconnections in gas and electricity networks. The more connections there are, the more flexible the network is.

The SDI, HHI and market shares reflect the short-term level of security, when the number of interconnections is a long-term measure because it requires a major investment and time to install or improve the network.

Table 1: Availability indicators

N°	Indicator	Sub-dimension	Time	Space	WP2.1	POLES
1	Shannon Diversity Index	Diversity	ST	D/EU/W	✓	✓
2	Herfindahl-Hirschman Index	Diversity	ST	EU/W	✓	✓
3	Market shares	Diversity	ST	D/EU/W		✓
4	Number of interconnections	Diversity	LT	EU		
5	Reserve-to-production ratio	Reserves	LT	D/EU		✓
6	Strategic stocks	Reserves	ST	D/EU		
7	Fossil fuel capacity production	Reserves	LT	D/EU		✓
8	Energy intensity	Dependency	ST	D/EU	✓	✓
9	EROI	Dependency	ST/LT	D/EU/W		
10	Import dependency ratio	Dependency	ST/LT	EU		✓
11	Import/export to consumption	Dependency	ST/LT	EU		✓

ST – short term, LT – long term, D – domestic, W – worldwide, MA – maybe available

The reserves are the second measure to improve energy availability, which consists in having enough strategic stocks (e.g. number of mines, wells drilled or existing storage capacities) and level of the domestic energy production. The degree of possible reserves can also be expressed in reserve-to-production ratio, i.e. for how many years the country can rely on domestic production.

Finally, the third measure is to reduce energy dependency. The domestic dependency is described by the energy intensity of economy: how much energy the country sectors use. The country is very vulnerable when the sectors consume too much energy produced abroad. This problem can be addressed by improving the energy efficiency of economy, by reducing the demand or by reducing energy imports. There are several approaches to estimating the level of energy intensity; the researcher will choose the most appropriate for study. Another possible indicator – the Energy Return on Investment (EROI), can reflect efficiency. EROI is the ratio between the amount of energy delivered and the amount of energy required to deliver that energy. However, it concerns only the energy industry and serves to compare different energy sources among each other. The last two indicators measure the country dependency on the import. They are quite similar. The import dependency ratio expresses how much energy is produced in the country, while the import to consumption ratio is more precise and describes the dependence of domestic consumption. The import dependency indicators are both short (e.g. oil imports) and long term (gas long-term contracts).

2.1.2. Affordability

Energy plays an important role in the economy, ensuring comfortable and healthy living standards, and it is essential for the well-functioning of companies. For some companies and households, energy expenditure can represent a large part of their budget. From that perspective, it is important to ensure the affordability of energy. We describe this dimension by 9 indicators split into four sub-groups. The first goal is to ensure the affordability of energy for consumers: household (transport, space and water heating, lights and appliances) and companies (all companies, not only the energy intensive). The level of energy prices (current, average, variation) is the most used indicator to describe this dimension. We also suggest using the energy poverty indicator (for households) or/and the energy expenditure of all consumers.

Due to the essential nature of energy services, energy producers are, to a certain extent, partially constrained by government measures, energy and climate policies, as well as by energy producers abroad. The government should ensure the feasibility of domestic energy and climate policies. One of the measures is to evaluate the costs of energy transfers and the energy tax burden, which is borne by energy producers and can lead them to failure. While the cost of unforeseen events and accidents, such as a major blackout, concerns all economy sectors, the government has the best position to resolve this kind of problem. An example of electricity cost interruption is given in Winzer (2012), who measures it in terms of GDP losses.

Table 2: Affordability indicators

N°	Indicator	Sub-dimension	Time	Space	WP2.1	POLES
1	Energy prices	Consumer	ST	D/EU/W		✓
2	Energy poverty	Consumer	ST	D/EU		Proxy
3	Energy expenditure	Consumer	ST	D/EU		Proxy
4	Transfer costs	Producer	ST/LT	D/EU		MA
5	Energy tax burden	Producer	ST/LT	D/EU		
6	Cost of interruption	Government	ST	D/EU		
7	Intermittency cost	Investment	LT	D/EU		
8	Cost of New Entry	Investment	LT	D/EU		MA
9	LCOE	Investment	LT	D/EU		✓

ST – short term, LT – long term, D – domestic, W – worldwide, MA – maybe available

In addition to affordability of energy costs, the investment in energy measures mandated by the government should also be realistic and affordable. The lower the investment is, the better it is. The indicators found in literature focus almost exclusively on the power sector. This is logical because the countries exposed to energy insecurity are major importers of fossil fuels, thus the production capacity of them is outside the country. Whereas the investment in power production capacity is, in general, supported by domestic financial means. We selected three indicators that are easily applicable to prospective scenarios, as they are a part of the energy model. First, the entry costs of a new utility company for additional power capacity, and second, the additional cost to support the intermittent character of wind and solar energy (intermittency cost). Both of these indicators do not take into account low variable costs of I-RES. That is why we suggest using a Levelized Cost Of Electricity – a ratio between the power plant lifetime cost and amount of electricity produced over its lifetime. And third, it may also be necessary to evaluate the level of investment in fossil fuel extraction and projects, which

can lead to emission reduction without increasing fossil fuel imports (e.g. coal-to-gas and coal-to-liquid projects).

2.1.3. Grid Reliability

This dimension is the most challenging to evaluate. A few indicators were used in previous energy security studies and all of them measure the frequency of interruption, its duration and economic impact (CEER, 2016, Ang et al., 2015, Augistis et al. 2012, Nepal and Jamas 2013, Gouveia et al., 2014):

1) System average interruption duration index (SAIDI)[13]
2) System average interruption frequency index (SAIFI)
3) Customer average interruption duration index (CAIDI)
4) Energy not supplied (ENS)

Nepal and Jamasb (2013) use the statistics of the number and the duration of unplanned interruptions per year between 1999 and 2009 in some European countries (plus the USA) to investigate grid stability, and no change was observed. Gouveia et al. (2014) lead to the same conclusion analysing the electricity security level in Portugal between 2004 and 2011, the period during which the share of I-RES capacity increased from 5% to 24%. They use 34 indicators of electricity, but only 9 of them reflect reliability of grid: ratio of interconnection utilisation, share of I-RES, average number of interruption and its duration (both at low/medium/high voltage level), and the evolution of annual peak demand. In addition to these studies, the Benchmarking report of CEER (2016) highlights the diversity of electricity systems between EU countries and the risks involved. There are not even two EU countries with the same network, regulation, rules and indicator formula[14]. As an example, if a voltage cable is buried underground, the risk of accident and interruption is lower. In 2014, the share of underground cables varied from 10% in Ireland to 100% in Netherlands, and the duration of unplanned long interruptions varied from 15 minutes in Denmark to around 900 minutes in Slovenia (CEER, 2016, pp 38-39, Figures 2.5-2.6).

The four indexes above are based on past events, which are difficult to project in long-term scenarios due to the unpredictable nature of exceptional events (e.g. Fukushima nuclear disaster in 2011) and the future technological solutions that will take place. To find other indicators of grid reliability, we reviewed how researchers deal technically and mathematically with the implementation of new technologies (e.g. I-RES, storage) and management approaches (e.g. demand side management, smart grids etc.) ensuring at the same time the reliability of the grid.

First, the regulation and the design of the electricity market should be improved (CEER 2016, IEA 2014). Both the CEER and the IEA argue for the harmonisation of regulation rules, indicators and definitions. Other studies focus only on one of the problems, for example the harmonisation of gate closure time[15] among the EU electricity markets to improve market integration (Frontier Economics, 2007). The IEA goes further by suggesting reliance on a single system operator and on the use of local marginal pricing

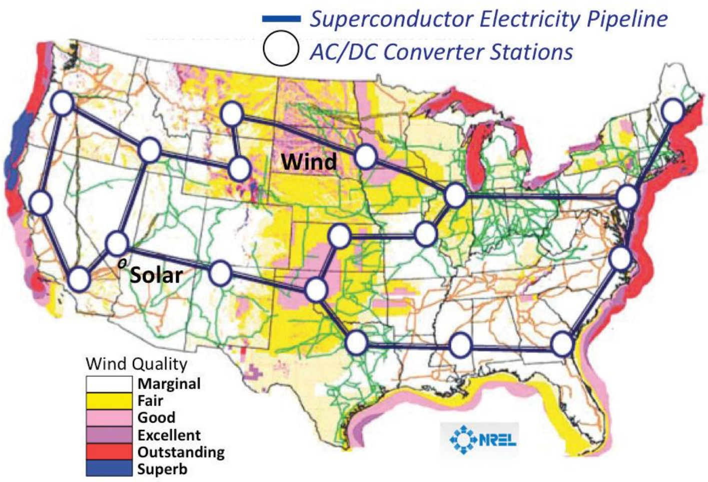
[13] See Appendix for more information

[14] The report compares definitions of long/short/transient interruption, definitions and rules of (un)planned interruption, definitions of voltage levels, how long interruptions are monitored, formulas for long interruption indicators and definitions of exceptional events. The report also proposes three case studies, which include calculation of security indicators for Czech Republic, Algeria and Israel.

[15] Gate closure time is a deadline for trading electricity in a day-ahead market.

(LMP). The single operator leads to a more flexible system, while the LMP takes into account transmission capacities and losses. Jacottet (2012) emphasises the need for new cross-border electricity exchange rules, when Hawker and Gill (2017) discuss the deployment of capacity mechanisms. Van der Bergh et al. (2017) advocate for the cross-market coordination of reserves[16] for an easier balance of the electricity system. Moreno et al. (2010) and de Maere d'Aertrycke et al. (2017) explain that long-term electricity contracts can help to finance new power and interconnection capacity as is a normal practice in the case of new natural gas pipelines.

Figure 5: An example of superconductor electricity pipeline for the U.S. (APS, 2011)



Technology and statistical modeling to improve forecasting or electricity system optimisation is the second solution. The APS (2011) estimates that better forecasting techniques, energy storage expansion and superconductor electricity pipelines (Figure 8) are the best way to implement high shares of I-RES without deteriorating grid security. In the same way, Steiner et al. (2017) suggest a mathematical model for a better weather simulation, while Belderbos and Delarue (2015) use the new system planning approach of electricity generation. Engineers, for their part, develop and assess highly sophisticated solutions at the microscopic scale. For example, Kia et al. (2017) evaluate the implementation of energy and thermal storage systems in the electricity market by comparing 18 and 24-bus[17] distribution systems. From a technical perspective, grid reliability is based on frequency stability, voltage stability and rotor angle stability (Kundur et al., 2004).

Even though electricity security is mostly described by technical means, we can find many articles discussing the impact of I-RES penetration on spot and future electricity prices. Considering that wind and solar energies are intermittent and can produce a huge amount of electricity in off-peak periods, they can lead to negative prices and, therefore, to losses for power companies. Moreover, in the case of large shares of I-RES in a system, the government and power companies have decided to close the conventional fossil fuel power stations that had become highly unprofitable. That might lead to price spikes at peak periods if I-RES generation was low. Can we use the wholesale electricity prices to

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[16] The system operator has three types of reserves to balance the electricity production and consumption: primary reserves with the short reaction time (< 15 sec.), secondary reserves (reaction time less than 15 min) and tertiary reserves (manually activation).

[17] In electronics, the bus is a connection between nodes.

investigate the level of grid reliability? Not certainly. Rintamaki and Siddigui (2017) conclude that I-RES increased the volatility of day-ahead prices in Denmark and Germany in 2010-2014, but this impact was lower in Denmark who could rely on hydropower from Nordic countries. On the contrary, Kyritsis et al. (2017) analysed daily German prices from 2010 to 2015 and concluded that wind power generation increases the volatility of prices, while solar generation has no impact on price variance. Kallabis et al (2016) investigated the evolution of Phelix Base Year Futures from 2007 to 2013 and highlight falling average prices. However, the recent data from EEX demonstrates that the futures have been increasing since 2016 with increasing trade volume. Lund and Mathisen (2009) consider that it is feasible to reach nearly 100% renewable energy in Denmark from a financial point of view (e.g. without increasing power costs). Staffell (2017) shows that the wholesale electricity prices in U.K. became more volatile in 2016 and reached negative prices several times, but the average price remains unchanged. Gulli and Balbo (2015) were lead to same conclusion for Italy. These articles lead us to conclude that electricity prices cannot be used as a proxy of impact of I-RES on grid reliability.

Thanks to literature, we found 7 additional measures that can be used as indicators of grid reliability (Table 4). Note that almost all of these indicators can only be computed through the highly detailed model of power system. The description of each indicator is given in the appendix with, where it is possible, a calculation approach.

