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Energy security: a review of studies of the economic value of energy security

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Alla mia famiglia,

Grazia, Ennio e Zaira;

Alla mia "famiglia" padovana,

Natalia, Marco, Mauro e Manuel;

A tutti i miei compagni di "Viaggio";

"Perché la felicità è vera solo se condivisa!"

Abstract

This thesis work was developed at Comillas Pontifical University, more specifically at the IIT department (Institute for Research in Technology). The aim of this thesis was to define and quantify the key aspects linked to the economic value of energy security, through an accurate review of current literature on this topic, in order to provide an effective support to policy makers.

The first step was to define the concept of "energy security" in the most accurate and clear way, considering the multi-faceted nature this issue has assumed, especially in the last years. After the choice of the definition to be used as reference in the following evaluations, it was explained how the economic value of energy security is based on two main aspects: energy price variation and physical unavailability of energy itself. Once defined the aspects to focus on in this research, using as a starting point an analysis of previously developed models, it was highlight which metrics could quantify the aspects linked to physical availability of resources and their economic "reasonableness", referring to energy systems.

To do this, a discussion on energy insecurity main causes was developed, followed by the identification of the metrics that are actually useful in the evaluation of energy security, between the ones previously classified. Among these indicators, those able to take into account the key aspects in the evaluation of the economic impact were identified. It was pointed out that the parameters linked to the flexibility of energy production and, thus, to the resilience after an unexpected events, to the dependence on energy foreign suppliers, to the diversification in terms of production and economic partners, to the infrastructure reliability, to the markets structure and the price stability, are the preferable indicators in evaluating the implications of energy security.

This work ends with a clarification about the problems related to the use of these indicators and with the suggestion of guidelines on their correct use in energy security assessment, in order to be helpful to policy makers.

Sommario

Il seguente lavoro di tesi è stato svolto presso l'università pontificia Comillas di Madrid, nello specifico presso il dipartimento IIT (Instituto de Investigaciòn Tecnòlogica). L'obiettivo che questa tesi si prefigge è quello di determinare, attraverso una vasta analisi della letteratura precedente, quali siano gli aspetti chiave collegati al valore economico della sicurezza energetica e come sia possibile quantificarli, così da poter fornire un valido supporto ai decisori politici.

In prima sede quindi si è cercato di definire in maniera chiara e precisa cosa realmente si intenda con il termine sicurezza energetica, considerando la natura polivalente che questa tematica ha assunto, in particolar modo negli ultimi anni. A seguito della scelta della definizione da utilizzare come base per le valutazioni successive, si è chiarito come il valore economico della sicurezza energetica si rifletta in due elementi chiave: la variazione del prezzo dell'energia e la sua non disponibilità fisica. Definiti gli aspetti fondamentali verso cui orientare la ricerca, utilizzando come punto di partenza un'analisi dei modelli presentati in passato, si è cercato di estrapolare le migliori metriche che, di un sistema energetico, possano quantificare gli aspetti legati alla reperibilità fisica delle risorse e della loro ragionevolezza economica.

A tal fine, si è condotta una discussione su quali siano le principali cause di insicurezza energetica e, come risultato, tra le metriche ricavate dalla classificazione dei modelli passati, si è proceduto a identificare quali indicatori abbiamo realmente significato nella valutazione della sicurezza energetica e, tra quest'ultimi, quali possano essere dei validi indici per valutare l'impatto economico nei suoi due aspetti chiave. Si è giunti, dunque, alla conclusione che i parametri legati alla flessibilità nella catena di produzione energetica e quindi alla resilienza in caso di eventi inaspettati, alla dipendenza estera di energia, alla diversificazione in termini di produzione e di partner economici, all'affidabilità delle infrastrutture, alla struttura dei mercati e alla stabilità dei prezzi siano, in linea generale, i migliori strumenti di valutazione da utilizzare nell'analisi delle implicazioni economiche della sicurezza energetica.

Infine il lavoro si chiude con una delucidazione circa le problematiche esistenti nell'uso degli indicatori come mezzi di valutazione e con una proposta di linea guida su come questi indici debbano essere impiegati per essere realmente significativi e quindi costituire uno strumento efficace di supporto per i decisori politici.

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Introduction

The adequate availability of energy resources has always been a major problem for every society, especially for the most industrialized ones. The reason is that accessing to a sufficient amount of energy, as the fundamental condition to wellness development and maintenance, has an economic value of primary importance. As a consequence, nowadays energy security represents an important issue in the political agenda of many countries. Throughout history, Winston Churchill, who first understood the advantages of energy resources diversification, put the concept of energy security forward. The modern issue of the inadequate energy supply and its catastrophic consequences came to light with the 1973 and 1979 energy crisis, due to an oil embargo proclaimed by the OPEC members and to the Iranian Revolution, respectively. From that time on, the need to define a clear strategy to achieve energy security seemed more and more evident.

Several solutions were proposed in trying to quantify how secure is a society from the energetic supply point of view. Therefore, especially in the past 20 years, literature provided an increasing number of models, aimed to define the energy security level of a country and consequently to evaluate the most critical aspects to improve.

Anyway, the large number of definitions and indicators found in literature have created confusion about the choice of the dimensions that should be taken into account in quantifying energy security. Hence, the aim of this thesis is to analyse the suggested solutions and to understand which ones are significant in determining the energy security level of a country. More focus is put on the determination of those parameters linked to the economic value of energy security, i.e. all those factors related to energy price variation and energy flows physical availability.

The first chapter deals with the concept of energy security itself, trying to describe its evolution over time. This is done through a deep analysis of the publications that mostly contributed to the debate and development of the topic. Afterwards a brief analysis of the differences between short-term and long-term security is provided. The first chapter ends with a general overview of the main energy insecurity causes, whose critical issues are classified considering if they are more impactful on flows interruption or price distortions.

Chapter 2 provides explanations about the use of indicators as monitoring tools. The indicators are successively classified according to their level of complexity, and their strengths and shortcomings are presented. After that, it is given a classification of models provided by previous literature, highlighting the dimensions taken into account in each model and the construction of each index. Finally, some considerations about the future developments of these indexes are made.

After explaining the relationship between energy price and physical availability of energy flows, Chapter 3 classified metrics provided by previously developed models. Through a detailed discussion of the main energy insecurity causes, it is defined which, between the aforementioned parameters, are potentially effective in the forecast of a possible price variation or energy flow physical interruption. The chapter ends with some recommendations of the correct use of the indicators, with the aim to provide a strong tool in decisions for policy makers.

Chapter 1

Energy security: Defining and describing the problem

Before facing the problems about different definitions and interpretations behind energy security, it is necessary to understand how the possibility in accessing energy represents a primary importance security issue, especially for industrialized country.

1.1 Energy question

Energy security has a relevant place in the policy agenda of many countries. This is because, in a first simple analysis, the availability of a certain amount of energy is the basic condition for developing and maintaining our industrialized societies, as European ones. We can take a lot of cases as examples. At first, of course, it would be impossible to have current level of welfare without the wide exploitation of electrical energy. All high productivity industrial activities and others, such as informatics systems that manage all human activities and communications, could be quickly interrupted without a huge amount of electricity. We can also discuss about the importance of oil and its derived products. Without them almost all the mobility, such as naval, road and aerial, would be impossible, causing a big shock in every commercial activity and the impossibility of having goods that aren't produced on site. Another consideration, to deeply understand how much the absence of a great amount of energy can be harmful, concerns urbanization. In fact, without a huge availability of energy, it would be impossible to adapt to some kind of extreme environment for basic survival conditions for big groups of humans. Heating in cold places and desalination of water in desert zones are just two examples of this situation. After showing why energy security is a real concrete problem, it is necessary to make a distinction based on a geographical approach: in the case where raw materials and energy sources are within the territory of a state, the problem addressed is a question of "economic policy". How to organize and manage these resources to ensure final use, it's a problem that a government should face internally. The situation requires a more complex approach if a significant and hard-to-replace share of energy of a state is imported. In this case the energy supply interruptions aren't directly under control of the importing state and consequently the risks of interruption are more difficult to control and manage. We can say that the energy security problem concerns all the countries but a deeper analysis, to address the problem, is requested especially for the importing states. Considering the European countries, the situation is quite complex. In fact, the level of energy imports in the European Union is approximately 56%, with peaks in some states such as Italy, where the importing share is around 80%. From these data, it can be concluded that for European countries and all other states with similar energy shares of imports, it's very hard to face a supply interruption for a long period of time, quantified in not more than some months. In these conditions and without a defined energy security policy, the damages, could be destructive and devastating for the society in a very short time. Starting from all these considerations, we can properly discuss about the energy security question. In the next sections we are going to describe the historical origin of this problem and we are going to try to give a significant interpretation to the many definitions of "Energy security" proposed in scientific literature.

1.2 Historical background

The twentieth century was the century of energy and consequently our growing reliance on energy made clear the primary role of energy security. Originally this concept was related to military questions because it was becoming more and more evident the function value of a huge amount of energy , especially oil, in allowing military actions at a great scale. In particular the introduction of energy security concept is attributed to Winston Churchill who, during his duty at British admiralty, understood for the first time the possible technical advantage in adopting oil, instead of coal, as fuel for the English navy. But there was a critical problem: while the coal could be directly extracted in the United Kingdom, oil, instead, had to be bought and imported from other countries that, often, weren't under English influence. From that situation, the problem of energy security appeared for the first time and since then it started to develop during the years. The modern energy question begins with the first oil shock price of 1973-1974, when after the Arab-Israeli war, the Organization of Petroleum Exporting Countries started to use the strategy of "oil weapon". OPEC boycotted some of the major energy consumers, such as U.S.A, bringing and underlining, with this strategy, how important was energy security to governments, to business and to normal citizens in their daily life. Furthermore, the concept of security assumed, in this context, an international relevance. Oil, in particular, had and have, even if nowadays it's less relevant than in the past, a special place in the discussion of energy security. For these reasons, in the late 1980s and 1990s, academic interest in this concern declined following the stabilization of oil prices and the reduced menace of political embargo. The attention to this problem re-emerged in the 2000s motivated by the disruption of gas supplies in Europe, the rising demand in Asia and the pressure to de-carbonize energy systems. The final decades of the twentieth century have seen the early signs of the shift from the oil age to the age of more diversified energy mix where renewables and gas have become more significant in the energy scenario and the environmental issue is a determinant factor in defining energy use. Energy security is no longer simply a question of oil supplies. In short we can say there is a big difference between contemporary and "classic" studies. In fact while during the 1970s and 80s energy security aimed to stabilize the supply of cheap oil under conditions of embargo and price manipulation of exporters, nowadays the idea of energy security has extended beyond oil supplies encompassing a wide range of issues, such as socio-economic and environmental. Consequently the meaning of this problem as presented in classic studies has become a subject of intense re-examination.

1.3 Literature review and a "functional" definition

The main journals that deal with this topic, such as Energy Policy and Renewable and Sustainable Energy Review, have published many articles on the concept of energy security in the past years. However, it is possible to point out that, despite the great amount of studies, academic research and government reports, there is no general agreement on a widely accepted definition of energy security. The problematical question is that energy security means many things in various situation to different people. First of all, energy systems change considering different places as reference scenario . Energy security is a property of energy systems, interpreted as assemblies of people, institutions, energy sources and technologies as well. The general security of energy services is correlated to the interaction of these different components whether they are technical or not technical and consequently, to ensure security, it's fundamental to protect all the components of the system and not just a particular one. We can also say that energy systems are subject to a range of different risks or threats and these vary with geography (internal infrastructure failures vs conflicts in foreign countries) and timescale (long term changes in the availability of supplies vs sources price shocks). In addition, energy systems are evolving rapidly due to the necessary transition to more low carbon forms of energy sources and the growth in energy demands from developing countries. Thus, it is also true that the "energy security" term, especially in these last years, has started to be extended to other energy policy issues ranging from climate change to energy poverty. Despite the confusion we can say, and is widely accepted, that energy security is concerned with risk even if the types are different and difficult to manage all together. The purpose is to try to reduce the limitations and to understand the ambiguities in order to define which one of the many definitions proposed is the most functional and applicable to different contexts. To reach this, it would be helpful to eliminate all the elements that are important to consider when we are talking about energy security but that are not strictly correlated to its definition. We are going to consider **(Ang, Choong and Ng2014 [138]),** where the authors have analyzed a wide literature that include papers from journals and reports of national agencies, international organizations and business/professional associations. The surveys, shown in **APPENDIX A** with some other definitions of energy security taken from **(Winzer 2010 [80])**, cover almost everything significant that has been said about the topic in the last fifteen years. About all the issues that we are going to list soon, it's interesting to underline the geographical distribution as show in **[Fig 1.1].** A wide share of the publications are country-specific but it can be seen that energy security is a decisive topic for both developing and developed countries and especially for the ones that are net importers. In **[Fig 1.2]**, it is reported the typology of studies taken into account in the given time. It shows how different points of view are considered. In fact, differently than the journals that proposed more neutral visions, the reports by governmental agencies generally present the official position and consequently the resulting concept of energy security is influenced by interests, concerns and national obligations.

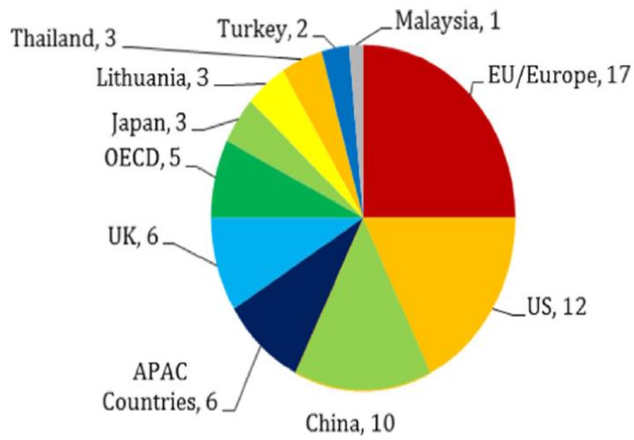

Fig 1.1: Number of energy security studies by country (APAC=Asia-Pacific)

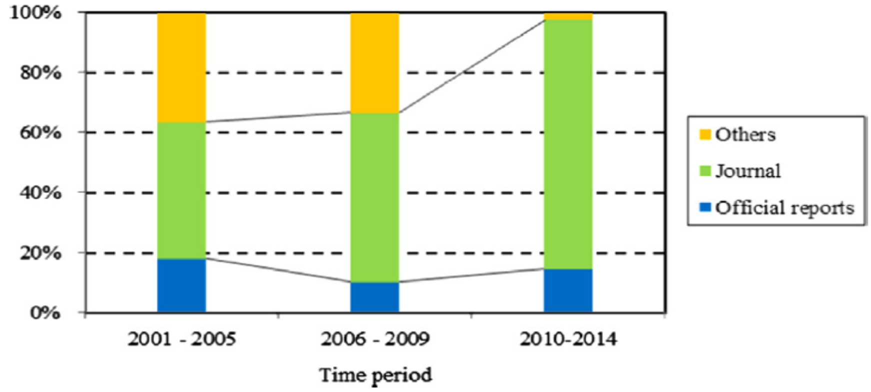

Fig 1.2: Distribution of energy security studies by publication type for different time period.