Table 3: Grid reliability indicators

N°	Indicator	Time	Space	WP2.1	POLES
1	Interruption frequency or duration	ST	D/EU		Proxy
2	Value of Lost Load	ST	D/EU		Proxy
3	Loss of Load Expectation	ST	D/EU		Proxy
4	Capacity adequacy	LT	D		✓
5	Under-investment	LT	D		✓
6	Ensured capacity factor	LT	EU/W		
7	Frequency stability	ST	D/EU		
8	Forced curtailment	ST	D/EU		Proxy

ST – short term, LT – long term, D – domestic, W – worldwide, MA – maybe available

We cited above the four main indexes to measure the reliability of a grid: it is sufficient to use one of them. We suggest in the appendix the number of exceptional events as a proxy of SAIFI index. If the mathematical model allows the arbitrage between power cuts and large investment (high price), the SAIFI is a number of cuts. Similarly, if the model provides enough information about the quality of frequency, we can use it: the stability of a system is deteriorated with high variance and spikes of grid frequency.

The second indicator, the Value of Loss Load (VoLL), expresses the consumer willingness-to-pay to avoid a disruption. A higher VoLL leads to a more secure system. Després (2015) considers that VoLL represents also an upper limit of investment in additional peaking capacities.

The next indicator, Loss of Load Expectation (LOLE), measures how long the available generation capacity is likely to fall short of the load demand. In most countries, the system operator recommends not exceeding three hours. As a proxy of LOLE, we propose considering the duration of curtailment per year. We assume that the consumer utility is not affected if the total duration of curtailment is no longer than 3 hours. The level of grid reliability downgrades for each additional hour of curtailment.

In addition to the VoLL, we can analyse the amount of electricity curtailed and its nature:

- The curtailment can be desired and consumers can accept reducing consumption. To take advantage of this measure, consumers should have an agreement with a utility company or have a specific tariff.
- In the case of oversupply, the system operator can decide to force the curtailment.

We assume here that the increasing level of forced curtailment reflects the difficulty for a system operator to balance the system.

The next three indicators are long-term ones. The capacity adequacy is suggested by Pietzcker et al. (2016): the ratio of all installed dispatchable or ensured capacities divided by peak-load demand. The ratio must exceed 100% to avoid blackouts. However, a high ratio may lead to investment in capacity that will be less used than expected and that may be never profitable. We can also analyse the cases of sub-optimal investment in network in the form of stress tests. What is the level of installed power capacity without cuts and with a power cut of 1 hour? What would happen if we limit exogenously the investments in interconnection capacities?

Finally, the ensured capacity factor can reflect the minimal level of generation of I-RES in the worst situation. Here, we assume that the countries with a large surface can compensate local fall on wind or solar generation by importing electricity from other regions because wind cannot be calm[18] with a minimum level of insolation[19] throughout the entire territory of the country.

2.1.4. Sustainability

The existing literature represents the sustainability dimension with environmental and climate indicators. Six generic indicators are presented in Table 5. Water is used in energy processing such as nuclear plants, biomass production, and fossil fuel extraction (gas, coal, oil). A large increase in the use of these energies may lead to water scarcity. When this dimension is a part of energy security, all studies have at least one GHG emission indicator. It can be formulated as the growth rate of emissions, the GHG intensity (i.e. the level of emission divided by GDP, GDP per capita or other macroeconomic indicators) or annual level of carbon costs/permit (Sovacool and Mukherjee, 2011). The other widespread indicator is the share of RES in the energy mix. A better performance of these indicators leads to a more sustainable development of a country in terms of climate change. However, this indicator conflicts with diversity indicators from the availability dimension. Next, the country should also reduce the level of pollution that deteriorates human health and the environment. The environmental sub-section can be described by the land use and water scarcity indicators (e.g. efficiency of water use, the amount of water used in industrial sector, deforestation, loss of farmland due to decline in soil quality). The last indicator is the energy, climate change, and environmental policies indicator expressed in a number of goals or targets.

[18] According to Beaufort Wind Scale, calm is the situation in which the speed of wind does not exceed 0.3 m/s.
[19] Except for solar eclipse.

Table 4: Sustainability indicators

N°	Indicator	Sub-dimension	Time	Space	WP2.1	POLES
1	Water scarcity	Environment	LT	D/EU		
2	Land Use	Environment	LT	D/EU		
3	Level of pollution	Pollution	ST/LT	D/EU/W		
4	GHG intensity	Climate change	ST/LT	D/EU/W	✓	✓
5	RES ratio	Climate change	LT	D/EU	✓	✓
6	Sustainable policy targets	---	LT	D/EU/W		✓

ST – short term, LT – long term, D – domestic, W – worldwide, MA – maybe available

2.1.5. Resilience to Risks

The resilience dimension evaluates possible risks and the ability of an economy to deal with them. It should be noted that all resilience indicators interact with indicators from other dimensions and strengthen some of them.

The 6 selected indicators are given in Table 6. First, we consider that the energy infrastructure at the end of its operational life has a further risk of accident, especially in the case of lifetime extension. The IEA (2014a) underlines the problem of an aging generation capacity and network in OECD countries: more than half of coal and nuclear plants are over 30 years old, when nearly all networks infrastructures were built 40 years ago. The aging infrastructure is also an opportunity to rethink the design of the system.

Table 5: Resilience indicators

N°	Indicator	Time	Space	WP2.1	POLES
1	Age of installations	LT	D/EU		MA
2	Accidents and failures	ST/LT	D/EU		
3	Exceptional events	ST/LT	D/EU/W		
4	N-1 formula	LT	D/EU		MA
5	Distance	---	EU/W		✓
6	Policy risks	---	EU/W		

ST – short term, LT – long term, D – domestic, W – worldwide, MA – maybe available

The next three indicators, accidents, exceptional events and N-1 formula, describe the possible physical dysfunctions of systems or gas supply disruption, temporal or sustained. Accidents and failures are very useful indicators in the short-term, but difficult to foresee (see SECURE project[20]; Burgherr and Hirschberg, 2014; Spada and Burgherr, 2016). The N-1 formula is used for gas and represents how vulnerable domestic economy is in the case of natural gas supply disruption from a main gas infrastructure or a main gas importer.

There is some correlation between the last two indicators (distance and policy risks), fossil fuel imports, and energy dependence on the foreign countries. The longer distance, as with the aging installation, can lead to higher risk, in particular if the exporter country is politically instable or has offensive policy. The political risk can be used as an independent index, for example the ICRG[21] indicator in Gupta (2008).

[20] An example of energy risks forecasts using ENSAD database : http://www.feem-project.net/secure/inside.php?page=23

[21] International Country Risk Guide : https://www.prsgroup.com/about-us/our-two-methodologies/icrg

The IEA (2007) suggests the Energy Security Market Concentration indicator ($ESMC_{pol}$) that takes into account policy risks from the exporter: the HHI is weighted by the political risk level of the exporter (3 for high risk, 2 for medium risk and 1 for low risk). Jewell (2011) suggests using an indicator of political stability of supplying countries. The index is a weighting average of the proportion of imports from each supplier and OECD political stability risk[22]. Similarly, Cabalu (2010) uses an adjusted Shannon Diversity Index weighted by the level of political stability of the fossil fuel importer (Worldwide Governance Indicator[23]).

2.1.6. Economic Development

Energy security indicators rarely take into account the impact of energy (security) and climate policy on domestic economy. However, an attempt to improve one of energy security dimensions, for example availability, may lead to the deterioration of the other (e.g. sustainability) or even of the domestic economy. In the case of EU countries, we are interested in if the eastern countries can combine both the improvement on energy security and the implementation of climate policies.

The indicators are given in Table 7. The Human Development Index[24] is useful to measure the evolution of country development. It is based on life expectancy, expected and mean years of schooling and Gross National Income per capita index. The transparency index of corruption or costs and losses due to corruption can, on the one hand, express the level of development. Indeed, the top 20 countries with the lowest levels of corruption[25] are also the top countries (1-24) according to the HDI. On the other hand, this indicator reflects an economic efficiency of domestic politics. The change in household and company behaviour captures how country inhabitants perceive energy (security) and climate policies and if their behaviour comes into conflict with energy security objectives.

Table 6: Economic development indicators

N°	Indicator	Time	Space	WP2.1	POLES
1	Human Development Index (HDI)	LT	D		
2	Transparency index of corruption	LT	D		
3	Change in behavior	LT	D/EU		
4	Electricity interconnection capacity or trade	ST/LT	EU		MA
5	Energy policy stability	LT	D/EU		✓
6	Dependence on energy revenue	LT	D/EU		✓

ST – short term, LT – long term, D – domestic, W – worldwide, MA – maybe available

The dynamic of electricity trade within Europe reflects the integration of the electricity market. We have seen above how the harmonisation of electricity (IEA, 2014, CEER 2016) and gas market (CEER 2016, EU commission 2014) is important for the EU. The next indicator, the stability of energy policies, is a long-term indicator of investment risk and efficiency of policy measures. In fact, the erratic incentives to encourage energy efficiency and climate-friendly investment can precipitate the bankruptcy of companies that are invested in such measures if these measures were to be abruptly cancelled. In the long run, this will discourage potential future investors. Finally, the dependence on

[22] http://www.oecd.org/trade/xcred/cre-crc-current-english.pdf
[23] http://info.worldbank.org/governance/wgi/index.aspx#home
[24] http://hdr.undp.org/en/content/human-development-index-hdi
[25] http://www.transparency.org/news/feature/corruption_perceptions_index_2016

energy revenue describes the weakness of the country against the domestic energy production. This indicator can be used both for larger energy exporters and for countries where there is a high domestic fossil fuel production for its own needs. In the first case, the commodity price shocks can cause economic recession. In the second case, the high dependence on cheap and highly polluting energy can undermine climate change transition.

2.2. Composite Indicator

The most important challenge is to create an index of energy security based on several indicators. When there are several indicators, countries and/or studied years, it is possible to compare indicators one by one. However, we found 46 useful generic indicators and 12 additional measures, most of which can be broken down by energy source, origin, and time (short/long term). Moreover, we would like to compare energy security in more than 30 countries. Should we suggest the composite indicator or reduce dramatically the number of indicators? Ang et al. (2015a) dissuade using the second option as the results would be too sensitive to the value of indicators and would not be able to describe the complex situation of a country.

Ang et al. (2015a) identify 35 studies (from 2002 to 2014), which construct an energy security index. Most of them, 63%, use very simple approaches: equal weighting and additive aggregation (Sovacool and Brown, 2010), composite index using a few indicators (IEA, 2007), or focus only on one energy source (Gupta, 2008). Here, we decided to present the more sophisticated methods, summarized in Table 1. We compare 21 documents, written since 2008, which cover in some cases more than 20 countries. The number of indicators per study is high, 17 on average, ensuring the stability of the composite index (Ang et al., 2015a). The definition of energy security is different for each study, therefore we overview the indicators used by the authors and match them with our definition of energy security dimensions given in Section 1.1.3.

All studies cover the availability dimension. Sustainability is also present in all studies, except those focusing only on fossil fuel security. This is logical; the definition of sustainability dimension is based on the reduction of GHG emissions and environmental conservation. The affordability dimension is taken into account in 15 studies (75%). Finally, resilience (i.e. risks), economic development and grid reliability are present in only 6, 4 and 2 studies, respectively. Moreover, some studies offer prospective analysis. Ang et al. (2015b) analyse energy security in 2035 using a BAU scenario from the IEA World Energy Outlook. Eckle et al. (2011) propose 4 POLES scenarios for 2050 considering risks. Badea et al. (2011) evaluate energy security in the PRIMES scenarios for 2030. Augutuis et al. (2012) investigate a potential level of energy security if one of the investment projects[26] takes place in Lithuania. Finally, Ren and Sovacool (2015) rank the low-carbon sources of Chinese electricity by order of priority for future investment decisions in terms of energy sources, energy security dimensions and indicators.

As can be seen in Table 1, the authors create the composite index following three steps. First, the indicators are normalised to obtain a common unit and a comprehensive scale. For example, some studies ensure that all indicators have the same impact, positive or negative, on energy security. The goal of the second step is to find the appropriate weights for each indicator. Finally, the normalised

[26] Lithuanian–Swedish power connection, liquefied natural gas terminal in Klaipeda, nuclear power plant in Visaginas.

indicators are aggregated using weights. This procedure seems to be common to create composite indicators (JRC European Commission, 2008).

2.2.1. Normalisation

Ang et al. (2015b) and Augutuis et al. (2012) use the banding method to create K levels for each energy security indicator: from 0 (the least energy secure) to $K-1$ (the most energy secure). This method takes into account both quantitative and qualitative indicators. It is also useful to compare the countries for which the same value of indicator leads to different levels of energy security. The disadvantage of the banding method is the subjective choice of band allocation.

The nine studies (3, 5, 7, 9-11, 15, 19- 21 in Table 1) use the min-max normalisation, which allows one to obtain an identical range of indicators from 0 to 1, given by the following formula:

$$I'_j = \frac{I_j - \mathrm{I_{min}}}{\mathrm{I_{max}} - \mathrm{I_{min}}}$$

Where I_j stands for the j value of the indicator to normalise, $\mathrm{I_{min}}$ and $\mathrm{I_{max}}$ are the minimum and maximum values of indicator I_j. Eckle et al. (2011) use the same concept, but dividing the values of the indicator by its maximum value creates the normalised indicator.