From all the studies it is possible to identify these seven energy security issues whose distribution over the considered time scale period is shown in **[Fig 1.3].** It should be underline that rarely all of them are included at the same time in the same publication:

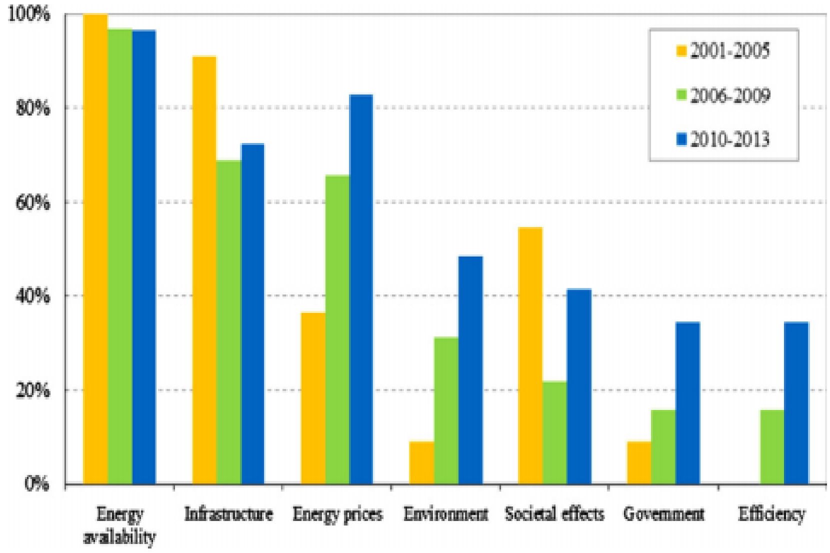

Fig 1.3: Coverage of each energy security theme in energy security definitions by time period

-Energy availability: The possibility of having uninterrupted physical availability of energy. *Diversification*, interpreted as energy supply diversity in all its several forms, and *geopolitical factors*, such as war, regional tensions and destabilized regimes, are fundamentals factors of energy availability;

-Infrastructure: An efficient infrastructure is a prerequisite to have "uninterrupted physical availability of energy". When we talk about infrastructures we are including energy transformation facilities and distribution and transmission facilities;

- Energy Prices: The affordability of energy supplies is determined by energy prices. Volatile price of fossil fuel and absolute price levels are some of the most important factors to consider in facing this aspect of the energy security;

-Social and Economic Effects: A lot of studies have tried to defined energy security in relation to potential externalities which could cause the loss of economic welfare.

(Bohi and Toman 1993 [114]) defined energy insecurity as "the loss of welfare that may occur as the result of a change in price or availability of energy". The problem is that a growing cost of energy input or a physical unavailability could have serious impacts on an economic system. This because energy demand is characterized, in the short time, by a low level of elasticity: for example if suddenly there are some problems to access to a particular source, in any case, it will be difficult to replace that immediately with another source, at least in the short period. Practically, it is possible to think to oil-based fuel in transport sector or to natural gas for domestic heating or industrial business. This rigidity can create big tensions within the economy and the society of states. Thus, in this scenario, difficulties of access to energy services could generate, in the better case, inflation or a general loss of competitiveness while , in the worst case, a high level of unemployment, economy collapse and consequently serious problem of political and social stability.

-Environment: Lately, especially in the past 5 years, environmental and sustainability issues have started to be often connected to energy security due to the growing attention for occurring climate changes;

As said, only recently environmental sustainability has become an energy policy issue and this, because, the size of energy impacts on environment reveals strong connections to energy security. Links between environmental restrictions, climate change and energy security are not simple to clearly define but, shortly, we can summarize these interactions using some of environmental dimensions of energy security exposed by **(Sovacool 2014 [140])** to describe the Asian situation, but that are easily applicable in other contexts. These dimensions, that represent just an attempt to briefly express a larger set of environmental concerns that had implications in energy security, are:

-Climate change: Climate change is a substantial energy security problem not only because natural catastrophes induced by climate change can damage power plants and transmission lines and disrupt the delivery of imported energy fuels but also because it has significant consequences on health and food security. Furthermore, mass migrations caused by ecological disasters could have serious repercussions that could threat energy and national security. In this context, energy contribution to the problem is clear because a total of 66.5% of global carbon dioxide emissions come from energy supply and transport.

-***Air pollution***: Worsening of environmental situation could adversely impact human and ecological health with high numbers of premature deaths connected with air pollution and relevant lost in terms of productivity and healthcare. Energy and transport sectors, in this sense, contribute with 80% of global sulfur dioxide emissions, 80% of particulate matter emissions and 70% of nitrogen oxide emissions. Even if this kind of question is more related to general energy issue, the way to solve the problem might adversely affect energy security, for example adopting worst energy sources in terms of reliability or affordability.

-***Water availability and quality***: Many typologies of power plants (for example fossil, nuclear and hydro) use big quantities of freshwater, in particular in thermoelectric power plants it is used 10%–15% of global freshwater. Thus, lacking availability of water could threaten the possibility to generate electricity other than the capacity of nations to feed themselves.

-Governance: We can shortly define it as the government's role in diplomacy, information collection, policymaking and regulatory processes that are essential to ensure short and long term energy security;

Energy security is a multi-level issue requires to act in different dimensions. It involves international, national and local players and a combined effort at all levels is strictly needed to guarantee the continuity of energy services. In this sense, Governance should define coordinated multi-level package of measures to promote energy secure way of acting by players at all levels. Basically, we can say that the role of governance, in short time, should cover all problems linked to energy disruptions while, in the long time scale, supporting clear policies to direct actor's choices is the main objective. For example the implementing of new infrastructures requires an optimum level of planning and , in the same way, policies related to subsidies and energy taxes should be defined very carefully because they have a crucial impact on the energy security of a nation and consequently on all the welfare system. In addition, in this current global situation of political instability, especially for strongly importing states, the role of diplomacy with foreign policy is increasingly fundamental to ensure energy supplies from exporting regions. Lastly, the government should be the organizer and the supervisor of key information because high quality data are the basic condition to take large-scale effective actions for energy security.

- Energy efficiency: All the technologies, practices and systems that allow to reduce energy needs.

Energy efficiency, defined as using less to provide certain energy services, has a general positive effects on every dimensions of energy security. Shortly, we can say that absolute demand reduction, as a consequence of energy efficiency improvements, is reflected in the less request of limited resources generating, in this way, an improvement in the long-term availability, resulting in a general positive security effect. In addition, strictly connected to energy efficiency, there is the concept of energy intensity shortly defined as the energy requested for each unit of output. It's clear that any measure to increase efficiency allow to lower the energy intensity and consequently an economy could improve energy security by cutting the amount of energy needed to function properly.

Analyzing all this issues and the periods in which they started to be debated, it's clear that the perception of energy security has changed over time. While energy price, availability and infrastructure, considering the last two strictly connected, are without doubts the most important and most common elements in the definition of energy security, the other concepts, especially environment, governance and energy efficiency, have gained importance just in the last five years. It's surely the consequence of the new challenges that global energy and economics are trying to face. Anyway, despite all, it's useful to understand which could be a "functional definition". Functional because energy security is increasingly a multidimensional and dynamic issue with greater and more complex patterns of interdependencies. Thus, one comprehensive definition is unlikely to encompass all kind of risks and dimensions and so it should be expressed in a more fluid way. In this sense, the conceptual definition proposed by IEA, understood as "**the availability of reliable energy flows at an affordable price"** seems to be the clearest one to point out which is, actually, the problem of energy security and how to solve it properly. Reflecting on the issues listed before, just the first three concepts are strictly needed in defining energy security. Energy efficiency and governance, instead, represent two ways which with it is possible to improve energy security. It's fundamental not to mix the definition of the problem with the possible solutions. Furthermore, in that definition environmental issues ,social effects and more in general the idea of sustainability ,in its various form, are excluded, at least directly. In fact, the amount of energy we can obtain from different sources is a different matter compared to effects on external environment caused by consumption of energy. According to the proposed definition, the only elements to discriminate, in terms of energy security, a source instead of another are the reliability of supplies and the final cost. Thinking in this way, 1 Mw generated from fossil fuel and 1 Mw from photovoltaic plant, assuming hypothetically a same generation cost and reliability level ,are two identical solutions to ensure energy security. This doesn't means that the environmental issue is not important ,but, energy and environmental security represent two distinct concepts and they shouldn't be confused at the analytic level while it tries to proposed a solution. In any case, it's possible to understand which are the links between the two kind of security and so, in the evaluation of possible intervention measures to ensure energy security, we should analyze which are the most sustainable and acceptable at environmental and social level. After these consideration, in the next subchapter we are going to examine in depth the ideas of "**reliability**" and "**affordability**".

1.3.1 "Reliability" and "Affordability"

We can define "**Reliability**" of energy flow as the possibility that raw materials could be extracted and brought to end users market without disruptions. In this case the integrity of infrastructures, which is the main issue in NATO and U.S.A interpretations of energy security, has a fundamental role ,especially considering that production and processing facilities of raw energy materials are usually big and expensive and consequently represent ideal targets for terrorist attacks. The protection of these infrastructures deals with the concept of physical availability of energy from a security point of view and therefore ensuring the integrity of this network is the way to satisfy the physical request of energy flows. But as we say before, the definition of energy security deals with another fundamental aspect that is the acceptable economic cost of supplies, what we can in short define as **"Affordability".** But this concept, differently from "reliability", is more complex to define. Basically it refers to the fact that the basic energy services should have a "reasonable price". The focus is on the size and on the impact of not having any more accessible energy prices. In fact, an increase of energy input cost would cause a considerable growth of costs to carry out every product activities generating a devastating impact on the economy of a state. However, considering the present-day supply and demand ratio, basically the global energy cost is going to rise due to dwindling of energy supplies and global competition increasing. From an economic prospective, in this sense, the IEA in 2007 claimed for "competitive or not overly volatile prices" but it's not very clear what "overly volatile" means and the same is for "competitive". The competitiveness, for example, is a relative concept that changes if we look at who should be referred to, so when we deal with term "competitive", and more in general with the idea of "affordability" it's quite important to determine a valid referent object. Many studies didn't explicitly define " for whom" energy price should be affordable. Speaking from the point of view of the developed world, interpreted as zones where the accessibility to basic energy services are guaranteed, we can say that "affordability" has different interpretations and which one is significant depends for whom we are trying to ensure energy security. An example of this is given in **[Tab1.1]** taken from **(Cherp and Jewell 2014 [140])**, where different interpretations for different referent objects are summarized according to four previous publications. Anyway we can assume that past models , which do not indicate a clear referent object, have as aim to ensure the concept of "Affordability" to all the possible recipients, supposing that proposed solution could work in the same way independently of "for whom". Furthermore we can add a geographical element, in fact the absolute level of "reasonable price" changes considering the differences in levels of economic development that exist between countries. Lastly, in aiming "affordability", it's also important to consider the timescale because we could have different results according to which period we are considering. Thus, a good balance between reasonable price "now" and "then" it's strictly required. For example, in many countries, energy could be made instantly more affordable by reducing taxes that support energy efficiency improvements. But evaluating this choice in a long time scale, it not seems to be a efficient decision because the energy efficiency improvements would not happen. At the end, despite these considerations, it can be said, in broad terms, that energy security is ensured if physical availability and accessible prices are guaranteed.

Table 1.1: Different interpretation of affordability- the importance of asking " Security for whom?"

Affordability for whom?	Energy price should be……
Household and private consumers	Low compared to household income [a,b,c]
Industry and business	Low compared to competitor's price [c]
Nations	Low enough to ensure the energy import bills is small enough to export earnings [c]
Energy companies and investor	Hogh enough to ensure sufficient profitability for energy companies and investor [d]

[a] Kruyt et al (2009) says the affordability translates to low energy prices but does not specify the consumer group (house hold or industry)

[b] Sharifuddin (2013) defines affordability relative to government accounts, private consumers and industries.

[c] Huges (2012) defines affordability relative to consumer income.

[d] APERC refers to investment cost affordability.

1.4 Temporary dimension: Long-term and Short-term energy security

When energy security has a political and public focus, this happens because usually there are emergency situations to face. We can include in this category for example, events like sudden black-out within electricity supply system; physical shortage at gas station and consumers facing unexpected energy price spikes. While these kind of problems generates much attention, risks to energy security on longer time scales do tend to have less consideration. Then, It's clear that energy security has a short-term and a long-term dimension. Dealing with them requires different approaches. IEA defines short-term energy security as "the ability of the energy system to react promptly to sudden changes within the supply-demand balance". Then, ensuring energy security in short timeframe means to prepare all the requested measures so that occurrence of risk situations does not result in any kind of devastating harms. In other words, we are saying that in case of incident, exceptional natural events, a crisis on the international market or a terrorist attack, the consequences on the economic and social system of a country should be contained and shouldn't generate an existential risk. The definition of adequate technical measures, for example obligation in accumulating reserves, and emergency management mechanisms are the most relevant strategies to ensure security in short-time period. Instead, talking about long-term energy security, IEA say about that "it mainly deals with timely investments to supply energy in line with economic developments and sustainable environmental needs". In general, in long framerate, we want to limit the arising of potentially risky situations. To achieve this result, some specific measures are required ,for example some of them could be: the adoption of energetic and technological mix resulting in an acceptable equilibrium between risk and economic advantages (in this sense, according to **(Jansen et al 2009[142]),** curbing the use of fossil fuel over longer timescale in a socio-economically efficient way, should be the most effective measure to achieve a more secure energy economy); a reasonable balance between the choices to ensure energy security and the strategic ones in other sectors, defined policy to support investments required to satisfy the internal energy demand and ,at the same time, a demand-side focus to reduce overall demand through energy efficiency and demand response.

1.5 Risks to energy security

Any kind of danger to the continuity of supply and consumption of energy is considered a risk to energy security. The consequences of harms are characterized by a different geographical level (international, national, regional and local), different time frame (hours, days and years) and they may be perceived at different levels of the economy (generation, trading and end using). Then, to ensure energy security, it's fundamental to understand which could be the causes of the risks and their level of interdependences, the nature of dangers and how the impacts of damages are going to influence the access to energy services. In this context, it's possible to predict some risks better than others (depletion of fossil reserves vs natural catastrophic events) and for the hardest to predict, anyway, we can utilize a probabilistic approach that, in some cases, it's quite efficient , for example LOLE metric, while in other cases, such as political risks, the probability can only be speculated. In the same way, it's possible to estimate quantitatively the consequences of some kind of damages, such as interruption of transmission line, while for other harms, the real effects are unpredictable, for example the case of political and diplomatic tensions. Furthermore we should consider that there might be some dangers of which we aren't still aware (consequences of new technologies on environment). Therefore, it's clear there are many threats that menace energy security. **[In Tab 1.2]**, the most common risks to energy security are shortly presented. Anyway, according to the definition, we can also grossly split risks in two categories considering in which aspect of energy security they have a bigger impact: risks about flows and risks about the price.