The Institute for the 21st Century (2016) normalises the indicators by the first year of observation (1980). It is similar to the "Distance to Reference" method (JRC European Commission, 2008). We can find the same logic in Sovacool and Brown (2010): the energy security indicators are equal to 1 if the level of energy security has been improved since 1970, 0 for no change and -1 otherwise.

Sharifuddin (2014) and the World Economic Forum (2016) standardise the indicator to have zero mean and a standard deviation equal to 1:

$$I'_j = \frac{I_j - \bar{I}}{\sigma}$$

Where I_j is the value of the indicator to normalize, $\bar{I}$ is its mean and σ is the standard deviation of the indicator. The World Economic Forum (2016) also uses the percentile ranking normalisation, which consists of splitting the indicator values into Q-quantiles and allocating the same value (between 0 and 100) for values in the same quantile.

Other normalisation techniques exist and are described in JRC's handbook (JRC European Commission, 2008):

- Ranking method evaluates the relative performance of countries for each indicator by ranking N countries from the best performance (1) to the worst (N).
- Indicators above/below the mean take three values: -1 if below the mean, 0 if equal to the mean and 1 othewise.
- Cyclical indicator (OECD) is useful for time series and is obtained by subtracting the mean over time and dividing by the absolute value of deviation from the mean.
- Balance of opinions from energy professionals.

- Growth rate over time for each indicator.

2.2.2. Weighting

Apart from equal weighting, many studies allocate the weights based on professional knowledge from the energy sector (1, 2, 4, 6, 15, 17, 19 in Table 1). However, this approach is subjective and depends on the professional position of the expert. To overcome subjective judgments, some authors estimate the weights using mathematical approaches.

The Principal Component Analysis (PCA) is used in Ediger and Berk (2011), Erahman et al., (2016), Gupta (2008), and Martchamadol et al. (2013). The PCA transforms linearly correlated data into a set of linearly uncorrelated, i.e. orthogonal, variables. The aim is to give a new optimal projection of data in lower-dimensional space, and then to choose the most informative viewpoints (principal components or, in other words, axes). Note that the PCA weighting does not measure the relative importance of each indicator, but it reduces the overlapping information between linearly correlated indicators (JRC European Commission, 2008). Hence, the first point is to check which of the indicators is linearly correlated using, for example, Barlett's test for sphericity (Ediger and Berk, 2011). The indicators without linearly correlation must be withdrawn. For the rest of the indicators the authors apply the PCA: the diagonalization of the correlation matrix (or the covariance matrix in the case of non-normalised indicators) allows them to obtain the principal components, as well as corresponding eigenvalues and eigenvectors. The components are ranked from the most representative, with the largest eigenvalue, to lowest one, with the smallest eigenvalue. The JRC European Commission (2008) suggests choosing a few first principal components:

1) For which the eigenvalues are larger than 1.
2) Only the components with explained variance larger than 10%. The explained variance of the component n is given by a ratio between eigenvalue from component n to the sum of all eigenvalues.
3) The cumulative explained variance of chosen components must be larger than 60%.

The authors use the eigenvalues and eigenvectors of selected principal components to compute the weights, but there is no common formula. Moreover, the results of the PCA are sensitive to extreme values.

Zhang et al. (2013) obtain the weights through Data Envelopment Analysis (DEA). The DEA is a nonparametric method to estimate the production function or the efficiency frontier. The obtained curve serves as a benchmarking frontier, i.e. the best possible performance, to which the countries or indicators are compared.

The third technique, used to determine the weights, is the Analytic Hierarchy Process (Ren and Sovacool, 2015; Wu et al., 2012). This methodology considers if the country has objectives to reach in terms of energy security, e.g. a reduction of energy dependence on a foreign supplier, a level of GHG emission not to be exceeded, etc. The AHP represents the trade-off across indicators, energy security dimensions or energy sources through pairwise comparisons. The goal is to identify in each pair of indicators which indicator is more important, as well as the degree of importance expressed on a scale from 1 (equal importance) to 9 (absolute importance).

The JRC handbook also references and describes other methods to build a composite index: benefit of the doubt approach, unobserved components model, budget allocation process, public opinion, and conjoint analysis (JRC European Commission, 2008).

2.2.3. Aggregation

Aggregation is the last step to create a composite index. Indicators can be aggregated first by the energy security dimension, and then to a composite index. The most popular approach is the additive aggregation according to the weights obtained in the second step, more than half of the studies in our case. An example of such aggregation using different weighting methods is given by the JRC European Commission (2008). The study compares some of the composite index using the following methods: PCA, AHP, equal weighting, benefit of the doubt approach and budget allocation process. The results are quite similar for the extreme positions (top and bottom positions). For the rest, the results from the equal weighting method are close to the budget allocation process, the PCA is close to benefit of the doubt, while the AHP gives a very different ranking. The additive aggregation is simple, but it is based on the assumption that the indicators are mutually preferentially independent (JRC European Commission, 2008).

Among the simple aggregation methods, we can cite the root mean square aggregation (Cabalu, 2010; Kanchana et al., 2016):

$$I_j = \sqrt{\frac{\sum_{k=1}^{K} \varphi_{kj}^2}{K}}$$

Where φ_{kj} is a value of indicator k for country j and K is the number of indicators.

The JRC handbook identifies three other issues:

- The rank composite index can be used to compare the level of energy security between several countries, prospective scenarios or through time. We start ranking the countries/years for each indicator (e.g. 1 for the highest value of indicator or the best performance in terms of energy security), and then we take the sum of the resulting ranks.
- The deviation from the benchmarking point – for each indicator we choose the benchmarking value and we compare how far the other observations are. Then we can just add the deviations (Sovacool and Brown, 2010) or use a more sophisticated formula (JRC European Commission, 2008).
- Instead of additive aggregation, we can use the Deprivation Index (geometric aggregation): $DI_j = \prod_{k=1}^{K} \varphi_{jk}^{w_k}$ where φ_{kj} is a value of indicator k for country j and w_k is a weight of indicator k.

A more advanced approach is to apply the Multiple Criteria Decision Analysis (MCDA). Some MCDA methods were cited as weighting methods: AHP approach (Wu et al., 2012; Ren and Sovacool, 2015) and DEA (Zhang et al.). We present here the 6-step TOPSIS[27] approach used in Ren and Sovacool, 2015; and Eckle et al., 2011. First, the matrix of M alternatives or scenarios and J indicators is normalised

[27] Technique for Order of Preference by Similarity to Ideal Solution

using one of the existing methods. In the second step, the weights are created (using the AHP approach (Ren and Sovacool, 2015) or the average importance of each indicator (Eckle et al., 2011)). Third, the best and worst solutions are identified. In the fourth step, the distances from the best and worst solutions are calculated for each indicator. These distances are aggregated to obtain the closeness index in the fifth step. Finally, the alternatives are ranked according the closeness index.

To create a composite index, there are too many methods issued from the decision, voting and social choice theories that can be used. However, there is no common or best approach. The goal is to facilitate the comparisons in the case of a high number of indicators by choosing one of the methods, consistent with the data and the nature of energy security indicators. The sensitivity analysis can be used to check the potential weaknesses of a composite index or to facilitate the choice of method to create a composition index.

Table 7 : Studies with composite index of energy security[28]

					ES dimensions						Energy sources										
N°	Authors	Year	Countries	Indicators	Availability	Affordability	Sustainability	Resilience	E. development	Grid reliability	Oil	Gas	Coal	Nuclear	Electricity	I-RES	Normalization	Weighting	Aggregation	Ex-post analysis (period)	Year of projection
1	Ang, Choong, Ng	2015	Singapore	22	+	+	+			+	•	•			•		5 levels	Subjective	Σ	1990-2010	2035
2	Augutuis et al.	2012	Lithuania	68	+	+	+	+		+	•	•	•	•	•		0-1	Subjective	Σ	2007, 2010	+
3	Cabalu	2010	Asia (7)	4	+			+				•					Min-Max		RMS	2008	
4	Eckle, Burherr, Hirschberg	2011	World, EU	13	+	+	+	+			•	•	•	•	•	•	0-1	Subjective	MCDA		2050
5	Ediger, Berk	2011	Turkey	5	+	+					•						Min-Max	PCA	Σ	1968-2008	
6	Institute for 21st Century	2016	U.S. + 24	29	+	+	+	+			•	•	•		•		1st year	Subjective	Σ	1980-2014	
7	Erahman et al.	2016	71	14	+	+	+		+		•	•	•		•		Min-Max	PCA		2008-2013	
8	Le Coq, Paltseva	2009	EU	4	+			+			•	•	•							2006	
9	Gnansounou	2008	37	5	+		+		+		•	•			•		Min-Max	ED distance	RMS	2003	
10	Dimakis et al.	2012	Greece	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	Min-Max	equal	Σ	1974-2004	
11	Gupta	2008	26	7	+	+					•						Min-Max	PCA	Σ	2004	
12	Badea et al.	2011	EU	8	+		+				•	•	•	•	•	•		Different	Σ	From 1990	2030
13	Kachana et al.	2016	Asia (9)	15	+			+			•	•	•				0-1	equal	RMC	2012	
14	Martchamadol et al.	2013		25	+	+	+				•	•	•		•	•	From -1 to 1	PCA	Σ	NR	
15	Narula, Reddy et al.	2017	India	16	+	+	+				•	•	•	•	•	•	Min-Max	Subjective	Σ	2002, 2007, 2012	
16	Ren, Sovacool	2015	China	NR	+	+	+				•	•	•	•	•	•		AHP	MCDA	NR	+
17	Sharifuddin	2014	Asia	35	+	+	+		+		•	•	•		•		0-1 Normal	Subjective	Σ	2002, 2005, 2009	
18	Sovacool and Brown	2010	22	10	+	+	+				•	•			•		-1, 0, 1		Σ	1970-2007	
19	World Economic Forum	2016	126	18	+	+	+		+		•	•	•	•		•	Several	Subjective	Σ	2016	
20	Wu et al.	2012	China	14	+	+	+				•	•	•		•	•	Min-max	AHP	Σ	1980-2009	
21	Zhang et al.	2013	China	8	+	+					•						Min-max	DEA		1993-2011	

[28] RMS – Root Mean Square, PCA – Principal Component Analysis, ED – Euclidian Distance, MCDA - Multiple Criteria Decision Analysis, AHP - Analytic Hierarchy Process, DEA - Data Envelopment Analysis, NR – Non Relevant.

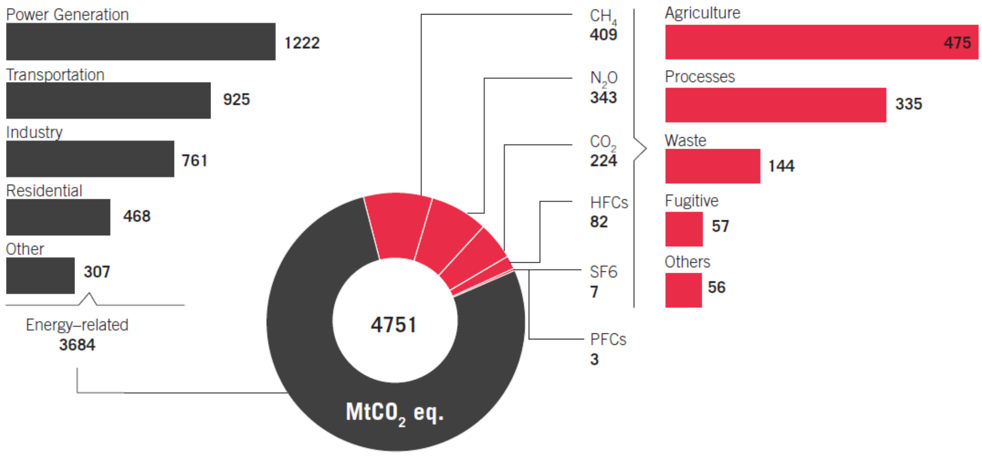
3. European Background of Energy Security

The goal of this section is to review the European background on energy and climate policies. First, we recall the main targets and commitments of EU climate change policy. The second subsection is devoted to the case studies of energy security stakes in Bulgaria and Poland, which allowed us to identify useful indicators suitable to country specificities. Finally, the potential trade-offs between climate policy and energy security are reviewed.

3.1. EU Climate Change Framework

The EU climate strategy and targets are represented by three energy packages. First, the European 2020 strategy sets 20/20/20: 20% reduction of GHG emissions, 20% of EU energy from renewables and 20% improvement in energy efficiency[29]. The EU Emissions Trading System (EU ETS) is a key tool for GHG reduction in power and industrial sector covering approximately 45% of total domestic GHG emissions. The 2020 target for EU ETS was to reduce the emissions by 21% compared to 2005 levels. This strategy was completed through national targets and measures (GHG emissions, share of renewable energy, energy efficiency and financial supports for innovations).