1.5.1 Flow risks

Talking about the reliability of energy flows, first of all exists the possibility of **technical failures**: it's the case of production and transport infrastructures, such as gas and oil pipeline that could stop working as result of a technical malfunction, or dams that, after a natural catastrophe, could be rendered inoperative. Technical failures in any stage may threat energy supply and considering energy systems as assemblies of different components and interactions between them, incidents or a problematic natural event, not due to any intentional actions, may happen. In this sense, the global dimension of energy market and the separation of consumption places from the production sites of energy raw materials have exacerbated this kind of risks. Anyway, technical failures are not the only critical point in ensuring reliability of energy flows. In fact, there is the possibility of **deliberate hostile human acts**: terrorist attacks, strikes, domestic activism and piracy are included in this category. Reflecting on this, big fixed infrastructure and strategic routes for transport of energy commodities represent perfect target for these kind of actions. In this context ,an added problem is given by the fact that the defensive activities to protect these strategic elements are left to the state that own the natural sources, such as Saudi Arabia with their oil wells. From the Arabian protection to their oil infrastructures depends the stability of the oil market itself and consequently the energy security of strongly importing nations. Talking about human factor, we can find another source of risk linked to the international nature of supplies: deliberate political choices of production or transit states that could interrupt energy flows. This situation generally happens less frequently then technical failures or sabotage attacks, but, potentially it's the most dangerous considering the growing concentration of resources in increasingly small number of countries. For example, an intentional act of interruption between exporters and importers was the cause of the first oil shock in 1973. OPEC, in that occasion, deliberately decided to imposed oil embargo on U.S.A and some European states for their support to Israeli during Yom Kippur war. Instead, the crisis between Russia and Ukraine in 2006 and 2009 when, after periods of tension between the two countries, the Ukraine government decided to block gas flow towards European state, represented a case in which transit state had almost generated a critical scenario for some nations that had nothing to do with that political situation. Lastly, another risk is the natural depletion of some resources such as oil and gas. At certain point in the future, they will be totally consumed but before that time the limited availability will influence both the physical accessibility and economic aspects.

1.5.2 Price risks

The other category of risk concern the affordability of energy price. We can say that, even if energy raw materials are physically available but their price is too high, consequences would be similar to a real physical interruption because for consumers, in that situation, it would be difficult to access to energy services. Excluding variations in short time, principally due to speculations on financial products markets, the price of energy is generally defined by the equilibrium between demand and supply and therefore an increase of the first or a contraction of the second might generate a price increase. It's possible to have a contraction in the offer **when a monopolist or a cartel decide deliberately to limit the production generating an increase of prices**. OPEC is a clear example of this mechanism in which the strong part, using his market power, tries to impose a transfer of wealth in his favor. Another possible cause for a contraction of supplies should be sought in the **cyclic nature of energy investments**. In fact the basic condition for big projects to increase production capacity is that the price of raw energy materials or energy itself are enough high to pay back the invested capital. So it's clear that after a prolonged period of low prices where there aren't any kind of expectations of growth for the short period, the level of investments goes down and consequently the prices start to increase again so that it's necessary to wait for a long time before the new investments raise supplies and compress the prices. This because, often, there is a significant time delay between the decision to invest and the moment in which production start to increase, for example in nuclear sector. This situation is potentially dangerous also when there are **a lack of planning or a wrong forecasting of future energy demand and trends**. Basically if there is a demand that exceed previous estimates, there could be a rapid price increase that ,as it said before, could generate considerable tensions at regional and global level due to the competition to access energy resources. Considering the global dimension of energy market, there is another problem correlated to current system of energy resources exchange: **the central role of oil used as benchmark for the others markets**. We can say that the price of almost all the energy traded at international level is defined in relation to the quotations of oil. This situation generates economic distortions and instability: first of all because the price of oil is floating and hard to predict for a variety of reasons (for example low elasticity of end consumers, market power of exporters ,depletion of fossil sources, political instability and dollar as only trading currency) and this uncertainty has an impact on the other raw energy materials, secondly because the trends of different resources could be different from the oil one. For example, in this sense, if there is a high request of gas and a low demand for oil, it's possible that the link between two prices makes no economically advantageous investing in new infrastructures to satisfy the growing demand for natural gas.

Tab 1.2 : Classification of energy insecurity main causes

Category	Type	Brief description
Extreme events	**Extreme weather**	*Extreme weather events can temporarily disable energy infrastructures and the supply of energy. A recent example is the impact of Hurricane Katrina, which hit the Gulf of Mexico in 2005, disabling a significant portion of the US oil and gas production and processing capacity. There are however many other possible extreme weather events with potential energy security consequences including those which impact on the demand side (e.g. exceptionally cold or hot days) or on the supply side (e.g. reduced cooling water availability).*
	Large scale accidents	*Much like extreme weather events, accidents can lead to unplanned outages of key energy infrastructures.*
	Acts of terrorism	*Acts of terrorism against key infrastructures (e.g. refineries or pipelines) or bottlenecks along specific energy trade routes (e.g. the straight of Hormuz) can cause disruptions to energy systems.*
	Strikes	*Due to the strategic nature of energy, strikes or other forms of social unrest may specifically target the operation of key energy system components.*
Inadequate market structure	**Insufficient investments in new capacity**	*Market structures which fail to generate timely investments in key energy system infrastructures can contribute to making the system more vulnerable and ultimately generate energy insecurity.*
	Load balancing failure in electricity markets	*Because electricity is not storable in any meaningful volumes system operators must effectively balance supply and demand in real time to ensure system reliability. The task is challenging and requires that certain technical characteristics be met. When this is not the case systems sometime fail or do not operate in an efficient manner causing a loss of welfare for users.*
Supply shortfall associated with resource concentration		*Due to the concentration of resources in certain regions of the world, exploration and production as well as transport of fuels are also concentrated. This generates a certain degree of market power8 which can adversely affect energy systems.*

Chapter 2

Quantifying energy security performance

The use of energy security indexes to evaluate energy security or risks of a country has been growing in popularity. Indicators already represent the most common way in verifying how secure an energy economy is. We can define "Energy Indicator" as a tool which is used to assess the performance of an energy system. A collection of energy indicators can be used as a set of measures to reveal key relationships between energy use, energy prices and economic activity. Formulation of an index helps in quantifying the performance of a country over time and related to key trends which otherwise may not be apparent. It also helps to identify the connections within various dimensions and it can give an idea to define areas of improvement. Many efforts have been made to build a meaningful energy security index that could be acceptable to a majority of stakeholders. However, this kind of search for an index could be elusive, primarily because there isn't a definition of energy security which is clearly accepted by all and secondly, because there are a lot of differences between energy systems of different countries that could easily means a different weights for the same security aspect. Furthermore, another element of uncertainty is the high degree of subjectivity in energy security indexes construction. The accounting frameworks proposed, including the selection of indicators and the weights assigned, are personal and fairly arbitrary. Another problematical issues are the availability and the quality of data used as input. In some studies inputs are selected through surveys or expert opinions. Despite these critical elements, it has pointed out that indexes are useful for a number of purposes, such as in country self-assessment, scenario analysis, cross-country comparisons and tracking progress. For example, a country can use indexes to quantify and track the impacts of some developments, such as increases in international oil prices, energy diversification, energy efficiency improvements and the discovery or development of a new and major energy source. Basically, correlating dimensions of energy security to useful metrics and indicators and condensing a large amount of complex data into recognizable pattern could be utilized to help analysts and regulators to find the best energy solutions in a menu of available options and consequently to improve energy security policies.

2.1 "Simple" Indicators vs "Complex" Indicators

Metrics can be divided and classified considering which kind of information they express and the level of details provided. As example, IEA visually expresses its division of "Energy indicators" according to a pyramid representation **(Fig 2.1)**.

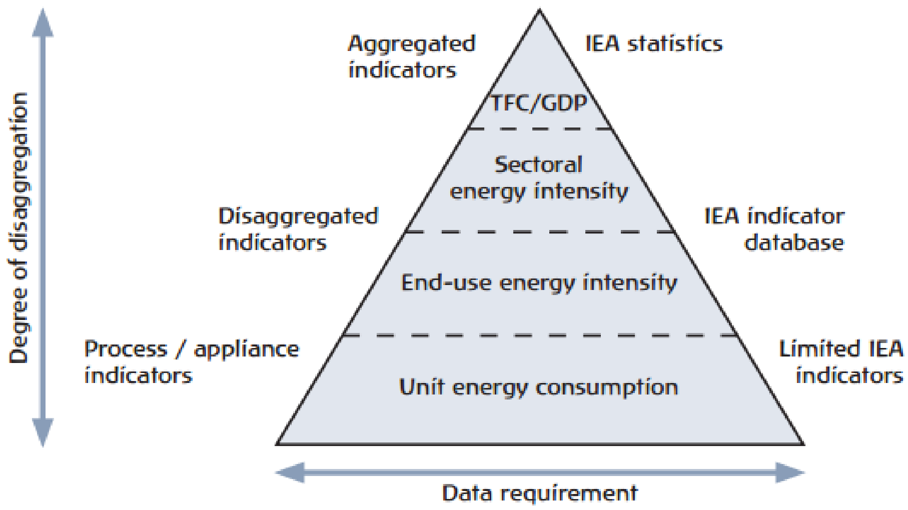

Fig 2.1: The International Energy Agency "Pyramid" of Energy Indicators.

Complex indicators, that composed the basis for the IEA statistics, are at the top while disaggregated and process indicators are respectively at the middle and at the bottom. A general idea of the reasons behind trends in energy consumption in a sector can be provided by aggregate indicators. Anyway, understanding the key drivers of energy developments and providing policy-relevant analysis require more detailed information. Given that, it should be underline that not all indicators are relevant to all countries and so it is important to determine which indicators could be significant. This selection is based on available information of the country and the policy topic that needs to be answered. A different approach to classify metrics is the one proposed by the Energy Security component of the IIASA's Global Energy Assessment. Indicators are divided in simple, intermediate, and complex. This kind of classification allow to use disaggregate indicators measuring quantity (simple), quality (intermediate) and context (complex) for different dimensions of energy security. **[Table 2.1]** gives as an illustrative example where some components of energy security are decomposed into their simple, intermediate and complex constituents.

Tab 2.1: Simple, Intermediate, and Complex Indicators for Energy Security

<table>
<tr><th>Aspect of Energy Security</th><th>Quantity (Simple)</th><th>Quality (Intermediate)</th><th>Context (Complex)</th></tr>
<tr><td>Energy Imports</td><td>Share of imported energy in total energy balance, or made more specific by type of fuel (e.g., oil, coal, natural gas, uranium)</td><td>Nature of energy imports (type of imported energy and mode of import)</td><td>Specific context of energy imports for particular country or community</td></tr>
<tr><td>Energy Production and Infrastructure</td><td>Diversity of primary energy supply in domestic production</td><td>Domestic energy resources, reserve-to-production ratios</td><td>Country specific energy production and infrastructure challenges</td></tr>
<tr><td>Energy Production and Infrastructure</td><td>National power generation capacity (total or per capita)</td><td>Domestic energy infrastructure investments</td><td>Mitigation readiness and capacity</td></tr>
<tr><td>Vulnerability to Disruption</td><td>Energy consumption per capita</td><td>Costs of imports versus export earnings</td><td rowspan="3">Sectoral vulnerability for transport, residential, industry, tertiary, agriculture</td></tr>
<tr><td>Vulnerability to Disruption</td><td>Energy intensity of GDP</td><td>GDP intensity by type of energy or sector</td></tr>
<tr><td>Vulnerability to Disruption</td><td>Fuel Economy</td><td>Fuel economy for on-road passenger vehicles, or new vehicles</td></tr>
<tr><td>Equity and Access to Energy Services</td><td>Percentage of households with a reliable connection to the electricity grid</td><td>Share of household income spent on energy services</td><td>GINI coefficient of energy use</td></tr>
<tr><td>Diversification</td><td>Renewable share of energy fuel mix</td><td>Diversify of primary energy supply</td><td>Hirshman and Shannon indices of diversity</td></tr>
<tr><td>Greenhouse Gas Emissions</td><td>Total greenhouse gas emissions or per capita greenhouse gas emissions</td><td>Greenhouse gas emissions by sector</td><td>Hirshman and Shannon indices of diversity</td></tr>
</table>

At the end, considering that aggregate indicators differ from disaggregated and process indicators and that indexes are characterized by different levels of detail measuring quantity, quality and context, we decided to classify our indicators, considering **(Sovacool 2011 [65])** for energy security into "simple" and "complex". Thus, we define:

•**[Complex Indicator]:** an established aggregate indicator that includes the measurement of multiple variables or that may involve considerations about time scale. Complex or aggregate indicators would be those derived by diversity indices such as the Herfindahl-Hirschman Index or ShannoneWiener Index. Synthetically ,the main strong and weak points of using composite indicators could be summarized as follows:

A) **Strong points**:

+ Summarize complex or multi-dimensional issues, in view of supporting decision makers.

+ They are easier to interpret than trying to find a trend in many separate indicators.

+ Facilitate the task of ranking countries on complex issues in a benchmarking exercise.

+ Assess progress of countries over time on complex issues.

+ Reduce the size of a set of indicators or include more information within the existing size limit.

+ Facilitate communication with ordinary citizens and promote accountability.

B) Weak points:

– May send misleading policy messages, if they are poorly constructed or misinterpreted.

– May invite drawing simplistic policy conclusions, if not used in combination with simple indicators.

– May lend themselves to instrumental use (e.g be built to support the desired policy), if the various stages (e.g. selection of indicators, choice of model, weights) are not transparent and based on sound statistical or conceptual principles.

– The selection of indicators and weights could be the target of political challenge.

– May lead wrong policies, if dimensions of performance that are difficult to measure are ignored

•**[Simple Indicator]**: an indicator more appropriate for a rapid and clear static evaluation of energy security. For example the following types of indicators would be classified as simple:

- Resource estimates and reserves;
- Reserve to production ratios;
- Share of zero-carbon fuels;
- Import dependence;
- Energy prices;
- Ratio of a country's consumption over the total market for a fuel;
- Energy intensity.

A) Strong points in using simple indicators:

+ Provide clear objective information

+ Hardly usable for an instrumental purpose

+ No subjective manipulations that may lead to a lack of significance

+ Give the possibility to clearly and deeply analyze each considered issue
of energy security

B) Weak point in using simple indicators:

– They have to be interpreted and this requires a deep experience and knowledge of the matter

– Not suitable to support decision-maker without help of experts

– They are raw information that make difficult to clearly communicate and justify results, especially to common people

– The availability of so many data may create problem of sensitivity if they are use in the wrong way

2.2 Review of energy indicators

Considering **(Ang,Choong and Ng 2014 ,[138]),** we are going to summarize and discuss about 61 (8 added considering the last two years) energy security studies that attempt to measure energy security performance. In **[Tab 2.2]** are showed and commented review publications that deal with energy security indicators and indexes. Considering the second and the third column, where respectively it is given the name of the energy security indicator as expressed in the original source and the summary of issues or energy security dimension covered, it is clear that there are a lot of differences among studies on how energy security indicators are named and on the focused topics in the development of these indexes. These diversities not allowed a real comparison among studies. In this sense, taking into account for example the same country as reference object of the investigation, it is possible to reach different conclusions using different studies. In **[Tab 2.2],** other basic elements of the reviewed studies are listed: the number of used indicators, the quality of the study (spatial or time-series) and specific focused areas in indicators construction. There is also another feature showed in **[Tab 2.2],** precisely in last three columns: the method used in composite index construction. The way to build an energy index will be discussed in the next sub chapter, while now we are going to deeply deal with the first listed features:

• **Number of indicators**: the number of energy security indicators varies from one to 68. The distribution is shown in **[Fig 2.2]** where each dot represents a study. About 75 % of the studies don't present more than 20 indexes. The use of large numbers of indicators is justified by the fact that a very specific index is defined for each energy technology. In the opposite case, studies that describe only a few indicators, basically, tend to use complex indicators using multiple data points as input. In the case of a small indicators number, the energy security index is generally very *sensitive* to changes in any of its composing metrics. A change in an indicator level may lead to a large swing in the index and this may generate a problem of instability of the index. Contrary, when too many indicators are used, changes in individual indicator could be useless because of the majority of unchanging indicators. In the literature, one of the most accepted practice is to use a representative set of indicators that can show a general overview of the energy security situation, balancing the number of metrics to not have problems neither of instability nor sensitivity of the index. At this purpose, a basket of 10 to 25 indicators should be reasonable. In any case, the appropriate or "ideal" number will depend, among other factors, on the scope, on the complexity of a study and on the data quality and availability.

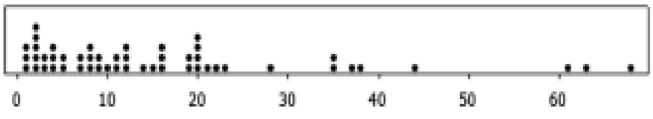

Fig 2.2: **Distribution of the number of indicators for energy security studies**

• **Temporal vs Spatial studies**: Studies of energy security can be divided in temporal and spatial types of studies. In the first type, energy security is evaluated considering two or more years and emphasis is placed on changes over time. In the latter, comparisons are made between countries. In the review, the number of temporal and spatial studies are about the same. Another consideration is about the fact that there is no significant difference in the number of indicators used in the two types of studies. Additionally, studying energy security for the future implies that some studies include projections or scenarios. In some cases, projections are made based on the IEA World Energy Outlook reference scenarios.

• **Specific focused areas in index construction:** Energy security indexes are often built considering a specific areas of concern. For example, a multi-country study deals with topics that are of general concern while a country specific study tends to focus more on issues that are significant for that specific country. The primary areas of concern, taken into account by a study in index construction, are defined as "specific focused areas" (SFAs). In a study, in the case of a distinction in terms of importance between SFAs, the most important one is indicated with a "p" (primary) while the other with a "s" (secondary). Attempting to identify SFAs considering the indicators and indexes in the surveyed studies has led to the identification of five areas:

- 4AS (SFA-1): It has to do with availability (availability of energy resources) ,affordability (closely linked to energy prices), accessibility (issues such as geopolitical, geographical, workforce, technological and other constraints that limit the extract of energy resources) and acceptability (the environmental concerns such as energy-related carbon emissions and the environmental impacts of energy systems). SFA-1 is usually used in cross-country comparisons because it is possible to evaluate countries considering various dimensions for a balanced analysis.

- Specific energy supply (SFA-2): Primarily it deal with individual energy sources. These indexes allow analysis of energy security issues considering separately each type of energy vector to facilitate the identification of threats for each source. An aggregate index for total primary energy supply could be composed by weighting the indexes of individual energy sources. SFA-2 has to do with fossil fuels, especially oil and natural gas and it is very significant for major oil and gas importers, or, in any case, for that countries which depend on other major energy sources such as nuclear energy.

- Economy (SFA-3): Considering that an increases in energy prices have an economic impact, many energy security indexes include an economic metric. This area could appear very similar to the affordability dimension of SFA-1. However, studies classified under SFA-3 are generally broader and are characterized by more economic-related indicators.

- Environment (SFA-4): In some works, it has become a focused area of energy security indexes and, due to the growing importance of sustainability, environmental and sustainability indicators have increasingly become part of the energy security considerations.

- Social issue (SFA-5): It's an important topic in countries where electricity connectivity is a major concern. Shortly, SFA-5 is usually associated with countries which have a less advanced energy system and where energy poverty is a major problem.

- Others (SFA-O): The category characterized by topics which are not covered in the areas listed before but that are presented in some studies. These areas include, for example, the crisis capability and demand and supply dimensions.

Based on this classification, **[Fig 2.3]** shows a graphical representation that shortly summarize how many studies deal with each SFA.

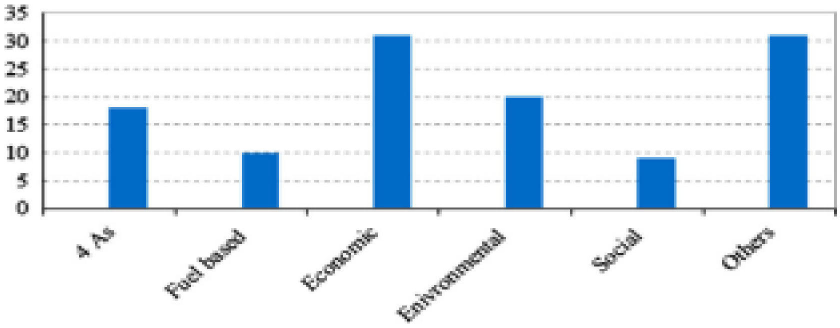

Fig 2.3: Number of studies focusing on each SFA in energy security index development.

Tab2.2: Studies incorporating specific energy security indicators and indexes. Details of notion used at the end of table[a]

Source	Name of indicator/index	Energy security dimensions/issues considered	No. of Indicators	Type of study			Specific focused Area (SFA)						Index construction		
				T	S	P	I	II	III	IV	V	VI	N	W	A
DTI [3]	Security of supply indicators	*Supply and demand forecasts; market signals; market response*	11			x			x			x			
Blyth and Lefevre [6]	Geopolitical energy security proxy measure; power system reliability proxy measure		2		x	x								2	+
Onamics [10]	aggregate country index	*Energy supply diversity; internal political and economic stability; domestic energy efficiency*	12		x				x			x		1	+
Sovacool and Brown [17]	Energy sustainability index	*Oil security; electricity reliability; energy efficiency; environmental quality*	10	x				x		x		x			
IAEA [20]	Energy indicators for sustainable development	*Equity; health; energy use and production patterns; security*	31	x								x			
IEA [21]	Energy security index	*Energy price; physical availability*	2		x	x	s		p			x			
Intharak et al. [22]	Energy security indicators	*Availability; accessibility; acceptability; affordability*	16		x	x	p		s						
Wu and Morisson [23]	Energy insecurity index		3	x	x	x								6	+

Source	Name of indicator/index	Energy security dimensions/issues considered	No. of Indicators	Type of study			Specific focused Area (SFA)						Index construction		
				T	S	P	I	II	III	IV	V	VI	N	W	A
Scheepers et al. [29]	Crisis capability index; supply/demand index	*Crisis capability; demand/supply*	63		x	x						x			
Streimikiene et al. [31]	Energy indicators for sustainable development (EISD)	*Economic; environmental*	12	x	x				x	x					
Frondel and Schmidt [34]	Energy supply risk indicator	*Crude oil; natural gas*	1	x	x			x					o	2	+
Gnansounou [35]	Composite index of vulnerability		5		x								m	3	o
Gupta [36]	Oil vulnerability index		7		x			x					m	3	+
Patlitzianas et al. [41]	Sustainable energy policy indicators	*Security of energy supply; competitive energy market; environmental protection*	36				x		x	x					
Augutis et al. [43]	Lithuanian power energy supply security	*Technical, economic; socio-political; environmental*	22	x		x			x	x	x	x	o	6	+
Greenleaf et al. [45]	Energy security indicators	*Based on root causes such as extreme events, insufficient investments in new capacity, load balancing failure, supply shortfall*	11		x	x						x			

Source	**Name of indicator/index**	**Energy security dimensions/issues considered**	**No. of Indicators**	**Type of study**					**Specific focused Area (SFA)**				**Index construction**		
				T	**S**	**P**	**I**	**II**	**III**	**IV**	**V**	**VI**	**N**	**W**	**A**
Jansen [47]	Energy services security indicators	*Reliability; energy costs; policy framework; public acceptance*	38						p		s	x			
Le Coq and Paltseva [50]	Risky external energy supply (REES); contribution to EU risk exposure (CERE)	*Oil; gas; coal*	2		x			x					o	2	+
Cabalu [52]	Composite gas supply security index (GSSI)		4	x	x								m	6	o
Lefèvre [54]	Energy security price index (ESPI); energy Security physical availability index (ESPAI)	*Price; physical availability*	2	x	x	x	s		p				m	6	+
Löschel et al. [55]	Ex-post and ex-ante indicators	*Ex-ante; ex-post*	2	x	x							x	o		
Sovacool and Brown [57]	Energy security index	*Availability; affordability; energy and economic efficiency; environmental stewardship*	10	x	x		p		s	s		s	z	1	+

Source	Name of indicator/index	Energy security dimensions/issues considered	No. of Indicators	Type of study					Specific focused Area (SFA)				Index construction		
				T	S	P	I	II	III	IV	V	VI	N	W	A
Vivoda [58]	Energy security assessment instrument	*Energy supply; demand management; efficiency; economic, environmental; human security; military security; domestic socio-cultural-political; technological; international; policy*	44						x	x	x	x			
Augutis et al. [59]	Energy security level	*Technical; economic; socio-political; energy sources*	61	x		x		s	p		s	p	o	1	+
Cohen et al. [61]	Diversification of oil and natural gas supplies; global and country-specific diversification indices	*Crude oil; natural gas*	2	x	x			x						2	+
Ediger and Berk [62]	Oil import vulnerability index		4	x									m	3	+
Jewell [63]	IEA model of short-term energy security (MOSES)	*Crude oil, oil products, natural gas, coal, biomass and waste, biofuels, hydropower, nuclear power*	35		x			x							

Source	Name of indicator/index	Energy security dimensions/issues considered	No. of Indicators	Type of study			Specific focused Area (SFA)						Index construction		
				T	S	P	I	II	III	IV	V	VI	N	W	A
Sovacool [65]	Metrics and indicators for Asian energy security	*Availability; dependency; diversification; decentralization; innovation;, investment; trade; production, price stability; affordability; governance; access; reliability; literacy; resilience; land use; water; pollution; efficiency; greenhouse gas emissions*	200				p		s	p		x			
Sovacool et al. [67]	Energy security performance	*Availability; affordability; technology development and efficiency; Environmental sustainability; regulation and governance*	20	x	x		p		s	p			m	1	+
Angelis-Dimakis et al. [68]	Overall sustainability index	*Social; economic; environmental*	9	x					x	x	x		m	1	+
Augutis et al. [69]	Energy security level	*Technical; economic; socio-political*	68	x		x			x	x	x		o	1	+
ERIA [71]	Energy security index	*Development of domestic resources; acquisition of overseas resources; transportation risk management; securing a reliable domestic supply chain; management of demand; preparedness for supply disruptions; environmental sustainability*	16	x	x							x			

Source	Name of indicator/index	Energy security dimensions/issues considered	No. of Indicators	Type of study					Specific focused Area (SFA)				Index construction		
				T	S	P	I	II	III	IV	V	VI	N	W	A
Dunn and Dunn [70]	W&J energy index		1	x									o	2	+
Hughes [73]	Energy security indicators	*Availability; affordability; acceptability*	3				p		s		s				
Institute for 21st Century Energy [74]	Index of U.S. energy security risk	*Geopolitical; economic; reliability; environmental*	37	x		x			x	x		x	r	6	+
Institute for 21st Century Energy [75]	International energy security risk index	*Global fuels; fuel imports; energy expenditures; price and market volatility; energy use intensity; electric power sector; transportation sector; environmental*	28	x	x			x	x	x		x	r	6	+
Martchamadol and Kumar [76]	Energy security indicators	*Energy demand; availability of energy supply resources; environmental concerns; energy market; energy price/cost/expenditure*	19	x		x	s		p	p		x	z	3	+
SheinbaumPardo et al. [78]	Mexican sustainability indicators	*Social; environmental; economic*	8	x					x	x	x		o	1	+
Winzer [80]	Energy security levels	*Sources of risk; scope of the impact measure; severity filter*	8	x	x							x	o		

Source	Name of indicator/index	Energy security dimensions/issues considered	No. of Indicators	Type of study					Specific focused Area (SFA)				Index construction		
				T	S	P	I	II	III	IV	V	VI	N	W	A
WEF [81]	Energy architecture performance index (EAPI)	*Economic growth and development; environmental sustainability; access and security of supply*	16	x	x		s		p	p			o	1	+
WEC [82]	Energy sustainability index	*Energy security; social equity; environment impact mitigation; political strength; societal strength; economic strength*	21	x	x				x	x	x	x	o	2	+
Wu et al. [83]	Composite index of China's energy security	*Energy supply security; energy using security*	14	x								x	m	4	+
Chuang and Ma [85]	Multi-dimensional energy security indicators	*Dependence; vulnerability; affordability; acceptability*	7			x	p		s			x			
Selvakkumaran and Limmeechokchai [90]	Energy security indicators	*Oil security; gas security; sustainability*	15		x	x		x		x					
Sovacool [91]	Energy security index	*Availability; affordability; efficiency; sustainability and governance*	20	x	x		p		s	s		x		1	+
Sovacool [92]	Energy security index	*Availability; affordability; technology development and efficiency; environmental sustainability; regulation and governance*	20	x	x		p		s	p		x		1	+
Zhang et al. [93]	Oil import risk index	*External dependence; supply stability; trade economy; transportation safety*	8	x					x			x	m	5	+

Source	Name of indicator/index	Energy security dimensions/issues considered	No. of Indicators	Type of study					Specific focused Area (SFA)				Index construction		
				T	S	P	I	II	III	IV	V	VI	N	W	A
Jewell et al. [95]	Indicators of energy security	*Sovereignty; resilience*	19			x						x			
Kamsamrong and Sorapipatana [96]	Energy supply security index	*Physical energy security; economic energy security; environmental sustainability*	5			x	s	p	p				m		o
Portugal-Pereira and Esteban [99]	Electricity security of supply indicator	*Availability and reliability of the electricity generation and supply systems; technological development; global environmental sustainability; local environmental protection*	9			x	p		p			x			
Ranjan and Hughes [100]	Energy security index	*Diversity; availability; affordability; acceptability*	4				p					x	0		
Sharifuddin [101]	Core aspects of energy security for Malaysia	*Availability; stability; affordability; efficiency; environmental Impact*	35	x	x		p		s			x	z	2	o
Yao and Chang [103]	Energy security status	*Availability of energy resources; applicability of technology; acceptability by society; affordability of energy resources*	20				p		s	s		x	o	1	o