Figure 6: EU28 GHG Emissions in 2010 (Paroussos et al., 2016)



Second, the 2030 climate and energy framework was adopted in 2014 with the objective of at least 40% GHG reduction by 2030[30]. Besides GHG reduction target, this framework consists of 27% renewable of gross final energy demand by 2030, improving energy efficiency, a roadmap for legislative development, structural reforms of EU ETS and a new governance framework taking into account the competitiveness, security and sustainability of energy. According to the EU Commission, the 40% target is achievable if the EU ETS sectors cut emissions by 43% and the non-ETS sectors by 30% compared to 2005. Both objectives are difficult to implement. Indeed, the carbon price fell below €4 in June 2013 due to the oversupply of CO_2 allowances which was driven by the reduction of emissions due to the worldwide economic recession after 2008 and the contribution to GHG emission reductions

[29] https://ec.europa.eu/clima/policies/strategies/2020_en
[30] https://ec.europa.eu/clima/policies/strategies/2030_en

of other climate policies related to renewables and energy efficiency. As for non-ETS sectors, energy efficiency is the key measure to achieving this ambitious target, which needs new regulation framework.

The third strategy concerns the long-term 2050 targets[31]: an 80% reduction of GHG emissions with two milestone targets (40% in 2030 and 60% in 2040). From the sector point of view, the power sector will have the greatest reduction of GHG emissions, followed by 90% reduction in buildings, 80% for industries and 60% for the transportation sector. Besides the last two strategies, the EU submitted the Intended Nationally Determined Contributions (INDC) to the UNFCCC in 2015 with the objective of at least 40% GHG reduction by 2030 and of 80% reduction by 2050 compared to 1990 levels (Paroussos et al., 2016, for more details about GHG emissions see Figure 9).

More recently, the Winter Package (Clean Energy for All Europeans[32]) sets up the three priorities: "Energy Efficiency First", "World Leader in Renewables" and "Fair Deal to Consumers". All targets remain the same, except for energy efficiency that shall be improved up to a 30% reduction by 2030. The European Commission considers that a 30% improvement in energy efficiency will lead to 12% reduction of fossil fuel imports and therefore will improve the level of energy security. The "Energy Efficiency First" priority focuses on building renovation, new eco-design standards[33] and priority for the best available technologies. Building renovation should be smart, simple, sustainable and incorporate electric vehicles[34] (for example 10% of parking spacing in new buildings and some parking near shopping facilities equipped with charging stations).

The "fair deal to consumers" aims to tackle energy poverty of European households, to provide easier digital consumer information, to simplify everyday operations (energy bills, new contracts, switching between suppliers), to increase the level of protection. In addition, the European Commission considers that the Winter Package could contribute to additional GDP growth (1%) and create 900,000 new jobs.

Finally, the Winter Package relies on the European leadership in renewable technologies and in the power sector. The EU commission would like to improve European position in renewable energy markets, not only for solar and wind energy, but also for bioenergy, while ensuring sustainable forest management. In order to improve electricity security, the package suggests enhancing the cross-border trade and utilisation of cross-border interconnections. Furthermore, they also set as an objective for the power sector a new regulatory framework, better integration of regional markets, better capacity mechanisms and higher flexibility. That is in line with CEER suggestions outlined in section 2 of this report. All of these measures also aim to reassure investors. Concerning EU ETS, the Winter Package increases the long-term target to 90% emission reductions by 2050.

To conclude, energy security is integrated in European climate policies through energy efficiency strategies (availability dimension), energy poverty (affordability dimension), a new regulation

[31] https://ec.europa.eu/clima/policies/strategies/2050_en
[32] https://ec.europa.eu/energy/en/news/commission-proposes-new-rules-consumer-centred-clean-energy-transition
[33] See Ecodesign Work Plan 2016-2019
[34] See Low Emission Mobility Strategy up to 2025

framework of the power sector (resilience and reliability dimensions), renewable strategy (sustainable dimension) and contribution to economic growth and job creation (economic development).

3.2. Focus on Security of European Gas Supply

The last European Energy Security Strategy package dates back to May 2014[35] and reports that the EU is highly dependent on energy imports: almost 90% for crude oil, 66% for natural gas, 42% for solid fuels and 40% for nuclear fuel. Among these imports, gas imports are the most vulnerable for three reasons: high dependency rate, nature of contract (supremacy of long-term contracts indexed on oil prices and take and take or pay clause) and political tension with some importers (especially Russia). In 2014, 37.5% of gas came from Russia, 31.6% from Norway and 24% from North Africa. Russia is the single gas supplier in six countries[36] and provides more than 40% of gas in 7 other EU countries[37]. This gas is primarily used for building heating in winter and to produce electricity. The domestic production and import flows are stable and the demand variation is offset by injections and withdrawal of gas to/from gas storage. In winter, the volume of withdrawn gas can be equal to imports from both Russia and Norway. This was the case on 19 January 2016 when 10,000 GWh were withdrawn from reserves to meet 24,000 GWh of demand[38]. Therefore, an extended disruption of the Russian gas supply can greatly affect European economies.

Due to continuous gas conflicts between Russia and Ukraine, the risk of disruption is high and has already happened in the past. In response to tensions after the annexation of Crimea by Russia, the EU updated their energy security strategy in 2014 and carried out stress tests[39] of partial or complete disruption of gas supply from Russia for a period of 1-6 winter months. The tests revealed two problems:

1) Some of the gas projects to increase energy security have not yet been commissioned due to the economic crisis in 2009 (e.g. Greek-Bulgarian, Romanian-Bulgarian, Bulgarian-Serbian, Moldavian-Romanian and Hungarian-Slovakian interconnectors).
2) Domestic energy security strategies are mostly unilateral, making them less effective. A more cooperative and optimised European gas system will mitigate the impact of disruption.

To deal with disruption, the EU relies on the potential increase in LNG supply, on the better use of gas storage (the volume of stored gas should be sufficient to cover 30 days of domestic gas demand), and on more flexibility (e.g. bidirectional use of gas pipelines). Moreover, European foreign energy policy should be coordinated between member states and gas infrastructure projects should follow all European market and competition rules (e.g. all companies should have access to the pipeline).

In addition to stress tests, the EU commission provided new gas regulation in February 2016: solidarity principles between neighbouring countries, a shift from country strategies to regional strategies (Europe is divided in 7 regions, see Figure 3), new prevention plans and better cooperation, as well as additional transparency measures. The EU commission will play the role of coordinator and will

[35] http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:52014DC0330&qid=1407855611566
[36] Estonia, Latvia, Lithuania, Bulgaria, Slovakia and Finland
[37] Czech Republic, Slovenia, Greece, Poland, Austria, Hungary and Germany
[38] ENTSOG system development map 2016 : https://www.entsog.eu/public/uploads/files/maps/systemdevelopment/ENTSOG-GIE_SYSDEV_MAP2015-2016.pdf
[39] https://ec.europa.eu/energy/sites/ener/files/documents/2014_stresstests_com_en_0.pdf

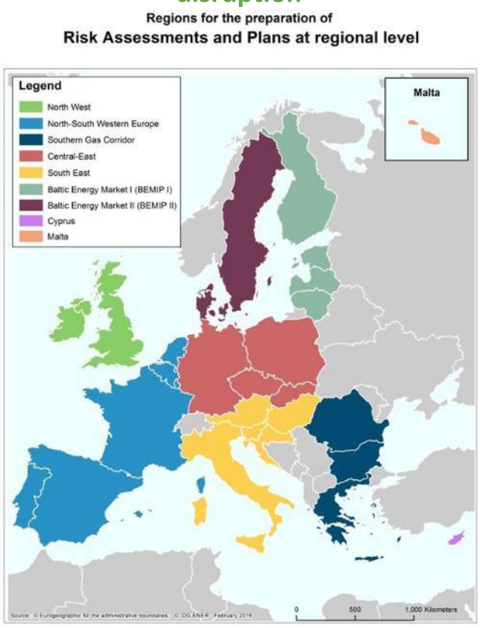
organise Preventive Action and Emergency Plans. They also suggest using a common indicator of gas security threat called $N-1$ formula[40] (or also called $N-1$ standard) that describes the ability of gas infrastructure (technical capacity) to satisfy total gas demand:

$$N-1[\%] = \frac{EP_m + P_m + S_m + LNG_m - I_m}{D_{max}} \times 100 \qquad \forall\, N-1 \geq 100\%$$

Where D_{max} describes maximum possible peak demand, at least once within a 20-year period. EP_m is a technical capacity of entry points other than production (e.g. gas storage). P_m is the maximal technical production capability, S_m is the maximal technical daily withdraw capacity of all storage facilities, LNG_m is the maximal technical daily send-out capacities at all LNG in a calculated area. Finally, I_m is the highest capacity to supply the single largest gas infrastructure. Therefore, $N-1$ formula expresses the adequate capacity of a gas network. Such an indicator could be used in the RIPPLES project if input data are available in prospective models.

The latest energy security update also highlights the stagnation of gas price for final consumers[41]. The fall of international oil prices has driven a reduction of the EU's energy import bill by 35% since 2013. The EU commission reported that wholesale electricity prices are the lowest for last 12 years, with a 50% reduction of gas prices since 2013 and a 60% reduction of oil prices since 2014. However, the retail prices remain the same. There is thus a potential for improvement concerning the affordability dimension of energy security.

Figure 7: Map of regional segmentation to lead to better cooperation in the situation of gas supply disruption



[40] https://ec.europa.eu/energy/sites/ener/files/documents/1_EN_annexe_proposition_part1_v13.pdf

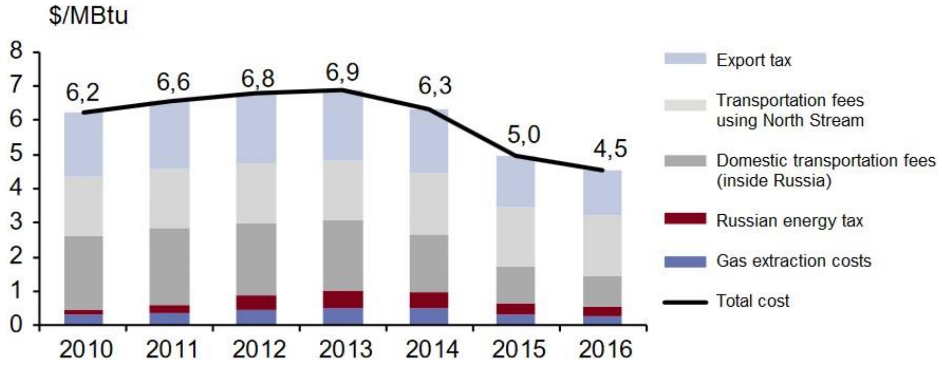
[41] EU's energy bill : https://ec.europa.eu/energy/en/news/eus-energy-import-bill-has-dropped-35-2013

For its part, Russia also reviewed national energy strategy due to high dependency on gas and oil export revenue. First, gas and oil revenues have decreased since 2014. Second, the Russian government would like to deal with a possible future reduction of European gas demand. Finally, they still depend on gas transition through Ukraine. In the short run, Russia counts on the new gas pipeline, North Stream 2, that may allow them to transport gas without being dependent upon a transit through Ukraine. In the long run, up to 2035, they would like to diversify gas exports by increasing Asian exports from 14 billion m^3 in 2014 to 128 billion m^3 and by increasing LNG production up to 74 billion m^3 (Ministry of Energy of Russian Federation, 2017). Gas diversification is also on the European agenda, but the Russian market power can reduce substantially this attempt. Currently, the gas price in Europe is around 5 $/MBtu and the cost of LNG exports remains high. While Russian gas cost through North Stream is lower: 4.5 $/MBtu including approximately 1.5 $ of gas revenue (see Figure 4; Ermakov, 2016). Another problem are the long-term contracts in which both the EU and Russia have an obligation for the next 10-30 years: Figure 5 shows the quantity of gas traded by long-term contracts.

Are answers to the three questions from Section 1.1.2. the same for European gas security? In our opinion – yes. The articles about energy security, which we reviewed, use the same definition of energy security indicator for oil, gas and coal (Cabalu, 2010; Eckle et al., 2011; Badea et al., 2011; Sharifuddin, 2014).

As regard to risks, the EU commission distinguishes 5 types that can undermine the security of gas supply. The political risk expresses the possible disruption from gas import in the case of war, terrorism, political unrest and other gas disruption from a third country. Second, natural risks are about natural disasters that can lead to gas supply disruption. Third, technical risks during gas production, transmission and excavation works; possible leakages, equipment failures, and cyber-attacks. Fourth, social risks, as presented by the European Commission, concern only human reliability (theft, sabotage, strikes or vandalism). All of these risks belong to the resilience energy security dimension. The last risk type concerns hazardous financial agreement, commercial disputes, price volatility, underinvestment, unexpected peak demand and other structural under-performances. This risk type may reduce the affordability and availability of gas supply.