Source	**Name of indicator/index**	**Energy security dimensions/issues considered**	**No. of Indicators**	**Type of study**					**Specific focused Area (SFA)**				**Index construction**		
				T	**S**	**P**	**I**	**II**	**III**	**IV**	**V**	**VI**	**N**	**W**	**A**
Kanchana and Unesaki [123]	Indicators for ASEAN countries	*overall energy balance, socio-economic aspect, domestic energy resources, overseas energy demands and resources, and diversification of energy supply*	42	x	x			p			x	x			
Radovanović, Filipovic and Pavlović [124]	Energy security Index	*Security of supply, environmental and social aspects*	6	x	x			x		x	x			4	
Tongsopit et al [125]	Energy security in ASEAN	*Availability, Acceptability, Affordability, Applicability*	16	x			p						m	1	o
Narula and Reddy [126]	Sustainable energy security index for developing countries	*Availability, Affordability, Efficiency and (Environmental) Acceptability*	70		x			x	x	x			o	6	
Franki and Viskovic [127]	Energy security index for South East Europe	*Energy cost, Reliability and Sustainability*	6						x	x		x		4	o
Ang, Choong and T.S. Ng [128]	Singapore energy security index	*Economic, energy supply chain and environmental dimensions of energy security*	22	x		x		x	x	x			o	4	o
Martchamadol and Kumar [129]	Aggregated energy security performance indicator (AESPI)	*Social, economy and environmental dimensions*	25	x	x	x			p	x	x		z	3	o

Source	Name of indicator/index	Energy security dimensions/issues considered	No. of Indicators	Type of study					Specific focused Area (SFA)				Index construction		
				T	S	P	I	II	III	IV	V	VI	N	W	A
B.W. Ang, W.L. Choong and T.S. Ng [130]	The most meaningful energy security dimensions and metrics	*Availability (energy resources and security of energy supply for a given country), Affordability (Energy prices for households and industries),Acceptability(environmental and social consequences) ,Accessibility (geopolitical and resilience aspects)*	24				p							6	o

[a] The following notations are used: temporal(T), spatial(S), projection(P), 4As(I), specific energy supply(II), economic(III), environmental(VI), social(V), others (VI), normalization(N), weighting(W), and aggregation(A); under SFA, primary area(p), secondary area(s);under normalization (N), min–max (m), distance to a reference(r), standardization(z), others(o); underweighting(W), equal weights(1), import/fuelshare(2), PCA(3), AHP(4), DEA(5), others(6), under aggregation(A), additive(+), others(o).

2.3 How to build an energy security index

After selecting relevant metrics and collecting needed data, building a composite energy security metric requires three more actions: (a) normalising the indicators, (b) weighting the normalized indicators, and (c) aggregating the normalized indicators. A summary of methods that can be used in each step are shown in [**Fig 2.4]**. In any case, insights on each method could be found in **(Nardo et al. 2008 [108])**.

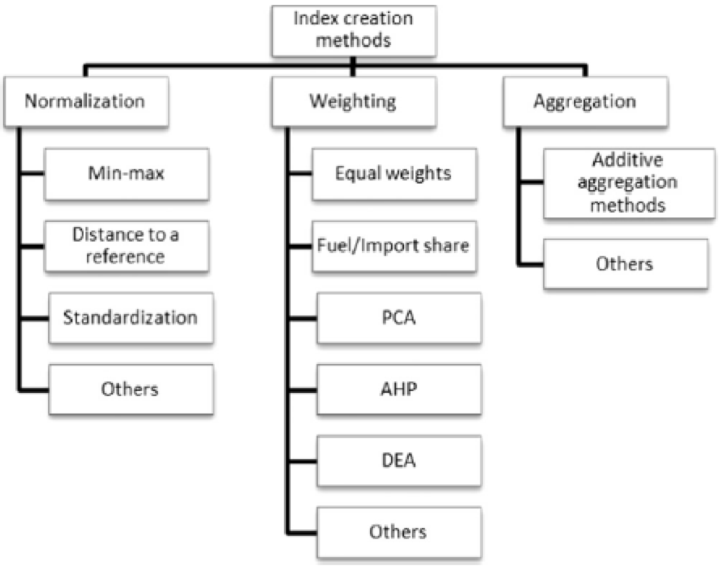

Fig 2.4: Normalization, weighting and aggregation methods in energy security index construction.

2.3.1 Normalization

The chosen indexes usually are characterized by different units and different scales. Transformation, generally through normalization, is required before aggregating data to form a composite index. The use of one of these following methods is the common practice: Min-max, distance to reference, and standardization. **The min-max method** consists of forming a scale taking into account the maximun and the the minimum values observed. After this, other values are placed with reference to the previously composed scale. An advantage of this method is the possibility to value results considering the best and worst performance, while a negative point is the necessity to reconsider the process in the case of data addition. **The distance to reference method** measures the deviation of a metric from a reference one. It is possible to choose different benchmarks as reference points and comparisons are simply done taking into account the distance from the selected benchmark. A problem of using this kind of method may be the fact that results obtained could be very sensitive and be strongly dependent to the benchmark chosen. **The standardization method** utilizes z-transformation, where scaling is based on deviation from the mean , to normalize indicators. This method is used especially in the case of comparisons among countries. The drawbacks are the sample size, that should be sufficiently large ,and recalibration, that is required when new data points are added. A relevant part of considered studies use some other methods. An example could be the one proposed by **(Augutis et al 2011 [43])**, in which a scale, that allow to define for each indicator the normal, pre-critical and critical state ,is composed. It may be concluded that many way to normalize energy security indicators are available but none of them has really played a dominant role. The breakdown by normalization method for the surveyed studies is shown in **[Fig 2.5].**

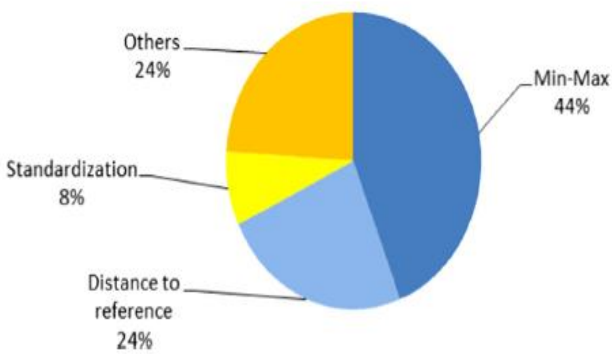

Fig 2.5: Distribution of normalisation methods in energy security index construction.

2.3.2 Weighting

The weights of indicators can be assigned based on subjective procedures or experts opinions. In the last case, the assessments of experts or stakeholders are collected through various options such as surveys, interviews or through more structured methods such as the Delphi one ,that is an established method used to get answers for a problem from an independent experts panel. Specifically, it is possible to use one of the following methods. The **equal weights method** is the simplest one to apply but, as negative effect, it's impossible to do any differentiation in terms of importance of an indicator. The **fuel/import share method** considers the relative importance in energy mix or imports of each fuel type, but it is not applicable in case of use of non-fuel indicators. The **principle component analysis (PCA) method** corrects overlapping information between correlated indicators and try to reveal how different variables change in relation to each other, or how they are associated. **Analytic hierarchy process (AHP)** is based entirely on experts opinions. **Data envelopment analysis (DEA)** measures performances of multiple countries establishing a benchmark and consequently it's meaningless for studies that take into account just a single country or only a few ones. Assigning equal weights to all indexes seems to be the most common technique, and this approach is used in over a third of the studies. Quantitative methods , such as, fuel import share and PCA, are also quite popular. In general, we can say that the chosen weighting methods in literature varies substantially among studies. The fact that equal weights method is the most used does not necessarily mean that it is the best one. Differently, it would be more correct to define this technique as the "default" method due to its simplicity and due to the difficulty to clearly define an alternative that is superior and acceptable to all stakeholders.

[Fig 2.6] shows the breakdown by weight assignment method for considered studies.

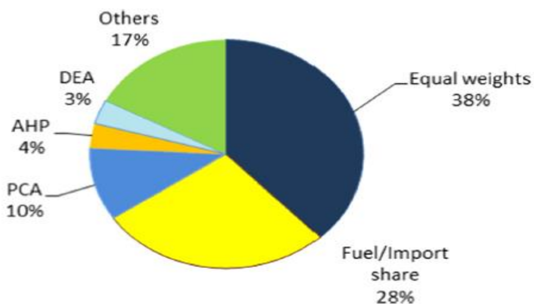

Fig 2.6: Distribution of weight assignment methods in energy security index construction.

2.3.3 Aggregation

Aggregation is defined as the combination of the weighted indicators into a composite index. In some works, indicators are first combined into sub-indexes, which are further aggregated into a main index using another set of weights for the sub-indexes. The simplest and most popular aggregation method is the **additive aggregation**, in which, at first, the indicators are multiplied by the weights assigned and then summed to compose the index. It is used in almost all energy security aggregated indexes. The remaining indexes use some other methods including, for example, the root mean square of indicators. Some negative aspects, that clearly characterized the aggregation step, are the loss of information during the process and the increasing complexity due to artificial manipulations.

2.4 Some considerations

It's clear that energy security indexes research is still in early stage considering a methodological point of view. We can't find in literature a generally accepted method for constructing energy security indexes. In this sense, improving the robustness of composite energy security indicators through the implementation of new areas such as the use of simulation and trough a more specific analysis on how the interaction of different normalization, weighting, and aggregation can effects the results obtained, may represent the scope for further researches. Other areas of further investigations may be pointed to develop indexes that are less sensitive against data ambiguities, such as incomplete information and missing data. A better understanding of the various analytical methods, including their strengths and weaknesses, may be the first step in the direction of developing a "standard" framework to build an energy security index. Generally, the suitability of an analytical method is context and data dependent. Ensuring that the method used is appropriate in that particular situation requires an accurate analysis on the energy system of the country studied, the study objective and the quality of the data available. The same considerations concern multi-country studies in which case certain trade-offs are likely to be done. Again, further works that investigate the impacts of different indexing methods on energy security indicators could be very helpful to provide guidelines on energy security index construction for practitioners.

Chapter 3

Evaluating indicators: Economic value of component metrics

In the previous chapter, it has been submitted a summary where most of indicators present in literature, which attempt to quantify the energy security situation, are described, considering covered topics, number of indicators and the way they are aggregated. In most cases, these indicators address many different issues of energy security. Various dimensions are described by metrics (simple or aggregated indexes) that cover a specific aspect of the problem and, only then, they are aggregated to have a general indicator. Due to this, it's quite difficult to value composed indicators as a whole especially when they are varied and cover issues that have a little to do with the core problem of energy security. Then, it has been decided to proceed disassembling and cataloguing all metrics that compose the indicators reviewed in the previous chapter. By doing so, it is possible to understand in a more specific and appropriate way if each catalogued metric contributes to really measuring the energy security situation and also if it has any kind of economic implication. The evaluation has been carried out considering the definition of energy security adopted and expressed in the first chapter as "the availability of reliable energy flows at an affordable price" and to which this report makes reference in its development.

3.1 Economic implications of energy insecurity: prices and physical unavailability

In the case of failure in ensuring energy security, imbalances between supply and demand in the market might be arise as consequence. Whether the resulting energy security impacts take the form of price or physical unavailability effects depends on the type of energy insecurity cause and the energy market in question. The faster the initial imbalance can translate into a price signal the less likely physical unavailability will be of concern and the more the emphasis will be on energy security price effects. Time is therefore an essential dimension of energy security. In some cases, such as extreme events or load balancing failures in electricity markets, sudden imbalances are generated. This puts greater pressure on the system compared to more long term imbalances, such as those generated by resource concentration. Sudden imbalances are therefore more likely to generate both physical unavailability effects and price effects and in this sense supply flexibility and market liquidity are very important components in determining how well initial imbalances translate into price effects. Some forms of energy, such as electricity, are inherently less flexible than others and are therefore more prone to generate physical unavailability. In some cases the design of the market is such that the price signal is mitigated This is notably the case of regulated markets or the case of markets where prices are pegged to another commodity. This means that the initial imbalance in supply and demand cannot translate into a price signal. In such cases physical unavailability concerns are large and often play a preponderant role.

3.1.1 Energy security implications of extreme events: Weather events, large scale accidents, acts of terrorism and strikes

As expressed in **[James Greenleaf et al 2009 (45)]**, these are events that put exceptional strain on energy systems by creating an often sudden imbalance between supply and demand. They are so rare and so severe that it is difficult for private agents to account for them appropriately and they may therefore lead to energy insecurity. These types of extreme events have been grouped together as a result of the similarities among their effects on the energy system. Taking into account climate parameters, certain regions are more prone to extreme weather events than others and, generally speaking, extreme weather events can affect any sector of an energy supply chain (e.g. by disrupting transmission lines or in hot weather reducing the availability of cooling water such that power plants must run at reduced capacity). Considering instead the other kind of extreme events, we can classify them as:

- **Large-scale accidents:** accidents which fall outside the scope of tolerance levels typically accounted by industry.
- **Strikes**: industrial action by workers or other forms of social unrest.
- **Terrorist activities** : a direct attack affecting the physical supply of energy.

The first are similar to extreme weather events for the fact that they are random events. The latter two are targeted events, and in these cases therefore, disruptions are aimed to target specifically infrastructure or trade routes having strategic importance as, for example, the ones that are part of a market sector characterized by a high level of infrastructural concentration. As said before, the basic issue here is the effect of an imbalance between supply and demand. In this sense, a key difference between extreme weather conditions and all other extreme events is that the first can also impact directly on the demand for energy (e.g. via increased heating and cooling demand). Then, shortly, the imbalance for extreme weather events is represented by an increase in peak demand with a decrease of supply, whereas in all other extreme cases, the imbalance is reflected in a reduction of supply with a peak demand unchanged. Considering the supply side, one important determinant of the magnitude of the resulting energy security impact is the level of market share of the sector affected. For example, in the case of oil, if a refinery with large market share is made unavailable this will lead to a more severe impact than if it provided a much smaller share. Another important parameter in determining the resulting energy security impacts (whether a price or physical availability concern, or a combination of the two) is the flexibility of the remaining sectors of the supply chain both upstream and downstream from the sector affected, to find alternative input sources or reduce input demand while the problem lasts. Assuming that prices are set competitively, the more the supply chain is characterized by flexibility (particularly in sectors immediately up and downstream from the sector affected) the less likely physical unavailability is to occur. With the refinery example mentioned above, if oil production facilities are bound by pipeline to the refinery affected, their flexibility to divert deliveries to other refineries will typically be limited and the energy security impact of the disruption is likely to be more severe. Similarly, if the distribution of oil products occurs via fixed transport means, the energy security impact is also likely to be more severe than if undertaken by road, in which case distributors can get fuel supplies from other sources. . The most significant impacts of these extreme events might affect the supply of gas, oil and electricity while coal can be stockpiled relatively easily. Similarly, the impact of extreme events on uranium supply (given the higher energy density and extended refueling period) are not considered significant, although an extreme event related to electricity generation from nuclear plants will be significant. Considering, instead, the demand side, that how we said before it is affected only by extreme weather events, the most important aspect is how much the weather conditions increase short-term peak demand. Even in this case, flexibility, here considered in terms of the ability to rapidly increase short-term supply to meet the increased peak demand ,e.g. via the use of reserves and storage facilities, is a key factor. Useful, in this sense, could be an indicator that, for each of the most used source, show the availability (expressed in number of days) that could be provided by existing storage given the scale of the shortfall. It is also important to note that, as expressed in **[G. Girardi, J.C. Romero, P. Linares ,2015 (131)]**, climate change itself will likely have an impact on energy security on both the demand and supply side and on energy infrastructures as well. According to **IEA analysis**, we may resume the impacts of climate change on:

- **Energy demand**: It is expected to change, potentially dramatically in some areas, as a result of increasing temperatures and changing weather patterns, affecting heating and cooling demands. Forecast shows that while demand for heating may decrease, demand for space cooling will increase in all parts of the world, especially in China, the United States, Middle East and India.

- **Energy supply:** It will face changing conditions, including reduced efficiency of thermal plants, cooling constraints on thermal and nuclear plants, and pressure on transmission systems; electricity generation from hydro, wind and other renewable and biofuel production will also be affected. For example, according to IEA estimates, 1°C of warming can be expected to reduce available electricity generation capacity in summer by up to 19% and 16% in Europe and the United States, respectively, in the 2040s.

- **Energy infrastructure:** They could be exposed to sea-level rise, permafrost melt, as well as more frequent and intense extreme weather events including increased wind speeds and ocean storminess. These may threaten coastal power generation infrastructure, onshore transmission and distribution infrastructure, as well as offshore installations and pipelines and could ultimately lead to various interruptions of energy delivery systems.

Shortly we can say that, given the likely temporary nature of price shocks resulting from extreme events, we consider that the severity of this impact on energy security would therefore be limited. Physical unavailability of fuel due to extreme causes is therefore considered a much greater threat to energy security. Even if the effect of rising prices during extreme events have actually a limited impact, it represents an important aspect of concern in public perception. In fact, especially in industrialized countries, the problem is not that the people do not have access to enough energy to satisfy their needs, but rather that these circumstances require them to consume too much energy and therefore to spend too large a fraction of their income on it. If they cannot meet this expenditure, in the common opinion the access to energy is disrupted. In this context, the idea of the impossibility in achieving the minimum standard of what is needed for material well-being might start to spread generating, in borderline events, social disorders. In conclusion, in case of extreme events, the emphasis is on the short-run impacts of the event and so those indicators that highlight the flexibility of the system and the infrastructures market share are the most relevant.

3.1.2 Energy security implications of inadequate market structure

Energy markets are complex. Infrastructures often span several countries and therefore encapsulate different regulatory systems. They are also characterized by large and long lived capital investment cycles. Many markets have also only recently shifted to deregulated structure. This transition is tedious and involves an important learning process for all market participants. Energy market structures are therefore continually evolving and may at times themselves be the cause of energy insecurity.

Load balancing failure in electricity markets

Load balancing in the short term is especially challenging for electricity due to the network infrastructure and the lack of storage capability. The gas system has similar issues, but to a lesser extent due to the storage capability in specific facilities and the inherent "linepack" storage of the network itself. Considering then the most problematic market in this sense, electricity one, system operators are responsible for ensuring a given level of reliability (and also electricity quality) by balancing supply and demand in real time. About electricity market, **(Rodilla 2010 [136])** provides a useful classification ,from the time dimension perspective, of four dimension of the security generation supply as shown in **[Fig 3.1]**: security (a very short-term issue), firmness (a short to medium-term issue), adequacy (a long-term issue) and strategic expansion policy (a very long-term issue), with the last two more correlated to the problem of insufficient investment in new electrical production capability respect the real time balancing.

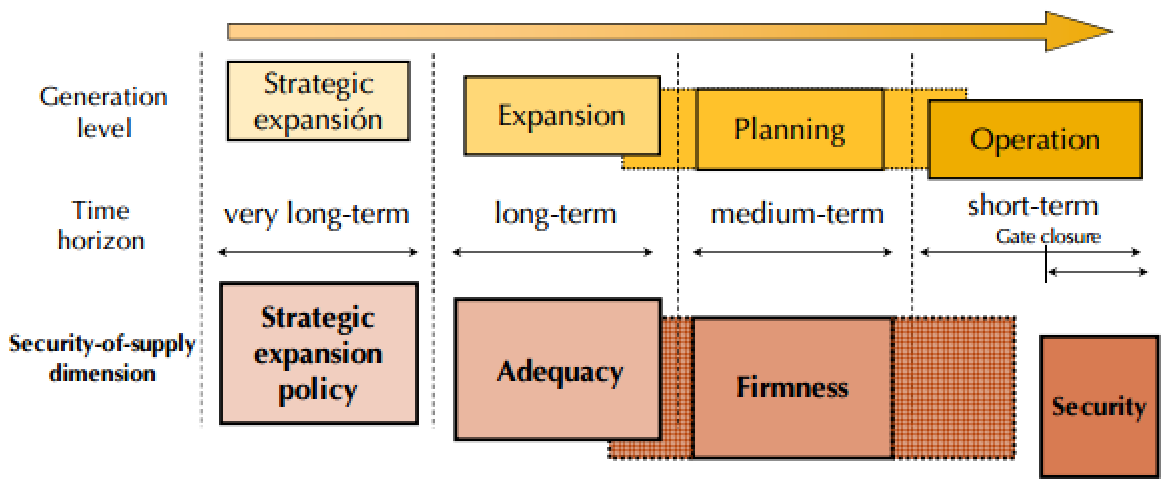

Fig 3.1: Security of supply dimensions

-Security: a very short-term issue (close to real time), defined by the NERC as the "ability of the electrical system to support unexpected disturbances such as electrical short circuits or unexpected loss of components of the system or suddenly disconnection" **(NERC 1997)**. The real-time operation of a power system requires a central coordination to ensure a continuous match between supply and demand. It is commonly accepted that the System Operator (SO) has to be responsible for such coordination. It is possible to define "gate closure" as the point at which SO takes control of the system and after which the problem of ensuring security arises. At gate closure, the scheduled generation is transferred to the System Operator that, acquiring ancillary services, should guarantee the quality (maintaining voltage and frequency within acceptable margins), security (short-term uninterruptibility of supply) and financial efficiency (supplying electric power at the lowest possible cost) of supply. Ancillary service are divided in three different categories: frequency control (operating reserves: primary, secondary and tertiary); reactive power for voltage regulation; and black-start capabilities (restoration of power). Furthermore, it is fundamental to underline that, traditionally, it was implicitly assumed that an electrical system with a high degree of installed and available capacity also presented a high level of available operating reserves, meaning that it had a high degree of flexibility to overcome short term contingencies. This is not always true in fact, for example, the trend of introducing large amounts of wind energy will require a higher than usual proportion of flexible generation. In this context, the availability of generation units which are able to ramp up power in the very short term also contributes to facilitating load balancing.

-**Firmness:** a short- to mid-term issue, which can be defined as the ability of the already installed facilities to provide generating resources efficiently (especially when most needed). This dimension is linked to both the generating units' technical characteristics (the amount of load-following units, the percentage of the so-called intermittent generation resources, etc.) and also to their medium-term resource management decisions (the management of fuel stocks, of hydro reserves and of scheduled maintenances) that are mostly driven by market signals. From the firmness standpoint, regulators should evaluate whether market signals are capable of ensuring efficient generation resource management, or if it would be appropriate to introduce some additional mechanism to ensure such a result. Considering instead the technical aspect, even with abundant installed generation, if, for a variety of reasons (lack of water in the reservoirs or of fuel in the tanks, units out of service for maintenance or because of a forced outage, etc.), a significant part of this capacity is not readily available when needed, then the demand may not be efficiently met. In this context, an indicator as the "de-rated peak capacity margin" ,that scales back nameplate capacity by the expected availability of each plant at peak demand, taking into account probability of forced outages and expected output from intermittent renewables, might be very useful. In these dimension, we can underline also the importance of Cross border trade, that can contribute to improve the reliability of the system but it requires significant coordination among system operators.

The next two dimensions, as said before, deal more with investment problem that is going to be discuss, more generally, in the next section.

-Adequacy: a long-term issue: which means the existence of enough available generation capability, both installed and/or expected to be installed, to efficiently meet demand in the long term.). A lot of discussion have been made about the convenience of introducing regulatory measures to provide an adequacy level (usually just based on reliability criteria) with which the regulator feels comfortable. The regulator's objective in terms of adequacy should be to guarantee appropriate incentives to attract new entrants (i.e. incentives to attract new efficient generating units).

-Strategic Expansion Policy: which concerns the very long-term availability of energy resources and infrastructures. This dimension usually entails the diversification of the fuel provision and the technology mix of generation. The introduction of this long-term criteria could be justify considering the possibility of changes in long term that are difficult to take into account at the present moment (drastic changes in fuel prices, resources exhaustion, etc.). An application of this criteria could be to invest in the development of a new technology given the expectation that after some years it will become an efficient alternative. Wind energy is a good example of this: after years of investing in support mechanisms for wind generation, it seems to be now a reasonable alternative.

It is important to note that these four dimensions are to a large extent interrelated and they cannot be completely decoupled from each other.

Summing up, the nature of the energy security concerns associated with load balancing is that a failure will lead to sudden price rises (e.g. due to inefficient use of plant for load balancing), or in extreme cases to physical unavailability of electricity (load shedding) in the case system operators are unable to balance short term supply and demand.

Insufficient investments in new capacity

Lately, given the competitive nature of energy markets (especially in EU), investments on the supply side are in many cases dependent on decisions made on a commercial basis within the private sector. There may be situations in which this could lead to under investment. In this sense, investors decisions may be influenced too strongly by a short term view of market developments, and as a result decision may not sufficiently reflect the impact of the potential longer term price movements associated, for example, with resource depletion or tightening environmental policies. Otherwise, in the case of high degree of regulation, from an energy security perspective, the main concern is that the flow of investment is hindered by problems within the regulatory structure governing energy markets and that this will ultimately affect economic welfare. Regulations may notably directly affect the revenue stream of projects. For example, in the electricity sector, while price caps are identified as a way to minimize short-term price disruptions, the drawback is that they directly affect the price signal and therefore the flow of investments in new capacity. Regulatory processes may also be overly burdensome and this can create a barrier to the flow of investments, particularly in terms of the timeliness of investments. As example, the administrative process involved for planning, sitting, and ultimately construction of new refineries or power plants, for example, requires numerous checks and approvals often from different branches of government. Summing up, Insufficient investment results in reduced capacity margins and therefore affects the ability of energy systems to cope with fluctuations in both demand and supply. Depending on the magnitude of the investment shortfall, consequences may result both in price changes and physical unavailability

3.1.3 Energy security implications of resource concentration

The concentration of energy resources in certain regions of the world provides a form of market power to the countries where the resources are concentrated in. If countries with high concentration of resources collude to further enhance their position in the market, the possible energy security threats might be even greater. For example we can mention the role of OPEC in coordinating production quotas and the impact this can have on oil (and indirectly gas) prices. The nature of the energy security impacts depends on the market in question. For example, in the case of the international oil, coal markets and gas traded under gas-on-gas pricing where , the price of natural gas is indexed to competitively determined gas market spot prices which change in response to natural gas supply and demand, the structures of market are well developed and the price mechanism minimizes physical unavailability risks. In this case, the main concern is therefore that market power leads to uncompetitive behavior, and in particular that prices will be set above the competitive levels. The magnitude of the energy security impact for a given country then depends on its exposure to the fuel market risk in question. Differently, in the case of gas traded under long-term, bilateral, oil-indexed contracts (take or pay contracts), the price mechanism doesn't contribute to balance gas supply and demand and physical unavailability becomes an important concern For a given country, the likelihood of physical unavailability occurring depends on the rigidity of the actual fuel supply infrastructure. For example, in the case where a country relies solely on imports from one country through one pipeline, if a supply shortfall occurs it will lead to the physical unavailability of imports. In contrast, if a country imports from a variety of countries and through a variety of transport means (namely pipeline and tanker), a supply shortfall from one of its trade partners may more readily be covered by increased exports from others and physical unavailability in the importing country may be avoided. It's important to underline that this kind of contractual arrangements between a single supplier and user do not necessarily eliminate energy security price concerns. . For example, taking into account take or pay contracts based on oil price indexation, much of the price risk is in fact transferred to what happens on the oil market, even if in the last years, differently from the past, for the buyer, it has been often possible to renegotiate contracts considering the recent fall in gas prices.

3.1.4 Considerations about uncertain role of market power and depletion of fossil reserves

Considered **[45]**, there are other potential areas of energy insecurity which have not translated into notable price or physical availability problems. One example is the possible negative effects of market power (i.e. monopolistic, oligopolistic structures) on energy prices. This may be of concern as much within EU energy markets as the international level. Such concerns are potentially important, and should be monitored even if they have not translated into clear energy security impacts. Another example is depletion of fossil reserves. Whilst this is a key driver of long-term concerns, it is actually the resulting resource concentration rather than the level of remaining reserves per se that has led to price or physical availability energy security concerns. Without concerns about concentration, depletion would be gradual , dynamic and with price increases that spur greater exploration as well as R-D in alternative energy sources leading, in this way, to an extended time period for depletion over which an economy could gradually respond. Even where there is greater concern that depletion may not be as gradual, the main threats of energy security is again not the level of reserves per se but the ability to develop new and alternative forms of energy and, consequently, this aspect should be dealt in the section concerning investments in new capacity.

3.1.5 The role of Supply flexibility and Market liquidity

A number of factors ,that are not themselves causes of energy insecurity, have an important role in determining the nature (price or physical availability) and magnitude of energy security impacts. This is notably the case of supply flexibility and market liquidity, which can both contribute to exacerbate energy security impacts. Supply flexibility is the physical ability of a given energy market to compensate for the supply shortfall resulting from a given threat to energy security. The more flexible the supply chain is, the less the event is going to result in significant energy security welfare impacts. Similarly, inflexibility may also contribute to worsen insecurity impacts. The nature of the fuel and associated infrastructure are key determinants of supply flexibility. Fuels that are easier to handle and transport tend to provide greater flexibility in case of a supply shortfall. For example, coal and oil tend to be relatively easy to handle. Over land, they can be transported through a variety of modes including rail, road, and pipe. They can also readily be stocked. In contrast, natural gas is mostly transported by pipe and it is both costly and more complex to stock. At sea, the shipping of coal and oil is also relatively straightforward while gas requires liquefaction at the point of departure and re-gasification upon arrival, both complex and costly steps. Finally, electricity offers even less flexibility. It cannot be stored cost-effectively and requires careful quality control along transmission and distribution lines to ensure safe transport. These characteristics affect the economics of each fuel and their inherent flexibility is largely reflected in each market. Within a given market, liquidity characterizes the ability of buyers and sellers to undertake transactions. A liquid market therefore requires that sufficient buyers and sellers are available and willing to trade. The more liquid the market is, therefore, the faster an energy security supply shortfall will translate into the appropriate price signal. In contrast, an illiquid market may exacerbate the energy security impacts. Both supply flexibility and liquidity also contribute to determine whether the energy security impact manifests itself as a price concern or a physical unavailability concern. The more flexible and liquid the market is the less a supply shortfall from a given cause is likely to lead to physical unavailability for end user.