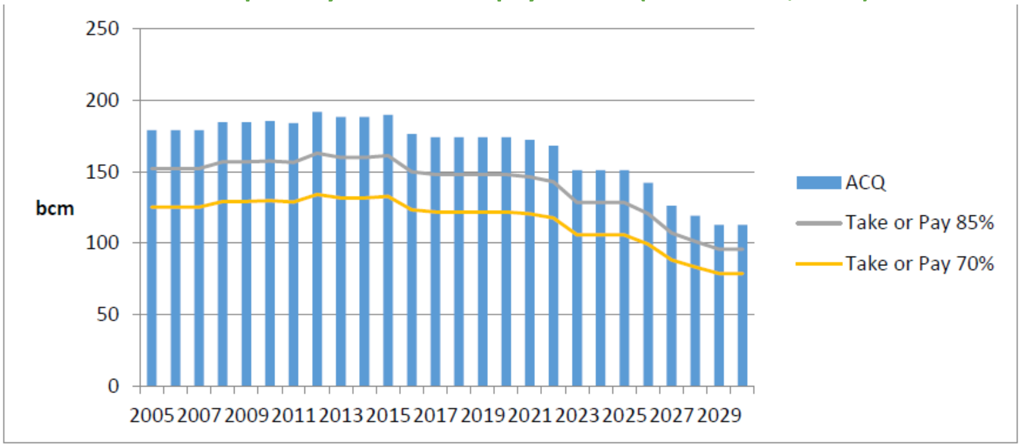
Figure 8: Production and transportation costs of Russian gas export[42] to Europe (Ermakov, 2016)



[42] From Bovanenko gas field to Germany through North Stream (≈ 3,200 km), supporting a return on investment (North Stream) and current rate of pipeline utilization.

However, there are two specificities for natural gas security. First, as the EU commission suggests dividing Europe in several regions to improve gas security, the same regional partition could be retained in prospective analysis. Second, even if natural gas can be stored, it is distributed through a large network and a network operator must ensure the continuity of gas supply, quality of gas and quality of services. In addition to these specificities, it is important to explore potential trade-offs between gas security and climate policy. For example, climate policy encourages countries to replace inefficient coal plants by cogeneration gas plants or to use them as backup facilities that can increase gas dependency on foreign suppliers.

Figure 9: Russian long-term export contracts with OECD European countries to 2030: annual contract quantity and take-or-pay levels* (Dickel et al., 2014)



*Data in Russian units; not including Baltic and south East European countries (aside from Turkey and Greece)

Source: ERI RAS in Henderson and Pirani (2014), Figure 3.3, p.60.

3.3. Energy Security Background in Poland and Bulgaria

In the next two subsections, we present the energy security stakes in Bulgaria and Poland. These studies allowed us to identify specific indicators presented in Table 8. For Poland it is important to evaluate the implication of climate policy on gas and oil import dependency, as well as energy prices and changes in coal sector. When Bulgarian case study highlighted the importance of fuel poverty (the worst performance in EU) and a potential dependency on revenue from electricity exports.

Table 1: Energy security indicators issued from case studies

<table>
<tr><th>Bulgaria</th><th>Poland</th></tr>
<tr><td colspan="2">Import dependency</td></tr>
<tr><td colspan="2">Energy intensity of GDP</td></tr>
<tr><td colspan="2">N-1 formula on gas import dependency</td></tr>
<tr><td colspan="2">Import price sensitivity for natural gas and oil</td></tr>
<tr><td colspan="2">Average energy expenditure</td></tr>
<tr><td>Fuel Poverty</td><td>Loss of Load Expectation (LOLE)</td></tr>
<tr><td>Local energy reserves and storage capacity</td><td></td></tr>
<tr><td>Dependency of some regions on natural gas</td><td></td></tr>
<tr><td>Access of population to gas network</td><td></td></tr>
<tr><td>Energy and CO₂ intensity</td><td></td></tr>
<tr><td>Policy risk</td><td></td></tr>
<tr><td>Age of installations</td><td></td></tr>
<tr><td>Electricity export dependency</td><td></td></tr>
<tr><td>Share of energy companies owned by state</td><td></td></tr>
<tr><td>Share of RES in energy mix</td><td></td></tr>
</table>

3.3.1. Bulgaria

As of 2017, Bulgaria has a territory of 110,879km² and a population of 7.1 million. Bulgaria is ranked as "Upper middle income" country by the World Bank. Eurostat[43] data show, that energy use in Bulgaria is 448.5 kg of oil equivalent per 1,000 EUR of GDP which makes the country the one with the most energy intensive economy in the EU.

Bulgaria is considered the most vulnerable EU country in terms of fuel poverty with 33% of fuel poor households (Pye and Dobbins, 2015). Moreover, two thirds of the Bulgarian households have difficulties to keep home "adequately warm" according to Statistics on Income and Living Conditions survey (Kisyov, 2014).

Being situated at one of the important crossroads between the East and the West, Bulgaria is usually seen as a country that could help to improve the European Union's overall energy security. Energy Security in Eastern and Southeastern Europe has always been an issue in the East-West foreign relations, but became a more pressing matter after the natural gas supply crisis in January 2009, when Russian supplies through Ukraine stopped for about a month for the first time in more than 30 years.

Energy Balances

Bulgaria is net importer of oil and gas and this affects negatively its trade balance. An analysis of the Directorate-General for Economic and Financial Affairs of the European Commission shows, that Bulgaria has the third largest total energy trade deficit in the period 2009-2013, amounting to about 6.4% of GDP, while the share of energy in total trade is 19.4%[44]. Regarding gas trade balance, it is

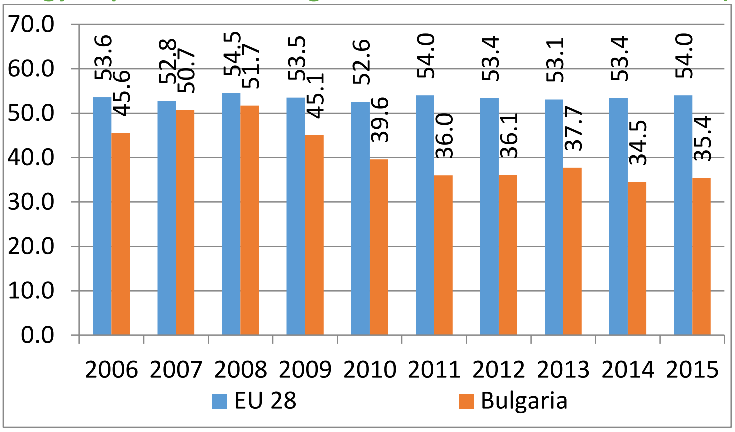
[43] Eurostat (2015) Energy intensity of the economy. http://ec.europa.eu/eurostat/en/web/products-datasets/-/TSDEC360

[44] European Commission (2014) Member State's Energy Dependence: An Indicator-Based Assessment. Occasional Papers 196

negative for all member-states of the EU, and the largest deficit for the same period is in Lithuania, Slovakia, Hungary, and Bulgaria. In Bulgaria its value is 2.3% of GDP.

According to Bulgarian government's data, Bulgaria had an overall dependence on energy imports for 34.5% of its consumption in 2014 – a better position than the average for the EU, which was dependent for 53.4% of its imports[45].

Figure 10: Energy Dependence of Bulgaria and EU-28 – 2006-2015 in % (Eurostat[46])



However, nuclear energy, which had a 37.1% share in primary energy production in 2014, is considered as local according to Eurostat methodology. In Bulgaria, there are 4 nuclear units under decommissioning (a total of 1760 MW) and 2 operational units with a total capacity of 2000 MW. All of the above are Russian design and the latter are still supplied only with Russian nuclear fuel. Also, the only oil refinery in Bulgaria, Lukoil Neftochim, which holds almost 50% of the local fuels market, is 100% subsidiary of the Russian energy company Lukoil. Thus, Bulgaria is dependent on Russia for about half of its oil and fuels, for more than 90% of its gas consumption and for 100% of its nuclear fuel imports.

The largest local energy resource is lignite coal, which is used for power production, but is also subject to stricter carbon, sulfur, and nitrogen emissions regulations.

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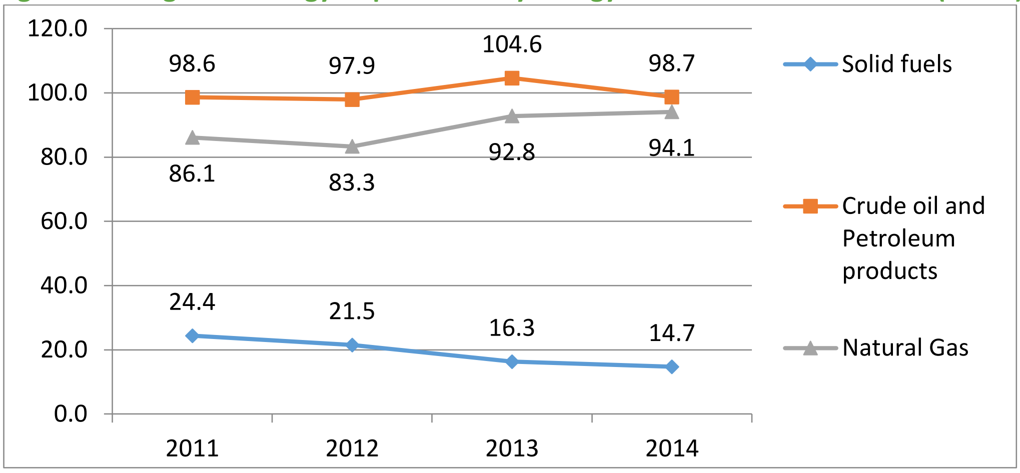
[45] Ministry of Energy of Bulgaria (2016) Bulletin on the State and Development of the Energy Sector in the Republic of Bulgaria, https://www.me.government.bg/files/useruploads/files/buletin_energy_2016_end.pdf

[46] Eurostat (2017) Energy dependence statistics, http://ec.europa.eu/eurostat/tgm/table.do?tab=table&init=1&language=en&pcode=tsdcc310&plugin=1

Figure 11: Bulgaria's Energy Dependence by Energy Resource 2011-2014 in % (NSI[47])



Natural Gas Infrastructure

The gas infrastructure in Bulgaria was designed and constructed mainly as a system for transporting natural gas from the East (from USSR and later from the Russian Federation) to Southern and Western Europe and is still primarily owned, operated, and used by the incumbent state-owned integrated gas company of Bulgaria.

The Bulgarian gas grid was built in the 70s of the 20th century mainly to solve a logistical task for Russia – connecting the Russian gas system with a consumer of roughly 10-15 bcm p.a.: Turkey. The "Trans-Balkan" gas pipeline connects Russia, Ukraine, Moldova, Romania, Bulgaria, Macedonia, Greece, and Turkey, but operates one-directional flows.

Gazprom has been negotiating the purchase of the Bulgarian grid very actively about 20 years ago and would have been the first foreign co-owner of some of the local transmission grids, if South Stream was built.

Currently, 100% of the Bulgarian transit pipelines' capacity is reserved for Gazprom and there is still no other source or supplier of gas with the exception of some test virtual supplies through the existing Bulgaria-Greece gas interconnector.

Most of the countries in the region are heavily dependent on Russian gas supplies with no alternatives. Currently Bulgaria is dependent on Russian supplies for over 98% of its consumption.

There is only one underground gas storage in Bulgaria – "Chiren", operated by Bulgartransgaz EAD. The total working capacity of the storage is 500 mcm and its maximum daily withdrawal rate is about 4-5 mcm. According to "stress tests" by the European Commission, the capacity and the withdrawal rate would not be enough to cover the winter daily demand of about 12 mcm during a new gas supply cut. In order to increase the security of gas supply, Bulgartransgaz intends to increase the working capacity of the storage to 1 Bcm and its daily withdrawal rate to 8-10 mcm. There is also an option for

[47] NSI (2017) Energy Balance Sheets 2015, http://www.nsi.bg/en/content/14918/%D0%BF%D1%83%D0%B1%D0%BB%D0%B8%D0%BA%D0%B0%D1%86%D0%B8%D1%8F/energy-balance-sheets-2015ibid.

a second gas storage at "Galata" – a depleting shallow offshore gas field, operated by Petroceltic. Its working capacity may be up to 800 mcm, but as of June 2017 there is still no decision on the future of the gas field.

Natural Gas Market

Data from the national incumbent wholesale supplier Bulgargaz[48] show, that Bulgaria consumed 3.04 Bcm of natural gas in 2016, and 99.83% of this gas was imported from the Russian Federation. The rest of the consumed gas is produced locally – right offshore the Black Sea coast, from a small field at the end of its life, operated by the British company Petroceltic.