3.1.6 The role of end-use demand

The level and structure of demand for energy plays an important role in defining the magnitude of the resulting energy security impact. It is only through the interaction of supply and demand that impacts materialize. In its simplest form the possible price / physical unavailability impacts of energy security depend on the absolute level of demand for the affected energy source. However, the linkage between supply and demand is more subtle and governed by two main factors. The first is the level of **demand side participation** that falls into two broad categories:

• **Over the short term**, the primary concern is whether end-use demand is sufficiently responsive to price signals to mitigate short-term price effects and potentially prevent physical unavailability. This is key concern in the electricity market, where technologies and processes are not yet widely available at the end use level to allow broad participation in the market. This reduces the flexibility of system operators, and in the worst cases may lead to physical unavailability (e.g. via load shedding).

• **Over the medium to longer term**, the price mechanism should help stimulate demand reduction, via conservation or improvements in energy efficiency. This helps to mitigate against price effects (by limiting the total demand for energy) and physical unavailability impacts (e.g. increasing the level of energy services that can continue to be delivered with a given level of energy storage). Where this improvement does not take place, and where overall demand continues to grow this increases the vulnerability of the system to energy security impacts. The second factor is the level of substitutability among energy sources. In addition to the level of demand side participation, the vulnerability of energy systems depends on the capacity of end-use demand to switch to other energy sources in case of an energy security threat. For example, electric space heating could be used temporarily in case of a natural gas shortage. The potential for substitution depends largely on the current technological capability and supporting infrastructure, as well as how this develops in future. A final remark should be done on the fact that not all forms of energy or energy carriers are necessarily equivalent and this element can further complicate the assessment of the impact of energy insecurity. In conclusion, we can say that, certainly, the demand side management might help in limiting the economic impact of energy insecurity, but we should also underline that it represents a solution of the insecurity problem and then, indexes correlated to this topic, especially those that express how efficiently energy is used (efficiency in end use sectors and energy intensity), do not represent tools to measure and quantify the energy security concept as we have previously defined it. Nevertheless, some metrics such as demand price elasticity, that provides information about the importance of price signal in avoiding physical unavailability, or the absolute level of demand, that is a fundamental parameter to evaluate capacity margin metric, might be useful in describing energy security situation.

3.2 Evaluation of catalogued metrics

In the following tables, component metrics of aggregated indicators reviewed in the previous chapter are listed. Metrics are classified according to five dimension: Availability, Affordability, Technology and Efficiency, Environment and Governance&Policy. These dimensions, in a general way, cover all energy security aspects described in literature. Taking into account the used definition of energy security expressed in the first chapter (considering for example energy poverty as an issue not covered in this report) and according to all considerations in previous sections, all metrics obtained from literature are evaluated considering:

• The ones that actually have nothing to do in quantifying energy security
(Black ones)

• The ones that actually are useful in measuring some aspect of energy security
(Cursive Blue ones)

• The ones that measure energy security situation and ,also, have economic implication that results in price changing or physical unavailability according to different situations previously described (Underlined Red ones)

Table 3.1: Evaluation of catalogued metrics

AVAILABILITY

Security of supply		
TPES (Total primary energy supply)	*TFEC (Total final energy consumption)*	*Total Primary Energy Supply (TPES) per capita*
Total final energy consumption (TFEC) per capita	*Reserves-to production ratio (oil, coal, gas, uranium)*	*Resources-to production ratio(Oil, coal, gas, uranium)*
Average reserve-to-production ratios for the four primary energy fuels (uranium, coal, natural gas, and oil) in remaining years	*Total electricity demand*	*Total installed electricity generation capacity*
Peak demand	*Base load demand*	*Per Capita Electricity Generation Capacity*
Secondary and tertiary frequency control reserve	*Thermal power capacity*	Crude Oil proportion of offshore production
Volatility of crude oil domestic production	Annual volatility of production hydropower	Refining/fuel processing capacity (as Fraction of TPES, Percentage of production, Volume refined per year)
Proportion of mining that is underground	Daily send-out capacity from underground and LNG storage	Proportion of offshore production gas
Intermittent renewable power capacity	*Average age of nuclear power plants*	*Number of nuclear power plants*
Diversity of reactor models		

Dependency		
Energy import dependence (% of TPES)	Energy Self-Sufficiency: Ratio of domestic production to total domestic consumption (Oil, Gas, Coal, Uranium)	**Net energy import dependency (NEID)** [(1)]
Import dependence Ratio: Share of net imports in total consumption (Oil, Coal, Gas, Uranium)	Net electricity import	*Annual change in net electricity import*
Share of foreign supplies of energy resources in the electricity generation portfolio (coal, natural gas, Heavy Fuel Oil and nuclear)	*Annual change in net fuel imports*	Dependence on imports of solid fuel
Share of end-use sectors energy produced from imported fuels	Carriers dependence on imported fuels: Share of energy carriers (Oil products, synthetic fuels, hydrogen, electricity, biofuels) produced from imported sources divided by the total energy carrier)	**ESIvolume**[(2)]
Share of the Middle East in total oil imports		

Decentralization		
Rate of distributed generation	*Share of energy needs met by distributed generation (units less than 1 MW)*	Number of installed residential solar photovoltaic systems
Installed capacity of fuel cells	Installed capacity of micro-turbines	Number of households served by micro-grids

Diversification [(a)]		
Diversification by sources in total primary energy supply [a]	Diversification of foreign supplier of source (Oil, Coal, Gas, uranium)[a]	Diversification (by transport routes) [a]
Share of RES in total primary energy supply	Share of RES in final energy consumption	Share of RES in electricity production
RES generation status excluding large hydro	Differentiation of energy fuel (Heating and cooling)[a]	Share multi-fuel plant capacity in total thermal power capacity
Diversification of electricity generation (by fuel type)[a]	*Geographic dispersion of energy facilities*	**Mean variance portfolio**[(3)]
Diversity of primary energy sources in end-use sectors(Transportation, industrial, residential and commercial)[a]	End-use sector diversity of carriers (Oil products, synthetic fuels, hydrogen, electricity, biofuels) [a]	Share of nuclear energy in total primary energy supply

AFFORDABILITY

Expenditures and General economic parameters		
GDP (Gross domestic production)	GNI (Gross national income)	GDP per capita
GNI per capita	*Ratio of net fuel import bill to GDP*	Export fuel earnings to GDP
Exchange rate (volatility)	US Dollar index volatility	Energy import cost-to-total export revenue ratio
Price elasticity of demand	Household income (total and poorest 20% of population)	*Household income spent on fuel and electricity*
World oil price	*Average household expenditure on energy*	

Access and equity		
Households (or population) without electricity or commercial energy)	Households (or population) heavily dependent on noncommercial energy	Fraction of population with access to basic energy services
Share of population with high quality connections to the electricity grid	Homes with continual access to electricity	Rate of electrification, expansion/number of new customers served
Annual household electricity consumption	Percent of population reliant on charcoal, dung, and biomass for cooking	Hours of electricity per day

Energy market and Price stability		
Average supply cost of imported energy	End-use energy prices with and without tax/subsidy by fuels and by sector (residential, commercial, industrial)	Historical Fuels price trend, fluctuations (after inflation) and volatility
Market/wholesale prices for oil, gas, coal, uranium, electricity(industrial and residential) and carbon	Retail gasoline/petrol prices	*Energy Expenditure Volatility*
Share of 3 largest suppliers by sources	Share of Energy use covered by long-term contracts	Marginal cost of electricity power generation
Fuel cost for electricity generation	Transmission and distribution cost for electricity	Market liquidity (oil ,coal, gas,uranium): the ratio of world source imports to the net source imports of a given country
OVI (Oil vulnerability index)[4]	**Geopolitical market concentration risk (GMC)[5]**	**Geopolitical Energy Security (GES)[6]**
$ESMC_{pool}$[7]	**ESI-price[8]**	

Technology and Efficiency

Infrastructure and Reliability		
Efficiency of energy conversion and distribution (Losses in transformation systems including losses in electricity generation, transmission and distribution)	SAIDI of electricity (system average interruption duration index)	SAIDI of electricity excl. exceptional event
SAIDI of heat	SAIFI (System Average Interruption Frequency Index)	Achievement in meeting planned target of domestic energy supply
GDP loss due to electricity interruptions	VOLL (Value of lost load)	Exposure of critical energy infrastructure to energy-related military/security risks (i.e. terrorism, conflict over resources, piracy, spread of nuclear weapons)
Entry points: ports, pipelines, railways (Crude Oil and Oil products, Gas, LNG, Coal)	Investment in electricity transmission	Power outage frequency: Ratio of Outage frequency per year to total number of customers
Power outage duration: Ratio of accumulated duration of power outage to total number for customers	*Spare pipeline capacity of major pipelines*	System stress: period when demand reaches 85% of total capacity of electricity supply system
Sum of electricity interconnection capacity	Number of electricity interconnections on national borders	Amount of interconnector trading of electricity

Resilience and Adaptive capacity		
Capacity margins (Electricity and Gas)(Total capacity/ Peak demand)	Peak-load to base load ratios	Generator profiles summer/winter
Emergency stockpiles (oil, coal and natural gas) expressed in percentage of import and consumption and days meet demand	Percentage of energy capacity actually utilized	De-rated peak capacity margin (Electricity and gas) (Total capacity corrected considering probability of forced outages and expected output from intermittent renewables/ Peak demand)

Energy intensity		
Energy intensity (Energy consumption/ GDP)	Energy intensities per sector (Industrial, Agricultural, Service/commercial, Household, transport)	Oil intensity(GDP)
Gas intensity(GDP),	Electrical energy consumption per Capita	Energy consumption growth/economic growth

Innovation and research		
Total energy-related R&D spending/GDP	Diversity of energy-related R&D spending	Cost of energy subsidies per person
Public research intensity (government expenditures on energy research compared to all government expenditures)	Research budgets for renewables	Industrial Energy R&D Expenditures

ENVIRONMENT

Climate change		
GHG emissions from energy production per capita	GHG emissions from energy production per unit of GDP	GHG emission to TPES
Share of Country s CO2 emissions out of global CO2 emissions	Non-carbon energy share in energy	Non-carbon energy share electricity

Others aspects (Land, water and air pollution)		
Rate of deforestation attributed to energy use	Ratio of solid waste generation to units of energy produced	Nuclear waste
Ratio of solid radioactive waste to units of energy produced	Ratio of solid radioactive waste awaiting disposal to total generated solid radioactive waste	Land used for electricity conversion in coal plants
Contaminant discharges in liquid effluents from energy systems	Fresh water use for electricity generation	Average volume of waste water discharged from coal plants
Ambient concentrations of air pollutants in urban areas	Air pollutant emissions from energy systems	Metric tons of SO2 per person

GOVERNANCE AND REGULATION

Governance and regulation		
Political stability of suppliers	Transparency international corruption index	Rule of Law
Political Rights	Rate of contractually flexible demand (interruptible contracts, fuel switch on government order)	Existence of energy security policy
Transparency of energy security policy	Regular policy reviews	*Supply issues addressed in policy*
Demand management issues addressed in policy	Efficiency issues addressed in policy	Economic issues addressed in policy
Environmental issues addressed in policy	Human security issues addressed in policy	Military/security issues addressed in policy
Socio-cultural and political issues addressed in policy	Technological issues addressed in policy	International cooperation issues addressed in policy
Historical relations with key suppliers	Share of Government revenue dependent on energy	Transparency international corruption index
Worldwide Governance Indicators (World Bank)	Presence of climate change goals or targets	

(a) HOW TO QUANTIFY DIVERSIFICATION

The two indices mostly used to measure diversity are presented below. The first is the **Shannon index** (sometimes Shannon–Weiner of Shannon–Wiener index):

$$H = -\sum_i p_i \ln p_i$$

with pi representing the share of fuel i in the energy mix or the market share of supplier i. The higher the value of H, the more diverse the system is. This index rises monotonically with increasing variety and balance.

Next, there is the **Herfindhal–Hirschman index** (HHI, also named Simpson index in ecology):

$$D = \sum_i p_i^2$$

with p_i again representing the share of fuel i in the energy mix, or the market share of supplier i. The lower the value of D, the more dual concept diverse the system is. The reciprocal of this quantity is therefore also used, so that a higher index value implies higher diversity.

(1) NEID (Net energy importance dependence)

Net energy import dependency (NEID) is a commonly used indicator for assessing energy security. It's define as the share of energy import weighted with its fuel diversity and a high NEID implies low energy security. It could be express as:

$$\text{NEID} = \frac{\sum_i m_i p_i \ln p_i}{\sum_i p_i \ln p_i}$$

m_i Share in net imports of energy carrier i (%) ,

p_i Share in total primary energy supply (TPES) of energy carrier i

Here, a higher value implies a lower SOS. With a specification of the fuel's role in the energy mix, this indicator provides a more refined indication of import dependence as the simple import numbers and is useful as such.

(2) ESI_{volume}

In the case of demand satisfied by long-term import contracts indexed on crude or oil-products, gas price movements do not reflect gas market supply and demand on the market. In this case, where prices do not reflect market fundamentals, the risks of physical unavailability are of greatest concern because the price effect is unable to contribute to balance demand and supply in response to a supply shortfall. Due to the relative inflexibility of pipelines, therefore, physical unavailability concerns in gas are predominantly linked to pipe-based imports. The measure of the gas supply availability can be expressed as:

$$ESI_{volume} = Gas_{imp\text{-}pipe\text{-}regulated}/TPES$$

Where $Gas_{imp\text{-}pipe\text{-}regulated}$ is the net imports of gas via pipeline purchased through oil-indexed contracts. ESI_{volume} ranges from 0 in the case of either a fully liberalized gas sector (i.e. 100% gas-based pricing), no pipe-based imports (i.e. 100% LNG), or 100% self-sufficiency in gas (i.e. no imports), to 100 in the hypothetical case of 100% oil-indexation gas consumption, 100% pipe-based import dependence and a fuel mix 100% based on gas.

(3)Mean variance Portfolio

Mean variance portfolio (MVP) theory stems from financial economics. It can be applied to electricity generating mixes or the wider energy system by not only taking into account the unit generating costs but also the variance in fuel costs and the correlations amongst different fuel costs. In addition to yield an optimal generating mix, portfolio analysis provides an 'efficient frontier', a limit in the cost-risk domain beyond which (energy) investment portfolios cannot be made less costly without increasing their risk, or vice versa cannot be made more risk adverse without increasing their cost.