The share of natural gas in the national gross energy consumption was only 11.6% in 2014[49]. However, about 31% of this gas is used for district heating services in the large towns of Bulgaria, including the capital city of Sofia. Leaving these plants without gas in the coldest days of the winter could cause not only discomfort for the households and businesses, but also a crisis with the electricity supplies, if all homeowners switch at once to backup electric heating devices. Another large consumer of gas in Bulgaria is the industrial sector – 35% for the chemical industry, 8% for glass production, and 3% for metallurgy. About 16% of the gas consumption in 2014 was directed toward gas distribution companies and their customers.

Currently there is no real gas market in Bulgaria. The country buys all the gas it needs from Gazprom, receives it via one pipeline (through Ukraine, Moldova, and Romania), and this gas is sold internally by the incumbent Bulgargaz EAD – a subsidiary of the state-owned Bulgarian Energy Holding EAD, and by the largest owner of local gas distribution companies – Overgas Inc. There is no diversification in the national gas market and this makes business and household consumers extremely vulnerable to supply crises and price changes. The gas is purchased via long-term contracts, dependent on oil price swings and with no real connection to the gas spot markets in Central and Western Europe.

Natural gas has a lot of growth potential in Bulgaria. Currently only about 3% of households use natural gas, as this market segment was not developed until the 1990s, but the Energy Strategy of Bulgaria until 2020, which was adopted in 2011[50] envisions a further development of gas use in households. About 75% of municipalities in the country are not connected to the gas transmission network, leaving businesses and households without the possibility to use natural gas. The document also puts as a priority the replacement of the electric energy with natural gas for domestic heating and for housekeeping needs, which would "contribute to three times higher saving of primary energy" and "should be viewed as one of the methods for improvement of the energy security".

According to the strategy's text, in order to guarantee the state's energy independence "with strict adherence to the environmental requirements", there would be development of new natural gas fields "including, without being limited to, shale gas and deep water wells in the Black Sea", which will be "actively supported".

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[48] Bulgargaz EAD (2015) Financial Statements 2014 http://bulgargaz.bg/upload/editorfiles/files/BGaz_god_fin_otchet_2014a.pdf. Accessed 22 Aug 2015

[49] Ministry of Energy of Bulgaria (2016) Bulletin on the State and Development of the Energy Sector in the Republic of Bulgaria, https://www.me.government.bg/files/useruploads/files/buletin_energy_2016_end.pdf

[50] Ministry of Economy, Energy, and Tourism of Bulgaria (2011) Energy Strategy of the Republic of Bulgaria till 2020. http://www.mi.government.bg/files/useruploads/files/epsp/23_energy_strategy2020%D0%95ng_.pdf

The EIA estimates[51] that Bulgaria has technically recoverable unproved resources from wet shale gas amounting to 17 Tcf. However, Bulgaria was the second member-state of the EU to enact a moratorium and a ban on hydraulic fracturing in January, 2012. The Bulgarian government was initially extremely enthusiastic about the prospects of shale gas. The Energy Minister Traycho Traykov (2009-2012) has even said in 2011 that 1 trillion cubic meters of gas could be found in Bulgaria, which would cover the country's consumption for 300 years[52].

There are also about decade-old plans for building gas interconnectors to Romania, Greece, Serbia and Turkey. And last but not least, gas transmission projects such as the EU-supported Eastring and the Russian South Stream, if they are ever built, would cross the country, promising the possibility of new connections to the gas network, for instance for some of the municipalities that now have no access to gas and no distribution networks. All of these developments augur well for gas consumption in the coming years.

In 2012, a consortium of the French company Total, the Austrian company OMV, and the Spanish company Repsol signed a contract with the Bulgarian government for exploration of one of the most promising conventional gas fields in the offshore Black Sea – "Khan Asparuh". The initial studies show potential reserves between 1.5 and 3 Tcf. In April 2015 the Bulgarian government published additional tenders for two additional blocks in the Black Sea: "Silistar" (renamed to "Khan Kubrat" in 2017) and "Teres". Shell won the tender for "Khan Kubrat" and has already performed seismic studies of the block. The three Black Sea blocks are seen by the government as the only current viable option for local gas production.

Electricity Market

Bulgaria has been the fifth largest exporter of electricity in the European Union in 2014, after France, Germany, Sweden, and the Czech Republic[53]. Due to national regulatory imbalances, Bulgaria's net physical exports dropped from 9,451 GWh in 2014 and 10.5 TWh in 2015[54] to 6.3 TWh in 2016[55]. The electricity net exports accounted for 23% and 16% of net electricity production in 2015 and 2016 respectively.

The majority of power generation in Bulgaria is owned by the state through the 100%-owned Bulgarian Energy Holding EAD (BEH). BEH is the 100% shareholder in the following companies: NPP Kozloduy (2000 MW), the lignite-fired TPP Maritsa East 2 (1600 MW), the public supplier NEK EAD (with hydro capacities of 2700 MW, including all the pumped storage hydro power plants with a total capacity of 940 MW), and the whole transmission network and TSO under the subsidiary company ESO EAD. NEK EAD also has two PPA contracts with two US-owned lignite thermal power plants for 100% of their production – TPP AES Galabovo (670 MW) and TPP ContourGlobal Maritsa East 3 (908 MW). BEH is also the 100% shareholder of the public supplier for natural gas Bulgargaz EAD and the national gas transmission system operator Bulgartransgaz EAD.

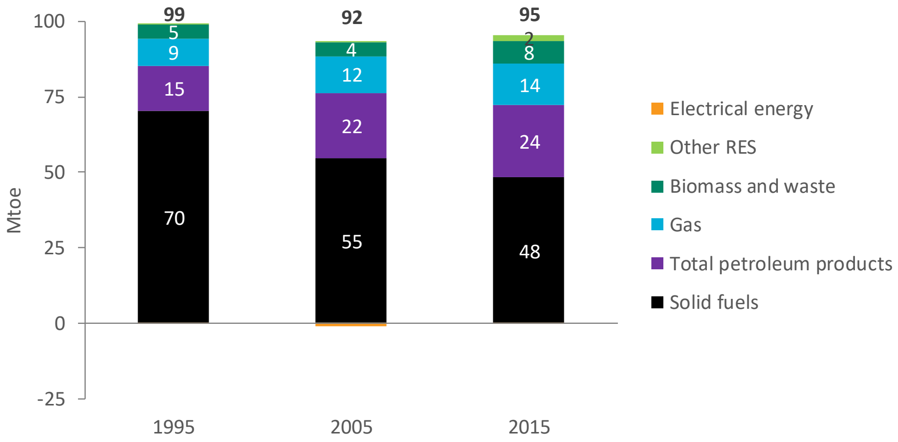
[51] Energy Information Administration (2013) Technically Recoverable Shale Oil and Shale Gas Resources: An Assessment of 137 Shale Formations in 41 Countries Outside the United States. http://www.eia.gov/analysis/studies/worldshalegas/
[52] Tsolova T (2011) Bulgaria seeks to ease fears on shale gas drilling. http://www.reuters.com/article/2011/07/19/bulgaria-shale-idUSLDE76I12520110719
53 ENTSO-E (2015) ENTSO-E Statistical Factsheet 2014
[54] ENTSO-E (2015) ENTSO-E Statistical Factsheet 2014
[55] http://www.nsi.bg/en/content/5027/production-and-deliveries-electricity

The Bulgarian power sector has been diversified with a rapid growth of renewable energy sources in the period 2011-2012. The poorly-structured supporting scheme for renewable energy through feed-in tariffs has initially led to applications for 12,000 MW of new RES capacities in a market with a minimum consumption of about 2,662 MWh/hour and peak at about 7,105 MWh/hour. Currently there are 1040 MW of photovoltaic power plants, 701 MW of wind, and 47 MW of biomass power plants[56].

3.3.2. Poland

On the aggregate level, Poland is amongst the least energy import dependent countries in the EU. In 2015, its total import dependency ratio was 29.3%, while the EU average was 54%. However, this aggregate figure does not reflect several significant energy security challenges faced by Poland, including high dependency on imported gas and oil products, unfavorable domestic extraction dynamics, high sensitivity to oil price shocks, and security of electricity supply problems.

Figure 12: Primary energy consumption in Poland, 1995-2015

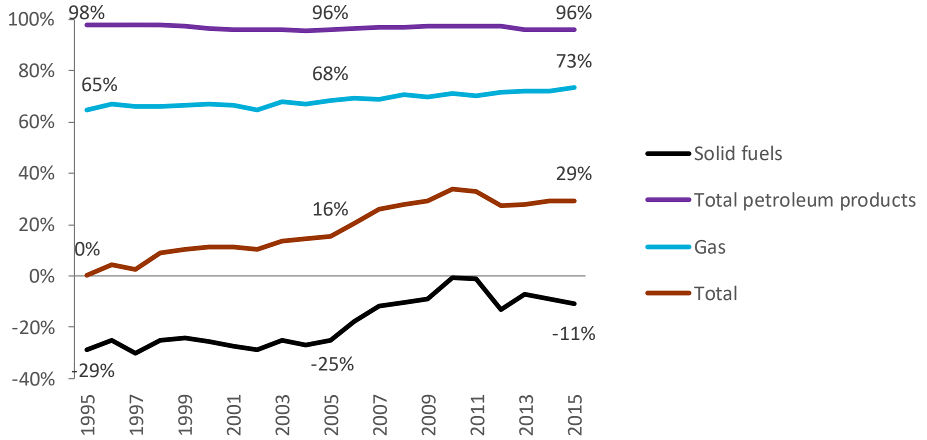


Source: own elaboration based on Eurostat data

Closer look at energy import dependency ratios for different types of fuels shows stark difference between solid fuels (lignite and hard coal), for which Poland remains a net exporter, and natural gas and oil-based products. In case of natural gas, domestic sources cover less than 30% of Polish needs; domestic oil extraction has marginal impact on total energy balance. Import dependence is somewhat reduced by RES use, which is still dominated mostly biomass used for heating. With limited hydropower potential and lack of significant PV deployment in recent years, onshore wind farms remain only significant non-biomass renewable source contributing to Polish energy self-sufficiency.

[56] Georgiev, A. (2015) Statistical Data and Indicators for electricity production in Bulgaria during 2014, Energetika 2015(4):28 41

Figure 13: Energy import dependency in Poland, 1995-2015

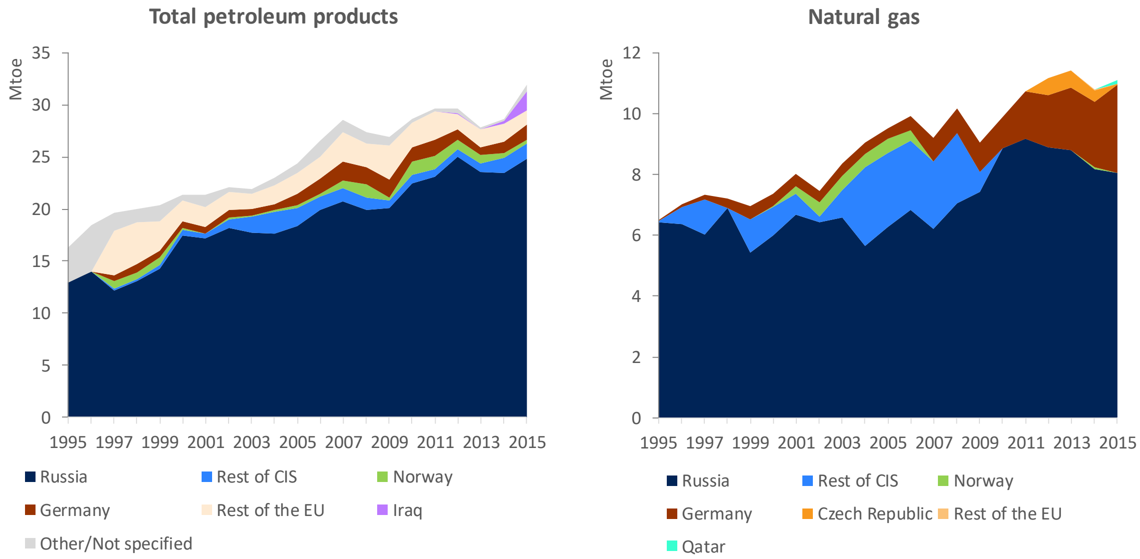


Source: own elaboration based on Eurostat data

Gradual increase in energy import dependency of Poland is explained by two key factors:

1) Decreasing potential of domestic hard coal mining, which gradually lost its position as a major net exporter.
2) Gradual shift of energy mix away from solid fuels towards petroleum products and natural gas, driven by changes in industrial energy use associated with economic restructuring since early 90s, as well as rapid increase in transport fuel consumption, as increasing affluence of Polish consumers led to gradual decrease in mobility gap between Poland and Western Europe.

Figure 14: Sources of petroleum products and natural gas imports to Poland, 1995-2015



Source: own elaboration based on Eurostat data

Despite diversification efforts, Russia remains key source of imports both for crude oil and natural gas. The role of intra-EU trade in natural gas is increasing, which is the result of cross-border infrastructure development (see details in the next section). In recent years, new Middle Eastern suppliers have entered Polish market. After the completion of both LNG terminal (2015) and new crude oil terminal

(2016) on Baltic sea, the potential of geographical diversification of energy imports to Poland has increased significantly.

Security of natural gas supply

Poland has historically depended on natural gas supplies from Russia. Lack of alternative import routes limited the negotiating power of Polish state-controlled company PGNiG when it signed the long-term supply contract with Gazprom in 1996. Since then, PGNiG is obliged to purchase substantial volumes of natural gas at oil-linked prices. These are typically higher in comparison to Western European markets and expose the buyer to the risk of divergence of oil and gas market. Russia has also been gradually diverting the route of its exports to Western Europe by constructing Nord Stream (and planning to construct Nord Stream II), which may result in Poland the status of a gas transit country.

Poland has been pursuing diversification in recent years, aiming to avoid renewal of long-term contract with Gazprom which expires in 2022. Past investments in this area include expanding access to German market through interconnection point in Mallnow and building first Polish LNG terminal (Świnoujście). LNG terminal capacity enhancement and additional interconnections with Czech Republic, Slovakia, Lithuania, and Ukraine are expected to be commissioned by 2022. Further diversification plans focus on construction of the Baltic Pipe, connecting Poland, Denmark, and Norway, in order to gain direct access to the Norwegian gas supplies before the expiration of the Gazprom contract. An alternative, LNG-focused scenario is also envisaged, i.e. commissioning of a FSRU57 Terminal in Gdańsk.

Table 2: Natural gas consumption dynamics and its share in gross inland consumption in Poland and the EU-28 under the EU Reference Scenario 2016 up to 2030

	2000	2005	2010	2015	2020	2025	2030
	Natural gas consumption dynamics (2010 = 100)						
Poland	78	96	100	103	127	143	160
EU-28	89	100	100	87	86	87	83
	Share of natural gas in gross inland consumption						
Poland	11%	13%	13%	13%	15%	17%	19%
EU-28	23%	24%	25%	23%	23%	24%	24%

Source: own elaboration based on Capros et al. (2016)

While such significant investment in fossil fuel-based infrastructure may be perceived as an example of conflicting priorities (energy security and climate protection), there is an additional justification for short-term investment in gas infrastructure in Poland. While on the EU level natural gas consumption is expected to decline in the coming years, in Poland it is projected to significantly increase in 2020s, even despite European climate and energy policy framework supporting in RES and energy efficiency. This is explained mainly by current low share of natural gas in Polish energy mix. Historically, both price differentials and security concerns favored the use of hard coal instead of natural gas in energy sector, district and individual heating, as well as in industry. Thus, even after accounting for increased energy efficiency and RES deployment, coal-to-gas shift resulting both from idiosyncratic trends in energy mix evolution and decarbonisation policies will lead to increase in natural gas consumption in medium term. Recent analysis for CEE region confirms that additional infrastructure investments in Poland are

[57] Floating Storage Regasification Unit

required to avoid the risk of gas supply disruptions in 2020s (ENTSOG 2017). From the perspective of long-term security of natural gas supply, it is important to estimate when the peak in gas consumption in Poland will occur within its decarbonisation pathway, as well as what maximum amount of gas imports will be required. Broader European context is also relevant, as, for example, increase in gas imports to Poland may correspond to increase in overall rise of gas import dependence in the region, which lowers effectiveness of diversification measures based on interconnection investments.

Security of electricity supply

The combination of aging power fleet and increasing demand, especially during summer months, is driving concerns over security of electricity supply in Poland. In August 2015 a major heatwave caused serious blackout risk, forcing Polish TSO to limit electricity supplies to industrial consumers (ENTSO-E 2015, p. 43-44). The problem has been alleviated in the short term by combination of better planning of maintenance works, demand-side management measures, increased interconnections (including measures aimed at limiting unscheduled loop flows which cause congestion on Polish-German border) and ongoing investments in several new power plants. Nevertheless, significant capacity gap is projected to emerge in the early 2020s, driven by expected power plant decommissioning due to new, more stringent air pollution regulations, as well as electricity demand growth.

The key solution preferred by Polish policymakers is capacity market, focused on supporting new large coal power plants. Alternatives are deemed as less secure: intermittent RES are seen as contributing to “missing money” problem, regional integration of reserves raises worries related to their management in crisis situations, while investment in gas power plants is viewed as an option which increases import dependence. Thus, complex assessment of energy security impacts of low-carbon transition should take into account these issues, with particular focus on interaction between electricity and gas supply security. For example, a scenario combining gas supply disruption and lengthy period of low output from variable RES may be considered.

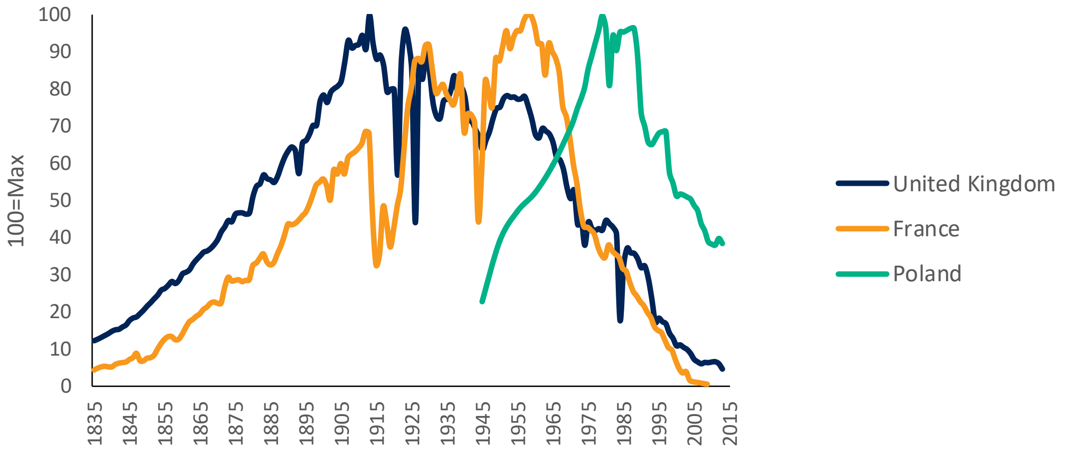
Declining potential of domestic coal mining

For decades, domestic hard coal and lignite extraction were crucial for maintaining high energy self-sufficiency in Poland. Nevertheless, future prospects of domestic coal mining are pessimistic, even before taking into account the impacts of climate policies.

Currently operating lignite mining pits will be exhausted by mid-century, with major Bełchatów mine expected to be decommissioned in 2030s. While Polish energy companies consider several new lignite projects to replace existing ones, in practice these major investments face significant barriers. Apart from high financial risks associated with capital-intensive, long-term investments in emission intensive forms of electricity generation in Europe, there is significant public opposition to new lignite mine investments. Objections are voiced by local residents, many of whom will have to be reallocated, as well as farmers concerned with the mines’ environmental impacts.

While lignite extraction faces decline due to exhaustion of currently operating mines, in case of Polish hard coal mining the key driver is its low competitiveness which results from low productivity and gradual increase in local labour costs. In fact, current decline of hard coal mining closely resembles developments in Western Europe several decades ago. Continuation of this trend is likely to lead to complete or near-complete phase out of hard coal mining in Poland by mid-century (Bukowski et al. 2015).

Figure 15: Long-term coal mining dynamics in the United Kingdom, France, and Poland



Source: Bukowski et al. (2015)

Implementation of climate policy is affecting Polish hard coal mining through two key channels. First, domestic mitigation actions decrease local demand, eroding associated transport cost advantage of Polish mines. Second, aggregate global decarbonisation efforts drive down the demand for coal compared to no policy scenario, thus decreasing the benchmark price for Polish mines. These two effects will magnify the internal competitiveness problems of the sector in Poland and are likely to increase the pace of its decline. However, at the same time domestic mitigation actions contribute to increase in alternative energy sources and energy efficiency improvements, decreasing needs for hard coal imports. Thus, the net impact of climate action on dynamics of hard coal import dependency ratio in Poland depends on specific energy transition pathways, internal restructuring potential of the sector and international developments.

Fuel import cost volatility

Similarly to other European countries, crude oil imports remain the key source of total energy import cost volatility in Poland. While per capita gross inland consumption of petroleum products in Poland was 43% below the EU average in 2015, the associated cost relative to the size of total economy was significantly higher. In 2015, the costs of imported oil amounted to 2.0% of Polish GDP, compared to the EU average of 1.2%58. In 2013, during the period of high oil prices, Poland had to spend 3.4% of its GDP on crude oil imports, compared to the EU average of 2.2%.

Costs of energy transition

As in the case of oil import costs, energy system costs in Poland are relatively high compared to GDP. This is also evident when the share of energy in total consumption expenditure is compared: in Poland, it amounted to 13% in 2014, more than double the EU average (EC 2016). While in the long term economic growth and energy efficiency improvements are likely to decrease relative costs of energy system in Poland, its dynamics in the short and medium term are highly relevant from the perspective

[58] Calculations based on Eurostat data for GDP and import values.

of affordability dimension of energy security, especially taking into account significant investment effort required to decarbonise the energy system in the coming decades.

As in the case of oil import costs, energy system costs in Poland are relatively high compared to GDP. This is also evident when the share of energy in total consumption expenditure is compared: in Poland, it amounted to 13% in 2014, more than double the EU average (EC 2016). Nevertheless, the overall incidence of fuel poverty is currently comparable to the EU average. While arrears on utility are several percentage points above the European average, almost 90% of Polish households are able to keep home adequately warm[59]. This can be explained by widespread use of comparatively cheap solid fuels (especially hard coal) for heating purposes.

While in the long term economic growth and energy efficiency improvements are likely to decrease relative costs of energy system in Poland, its dynamics in the short and medium term are highly relevant from the perspective of affordability dimension of energy security, especially taking into account significant investment effort required to decarbonise the energy system in the coming decades, as well as current focus on improving air quality, which may lead to decrease in use of cheap solid fuels for heating purposes.

[59] http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52015SC0234&from=EN

Conclusions

The aim of this report was to review the literature concerning energy security indicators in order to find the most feasible ones that should be applied in the RIPPLES project. As there is no common definition of energy security, our first step was to find one. We suggest representing energy security through multidimensional form. Energy should be ***Available*** for domestic uses, ***Affordable*** for households and companies, ***Sustainable*** to preserve our future, ***Resilient*** to better handle risk, ***Reliable*** to better integration of I-RES and should support a country's ***Economic Development***. Moreover, it is also important to separate time (short-term and long-term) and space (domestic, regional, EU and world) effects. It is also important to note that the emphasis on one or another dimension of energy security is different between countries.

If the first four dimensions are very common in literature, this is not the case for the **Reliability** and **Economic Development** dimensions. Until now, the increasing share of I-RES has been only considered as a positive action to improve energy diversity and reduce dependency on fossil fuels. In the RIPPLES project, we would like to understand how a high share of I-RES might affect the stability of an electricity network. We created this new dimension to take into account the specificity of an electricity system: the need to ensure supply-demand balance at any time. Concerning the Economic Development dimension, the goal is to limit negative spillovers between energy security and a country's economy.

In the second section, we described 46 energy security indicators, among which modellers in prospective energy scenarios are invited to select the most appropriate and useful. Note that the number of usable indicators depends on the model. For example, we can use only 7 indicators with templates used to report DDPP scenarios and between 24 and 35 indicators if scenarios are implemented in the POLES model. We also detect three major challenges to evaluate energy security indicators through prospective models. First, some indicators may refer to exogenous parameters used in prospective scenarios, as is particularly true for the Economic Development dimension (e.g. GDP for partial equilibrium models, or population growth). Thus, we cannot measure the influence of climate policies on them. Nevertheless, we can apply the sensitivity analysis of exogenous parameters by varying the values of parameters. Second, it is impossible to measure future risks and impacts related to the resilience dimension. Finally, the huge number of indicators does not allow comparisons between countries and prospective scenarios. It will be necessary to create a composite energy security indicator following three-step framework presented in Section 2.2: normalise the indicator values, and then create weights to obtain the aggregate energy security index. Such index facilitates comparison between countries or studied years, and shows the contribution of each dimension to energy security.

The last part of the report is a reminder of the most important aspects of EU energy and climate strategies and presents two case studies of Bulgarian and Polish energy security stakes. We finish the report by reviewing the existing literature on trade-offs between climate policy and energy security. Climate policies improve the availability and sustainability dimension of energy security in studied countries. However, the effect on the affordability dimension may be both negative and positive, while the impacts on grid stability and economic spillovers are unknown. Moreover, few studies analyse all EU countries.

Appendix: List of Energy Security Indicators

General energy security indicators

N°	Indicator	Description
1	Shannon diversity index	Widely used indicator of types/species diversities: $$SDI = -\sum_{i=1}^{I}(s_i \times \ln s_i) \quad \forall i = 1, \dots, I$$ Where s_i is the share of each type in population and i the number of types.
2	Distance	The distance from energy supplier or electricity generation site to consumer. We consider here that the risk and the severity of disruption increase with the distance.
3	Human Development index	The HDI is based on the life expectancy at birth, the expected years of schooling, the mean years of schooling and the gross national income per capita.
5	Self sufficiency	The ability to produce and deliver the energy by its own means.
7	Energy intensity	The energy intensity of economy (GDP) or sector (energy expenditure), for example as a ratio between Total Primary Energy Supply and GDP.
8	CO_2 intensity	The emission factor or carbon intensity of economy or sector.
9	Market share or energy mix	In addition to Shannon diversity index and Herfindahl-Hirschman index, it could be useful to analyse the market share of energy sources or energy suppliers. For example, what source of energy has the highest share in energy mix?
10	Import dependency ratio	The ratio between net imports for each energy source (and/or for each sector) and energy consumed by economy/sector.
11	Export or Import to production	The ratio between energy export or imports and domestic energy production. In the case of energy exports, the high ratio expresses the dependency on energy revenue.
13	Energy prices	We can compare here the growth rate of energy prices and inflation. If energy prices increase faster than inflation, the energy will become less affordable. The increase in price volatility can also lead to higher financial risk for energy and no-energy companies.

14	Change of behaviour	Some new technologies assume that households would change their preferences and behaviour. We can take it into account as a future change of consumer utility, demand elasticity, preferences, etc.
15	Energy poverty	In general, the energy poverty is expressed as a share of people for whom the ratio between energy bills and income is too high (e.g. more than 10%). We do not have such level of details in macroeconomic models, but the researcher can suggest a proxy, for example by comparing the evolution of average household expenditure from different scenarios.
16	Average energy expenditure	It is equivalent to energy poverty, but we consider here both households and companies.
17	Transition or transfer costs	Cost of electricity or gas transition through network, transfer costs fort other fuels (LNG, coal, oil, petroleum products, nuclear fuel, and biomass).
18	Energy patents	The number of patents is one of indicator of the ability of domestic economy to develop and introduce new energy technologies, as well as understand and anticipate future technology change. If there is not enough qualified people in economy, the economy will not be able to support and to drive technological progress. For more details, see New Skills Agenda for Europe and Blueprint for Sectoral Cooperation on Skills.
19	R&D and research expenditure	Same meaning as for energy patents.
20	Accidents, failures, disasters	The energy security declines with increasing number of accident, failures and disasters.
21	Policy risk	The policy risk affect the international relationship between several countries or regions and can lead to a higher risk of energy supply disruption.
22	Energy and climate policies stability	The cost of some new technologies, energy or climate commitments need for substantial funding to cover development and implementation costs. Companies should be able to plan the long-term investment strategy. If policies are too unpredictable and lead to risk of substantial losses, companies will decide not to invest.
23	Age of installations	We consider that the risk of accident increase with the increasing age of installations.
24	Energy Returned on Energy Invested	EROI is an efficiency ratio of energy process. EROI below 1 means the energy process consumes more energy than it produces.
25	Energy tax burden	Additional consumer taxes can finance some policy mechanisms or state companies could increase prices to cover unprofitable technology or tariffs. These taxes can lead to unaffordable, for final consumer, energy price spike.
26	Cost of corruption	The high level of corruption, especially in energy sector, will reduce or make inefficient policy measures. This indicator concerns more developing countries than developed.

27	Water scarcity	The water scarcity depends negatively on the level of biomass production, the level of fossil fuels extraction using water and electricity production from nuclear plants.

Indicators Specific to Fossil Fuel

N°	Indicator	Description
1	Herfindahl-Hirschman index	Diversity and market power indicator for energy source f: $$HHI_f = \sum_{i=1}^{I} s_{i\|f}^2 \quad \forall\, s \in [0;100]\,; i = 1, \ldots, I$$ Where $s_{i\|f}$ is the share of each supplier i in the market of fuel f. HHI_f ranges from 0 (maximum level of competition and diversity) to 10 000 (monopoly situation). This index implies that the degree of market power depends positively on the quantity of fuel. Nonetheless, this indicator is not appropriate to measure electricity market concentration.
2	Reserve to production ratio	RPR expresses how long domestic reserves of gas, oil or coal can be used to fill consumption. RPR is equal to the ratio between the amount of proved reserves and annual consumption.
3	Strategic fuel stock	The volume of strategic stock, or the number of days that can be covered in the case pf supply disruption.
4	Refining capacity	The refining capacity of domestic plants.
5	Reserves	The number of operational coal mines, oil and gas wells drilled, average field recovery rate.
6	N-1 formula	See Section 1.2

Indicators Specific to Reliability and Stability of the Electrical Grid

Four principal indicators to measure the reliability and stability of grid are used in European Union (CEER, 2016):

N°	Indicator	Abbreviation	Unit	Description
1	System Average Interruption Duration Index	SAIDI	min	$$SAIDI = \frac{(Installed\ Capacity\ Interrupted \times Calculated\ time\ of\ interruption)}{Total\ installed\ capacity\ in\ system}$$ N.B. extensive formula is generally specific for each country and depends on the location of failure in distribution system (low voltage, medium voltage, etc.)
2	System Average Interruption Frequency Index	SAIFI	N	$$SAIFI = \frac{Installed\ capacity\ interrupted}{Total\ installed\ capacity\ in\ system}$$ N.B. extensive formula is generally specific for each country and depends on the location of failure in distribution system (low voltage, medium voltage, etc.)
3	Customer Average Interruption Duration Index	CAIDI	min	$$CAIDI = \frac{SAIDI}{SAIFI}$$ N.B. extensive formula is generally specific for each country and depends on the location of failure in distribution system (low voltage, medium voltage, etc.)
4	Energy Not Supplied	ENS	MWh	The amount of energy not supplied due to interruptions

Indicators for prospective studies:

N°	Indicator	Abbreviation	Unit	Description
1	Value of Lost Load	VoLL	€/MWh	VoLL can be defined as a willingness to pay of electricity consumer to avoid a shortage or as a value of security of electricity supply. There is no single exact formula for VoLL. Maere d'Aertrycke et al. (2016) suggest that VoLL is equal to price CAP or, in other word, a reservation price of electricity demand. Hawer and Bell (2017) define it as an economic cost impact of not supplying consumers with their desired demand. Després (2015) assumed that VoLL might be reasonably approximated by the maximum fixed cost of peaking power plants: "the society decided that it was not efficient to build an additional peaking capacity at greater cost". London Economics consultancy (2011) estimated the VoLL using the data from discrete choice experiment. Winzer (2012) approximated the VoLL in sector j by the share of the yearly GDP of this sector which is lost in an interruption of duration up to k.

2	Ratio for capacity adequacy	Proxy	%	All installed dispatchable or ensured capacities divided by peak-load demand (Pietzcker et al., 2016).
3	System Average Interruption Frequency Index	Proxy SAIFI	N	In the case of model with highly detailed description of electricity system, we can approximate SAIFI by stress tests of the possible number of exceptional events. Let $n = 1, \ldots, N$ be representative days/hours of load curve and P_n – the probability that the day/hour n occurs. Then we calculate how many times a year the exceptional event happens.
4	Blackout frequency	Proxy	h	How many times a year the supply is unable to meet demand. The value of this proxy depends very much on model structure. The less there are constraints of supply-demand equilibrium, the more frequent the blackouts are. In the case of the models, where the supply-demand equilibrium is the part of objective function, the supply is supposed to meet demand at any time to avoid the blackout. However, we can assume that if the model is unable to provide the solution, then it is impossible to satisfy the equilibrium and the blackout will occur.
5	Arbitrage between storage capacities, curtailment and back-up capacities			We can consider that each option affects, positively or negatively, the social welfare. For example, the more secure scenario in terms of affordability is the one that maximises welfare. If the curtailment is forced, the consumer utility will decrease or will cause non-power accidents (e.g. patient death in the hospital). If the back-up capacities use fossil fuel to produce electricity, then the amount of CO2 emissions will increase, which is inconsistent with climate policy objectives. Some storage technologies may pose higher risk of accident or be too expensive. We can also assume that in the secure electricity system it is little or no need in curtailment and storage/back-up capacities.
6	Stress tests of under-investment in capacities		MW or €	How many MW can be avoided before a power cut of one hour? The value of stress test is the difference between the amount of capacities in prospective scenario without power cut and the one with the power cut of 1 hour.
7	Stress tests of under-investment in grid/interconnections		€	The aim is to measure additional expenditure on electricity in the case of sub-optimal network (e.g. insufficient number of interconnections or/and its capacity). To design the

				sub-optimum, the researcher can limit the transmission capacities, exogenously or endogenously.
8	Loss of Load Expectation	LOLE	h	LOLE is the measure of how long, on average, the available generation capacity is likely to fall short of the load demand. For most European countries, it is equal to 3 hours. Newbery (2015) emphasise that VoLE is used in capacity investment decision. So, if the value of VoLE is not pre-determined by market regulator, than the VoLE is equal to the ration of the cost of investing in capacity and Loss of Load Probability. VoLE can be used to calculated VoLL (Després, 2015).
9	Loss of Load Expectation	Proxy LOLE	h	Let us assume that X first hours per year/accident of curtailment are voluntary or do not affect consumer utility. Whereas the each additional 1 hour of curtailment is forced. Then the electricity system is secure if the curtailment does not exceed X hours. And the level of electricity system security decreases each additional hour after X. Overall, it is considered that the system is secure for $LOLE < 3$ h/year.
10	Ensured capacity factor of wind generation		%	The amount of electricity generation that will be produced in any case. We assume here, that in the case of country/region with large area, it is highly unlikely that aggregate wind generation would be equal zero.
11	Forced curtailment (POLES-EUCAD)	Proxy	MWh or %	Here we assume that curtailment may be desired by consumer or undesired, when the system operator tries to restore supply-demand equilibrium. The amount of this undesired cut represents, among other sings, the degree of electricity system weakness. In order to compute this amount, we simulate two similar scenarios. The first one is simulated using only POLES that does not include implicit constraints on electricity system (POLES is not optimisation model). The total amount of curtailment in this scenario can be considered as desired. In the second scenario, we use POLES coupling with EUCAD, that allow to optimise the electricity system and to take into account technological constraints. The amount of undesired curtailment is the difference between the level of curtailment in both scenarios. (à revoir plustard).

Others specific indicators, which can be used to build the electricity security indicators:

N°	Indicator	Abbreviation	Unit	Description
1	GDP loss due to electricity interruption (Winzer, 2012)		€	This indicator for country i is given by: $$lossGDP_i = \sum_{j} \sum_{k=1\ min,1h,1d} Out_{i,k} \times SAIFI_i \times VoLL_{j,k} \times GDP_{i,j}$$ Where j – sector type, k – duration of the outage (less than 1 minute, 1 hour or 1 day), $VoLL_{j,k}$ – VoLL of sector j due to k type interruption, $GDP_{i,j}$ – share of the total GDP in country i which is provided by sector j.
2	Number of interconnections		N	The level of flexibility of network in the case of unanticipated variation of electricity consumption, weakness of network or exceptional events (defined by researcher).
3	Quality of energy services			Percentage of household with high, medium or low quality connection (%), the quality definition is done by researcher.
4	Avoided cost of RES		€	Possible future market price of RES.
5	Cost of interruption		€	Financial losses due to electricity disruption.
6	Cost Of New Entry	CONE	€	The level of capacity payment needed to incentivize new build. This measure reflects the possible barriers to entry of new capacity that may improve energy security. CONE's formula: specific to each energy model (defined by researcher).
7	Levelized Cost Of Energy	LCOE	€	All plant-level lifetime costs dividing by the amount of lifetime expected power output.
8	Integration costs of I-RES		€	The difference between total system cost with RES and total system cost for a reference case without RES (Gowrisankaran et al.,2016). Hirth et al. (2015) expressed the integration cost as a difference between average electricity price and I-RES market value or the difference between Wind System LCOE and Wind LCOE. In Agora report (2015), the integration costs are defined through 3 components: grid costs, balancing costs and additional costs or losses from other power plants (back-up costs).
9	Intermittency costs (Narbel, 2014)		€	The ratio between integration costs and the quantity of electricity curtailed.

10	Load factor		%	The average load divided by the maximum peak load in given time.
11	Capacity factor		%	The ration between the actual electricity output ***Y*** to the maximum possible electricity output ***X*** in given time period (e.g. year): $$CF = \frac{\boldsymbol{Y}\ MWh}{365\ d \times 24 \frac{h}{d} \times \boldsymbol{X}\ MW}$$
12	Availability factor		%	The amount of time that the power plant is able to produce electricity over certain period.

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