EXAMPLE:

For a simple 2-stock (or 2-technology) portfolio the expected portfolio return is given by:

$$E(r_p)=x_1\,E(r_1)+x_2\,E(r_2)$$

with $E(r_p)$ is the expected portfolio return; xi is the share of asset i in the portfolio; $E(r_i)$ is the expected return for asset i. Specifically; the mean of all possible outcomes, weighted by the probability of occurrence; e.g., for asset i: $E(r_i)= \sum p_i r_i$, with p_i the probability that outcome i will occur, and r_i the return under that outcome.

The risk is a function of the individual asset-risks, as well as their correlation;

$$\sigma_p = \sqrt{x_i^2\sigma_1^2 + x_2^2\sigma_2^2 + 2x_1x_2\rho_{12}\sigma_1\sigma_2}$$

with ρ_{12} is the correlation coefficient between the two return streams; σ_i is the standard deviation of the periodic returns of asset i. Mean variance portfolio can be made to suit the analysis of energy portfolios, by interpreting expected returns as the reciprocal of unit generating cost (kWh/€ct or similar). The risk of an individual asset or energy technology is then given by the variance in generating cost, which is governed by fuel costs rather than capital costs.

(4) OVI (Oil vulnerability index)

Gupta (2008) computes an aggregated index of oil vulnerability based on seven indicators: (1) the ratio of value of oil imports to GDP; (2) oil consumption per unit of GDP; (3) GDP per capita; (4) oil share in total energy supply; (5) ratio of domestic reserves to oil consumption; (6) exposure to geopolitical oil supply concentration risks as measured by net oil import dependence, diversification of supply sources, political risk in oil-supplying countries, and (7) market liquidity. These are combined to yield an overall index, where the weighting is based on PCA statistical method. In this method, the covariance of the indicators above is used to assign weights, rather than (subjective) expert judgments. High value of OVI implies high oil vulnerability.

$$\text{OVI}_k = \text{Market risk}_k + \text{Supply risk}_k$$

$$\text{Market risk}_k = 0.26\text{OI}_k + 0.297\ \tfrac{\text{VOM}}{\text{GDP}}k + 0.216\ \text{GDP per capita}_k + 0.08\ \text{OS}_k$$

$$\text{Supply risk}_k = 0.07\ \tfrac{\text{DR}}{\text{DC}}k + 0.22\ \text{GOMCR}_k + 0.11\ \text{ML}$$

Where:

OVI_k	OVI of country k
OI	Oil intensity at market exchange rate (toe/GDP)
VOM/ GDP	Cost of oil import in national income (%)
GDP per capita	GDP per capita at market exchange rate OS Oil share in TPES (%)
DR/DC	Domestic oil reserves relative to total oil consumption
GOMCR	Geopolitical oil market concentration risk
ML	Market liquidity

5) GEOPOLITICAL MARKET CONCENTRATION

Geopolitical market concentration risk (GMC) indicator is used to assess the political factors associated with the (energy resource) exporting countries . High value of GMC attests to low political risk. Differently to $EMSC_{pool}$, it is defined considering a single country and the fact that its market might not be accessible to every exporter. So for each fuel type f, the geopolitical market concentration risk (GMC) for a given country is defined by:

$$\mathbf{GMC_f = \sum_I r_i \; x \; (S_{if})^2}$$

Where:

r_i Political risk rating of country i

S_{if} the share of each supplier i of fuel f defined by the supplier's net export potential to the accessible market of the country in question (Sif varies from to 100 per cent)

(6) GEOPOLITICAL ENERGY SECURITY

GES is obtained by considering the supply availability and the share of each fuel type in the total energy consumption to GMC index . High value of GES attests high energy security. Starting from the fact that for a given country a market concentration risk measure (GMC) can be determined separately for each fuel, GES combines all elements into a single measure by multiplying for each fuel the market concentration risk by the exposure of the country to that risk and then summing across all fuels. The exposure of the country to a fuel market risk is defined as the minimum share of total primary energy supply (TPES) which the fuel in question represents. This is detailed in equation below:

$$\text{GES} = \sum_f \left[\left(\sum_i r_i \times (S_{if})^2 \right) \times e^{(1/P_f)} \right] \times \frac{C_f}{\text{TPES}}$$

Where:

r_i Political risk rating of country i

S_{if} the share of each supplier i of fuel f defined by the supplier's net export potential to the accessible market of the country in question (S_{if} varies from 0 to 100 per cent)

P_f Total supply availability in the accessible market of fuel type f (Mtoe)

C_f Total consumption of fuel type f (Mtoe)

TPES Total primary energy supply (of all fuels)

(7) $ESMC_{pool}$

$ESMC_{pool}$ is a measure of market concentration in each international fossil fuel market it aims to represents the 'price risk' resulting from fossil fuel resource concentration. $ESMC_{pool}$ is based on the Herfindhal-Hirschman index (HHI), equal to the sum of the square of the individual market shares of all the participants and in addition, it considers the political stability of areas of the world where energy sources are located. Then, for each fossil fuel f, $ESMC_{pool}$ is defined by:

$$\mathbf{ESMC_{pool} = \sum_I (r_i \times S_{if}^2)}$$

Where:

S_{if} the percentage share of each supplier i in the international market for fuel f defined by its net export potential (Sif varies from 0 to 100)

r_i political risk rating for country i.

$ESMC_{pool}$ ranges from 0 for perfect competition amongst countries with the highest level of political stability to 30,000 for a pure monopoly of a country with the worst level of political stability. A higher $ESMC_{pool}$ value therefore implies higher insecurity.

(8) ESI_{price}

ESI_{price} capture the exposure of a given country to the price risks associated with resource concentration considering the share of the country's total final primary energy supply exposed to each $ESMC_{pool}$ value. The ESPI is then the sum of the products of $ESMC_{pool}$ and the corresponding share of the fuel mix exposed:

$$\mathbf{ESI_{price} = \sum_f [ESMC_{pool\text{-}f} \times C_f / TPES]}$$

Where:

$ESMC_{pool\text{-}f}$ $ESMC_{pool}$ value for fuel f

C_f / TPES The share of the fuel mix

3.3 How to significantly use indicators

Considering **(Narula, Reddy 2014 [132])**, the attempt in describing energy security situation using different indicators is similar to *"to three blind men assessing what an elephant is like. As each one feels a different part, they end up in complete disagreement. Therefore, while one's subjective experience is true it may not be the totality of truth. Similarly, although the ranking from each of the variants of the index is correct, they only give a part of the picture and not the whole picture."* Some of chosen indicators are common to various studies, while others are precisely defined to measure specific characteristics in relation to the end goal. In addition we can say that an energy security index gives little information, when read in isolation, and adds value and significance only when read in conjunction with the entire set of indicators. Lastly, it should be clear that *"no set of energy indicators can be final and definitive"*; *"indicators must evolve over time to fit country-specific conditions, priorities and capabilities"* and *"more work is needed, in most countries, for a systematic and complete analysis"* **[133,134]**. The work of **(Narula, Reddy 2014 [132])** is very useful to understand which is the properly way to significantly use a set of indicators and to give them the right role considering the information they actually could provide. For the study , It has been used 3 different aggregated indices, whose a short summary is shown in **[Tab 3.1]** (A more detailed description of indexes used for comparison is shown in **APPENDIX B**). There is a large variation in the composition of the indices considering dimensions, number of indicators in the respective dimension, selected indicators and the weight used. It is clear that , although the final goal is to evaluate the performance of various countries in assessing energy security ,different indices actually end up measuring different aspects of energy. These indices have been used to measure the security situation of the ten largest energy consuming countries of the world (by TPES (Total Primary Energy Supply)), according to Global Energy Statistical Yearbook 2013. After that, ranks of these countries evaluated by variants of the three indices, are compared.

Table 3.2: Comparison of energy indices for assessment of countries.

	EAP index	ES risk index	ESI
End goal	To measure the performance of global energy systems to meet the objectives of providing a secure, affordable and environmentally sustainable energy supply	To measure the risk to overall energy security	To rank countries in terms of their likely ability to provide a stable, affordable and environmentally sensitive energy system
Dimensions	3	4	6
Core dimensions	Economic growth and development', 'environmental sustainability' and 'energy access and security'.	Geopolitical, economic, reliability, and environmental factors	Energy performance: Energy security, social equity, and environmental impact mitigation Contextual performance: Political, societal and economic strength
Indicators	18	29	23

Below, the emerging consideration from the comparison are summarized:

-**Ranking of different countries** <u>(no sense of absolute value)</u>: Countries obtain different scores by using different indices and the country rankings are inconsistent for certain countries. This inconsistency in scores leads us to the conclusion that the ranking of the country varies widely across different indices, even for data which is derived from a common set of years as shown in **[Fig 3.2]**.

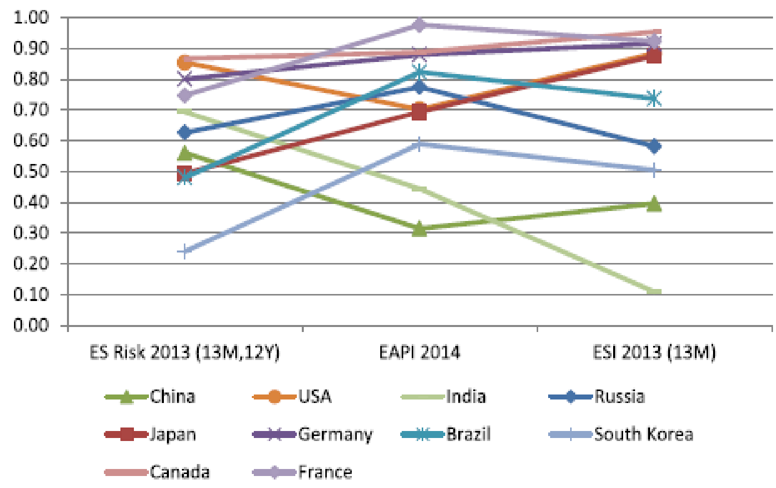

Fig 3.2: Variation in country scores for different indices

This is primarily due to differences in the construction of different indices which use different indicators with different weights. In general, numerical ranking of countries based on a relative comparison, inherently assumes homogeneity between the characteristics of the energy system of all countries. However, it is well known that there is heterogeneity in terms of resource concentration (importer/ exporter status), economic profiles (GDP), size of energy system (small/large), geographic and weather conditions (affecting per capita consumption), stages of industrialization (affecting demand), etc. amongst countries. Despite these differences, countries with different characteristics usually are grouped together ,without any kind of distinction, for a relative comparison. A better methodology to obtain a more significant rank consist in taking into account the non-homogeneity amongst countries. In this sense, different approaches might be adopted: one, for example, could be the **WEC [135]** approach where similar countries are clubbed into five clusters based on their GDP and net energy importer/exporter status for evaluating energy security status. Further, it is better to avoid numerical ranking, as it comes out with one specific number, which is interpreted to be an accurate assessment. A preferred solution is to organize countries which fall within a range of scores, together. Such an approach, which presents the results of country rankings into four quartiles (top 25%, 25/50%, 50/75% and bottom 25%), is used for presenting the results of AI, that is the first version of WEC index **[135]**. A similar approach is used by **MOSES,** which groups the performance of different countries which have similar combinations of risks and resilience factors together, without assigning a particular rank **[63].**

- Trend for a country: Trends derived for a particular country from various indices using different methodologies are fairly consistent and show the performance of a country over time. In addition, the performance of a country does not show significant changes over a short time period of four years. Then, it is possible to conclude that the process of ranking countries can be undertaken at larger time intervals (rather than yearly), particularly when the datasets overlap, without any significant loss of information. **[Fig 3.3]** shows the trends in performance of different countries for ESI using 2012 and 2013 methodologies over a period of four years. Comparison is made only for five countries. The aim is to assess the impact of different methodologies on evaluating the trends in the performance of the country. The first three columns of **[Fig 3.3]** show the score of countries obtained by ESI for the years 2013, 2012 and 2011 using the 2013 methodology and the last three columns in dotted lines show the scores for the years 2012, 2011 and 2010 using the 2012 methodology. Neglecting minor variations and evaluating some large variations in absolute scores, the direction of the movement of the score is fairly consistent. For example, as it can be interfered from **[Fig 3.3]**, a negative trend is revealed for China and India, a positive one for Russia while Brazil and South Korea are characterized by an inconsistent trend (increases over some and decreases over other time periods).

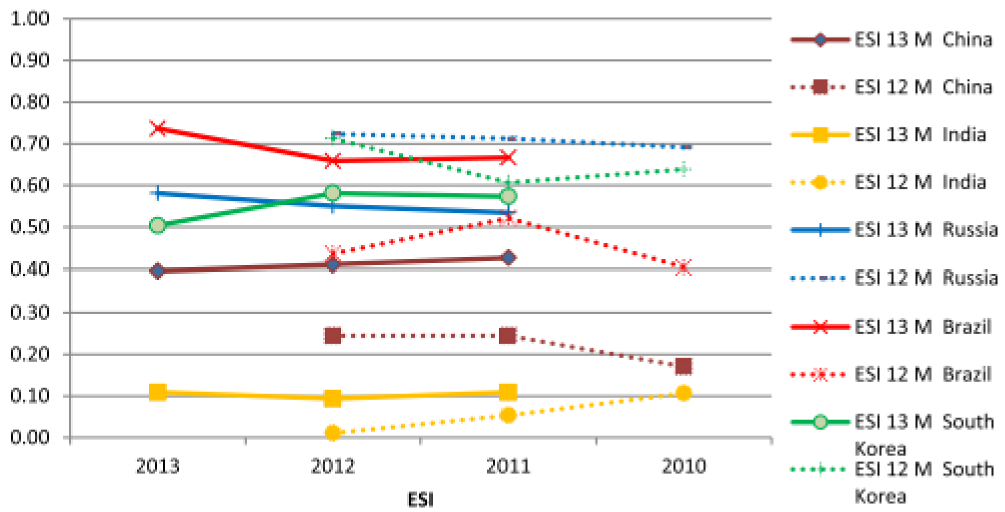

Fig 3.3: Trends in performance of different countries.

-Variation in same country score: It is possible to note that countries ,which perform consistently better in the ranking of all studies, have energy systems which perform robustly. These countries are in the top bracket of performers and the performance of these countries can be considered reliable, irrespective of the index. On the other hand , the same is not true for countries which show poor performance. It is observed that the ranking of these countries has a large spread across different indices which imply high sensitivity to the selection and weighting of the indicators. Then, indices for these countries do not give reliable information and further analysis is required for assessing the energy security of these countries. Considering **[Fig 3.4]** , that plots median value and the variation in score obtained using different variants (characterized by different methodologies and data set of different years) of three indices, it is clear that China, Russia, India, Brazil and South Korea show a large variation in the country scores. This implies that, as said before, these countries are very sensitive to the selection and to the weights allotted to indicators. Hence the performance of these countries is poor and their ranking is relatively unreliable. For the other countries characterized by high median value and small range of score, the performance is insensitive to variation in methodologies, selection of indicators and their relative weighting and , as pointed out before, this fact reflects a robust performance of the energy system for the country

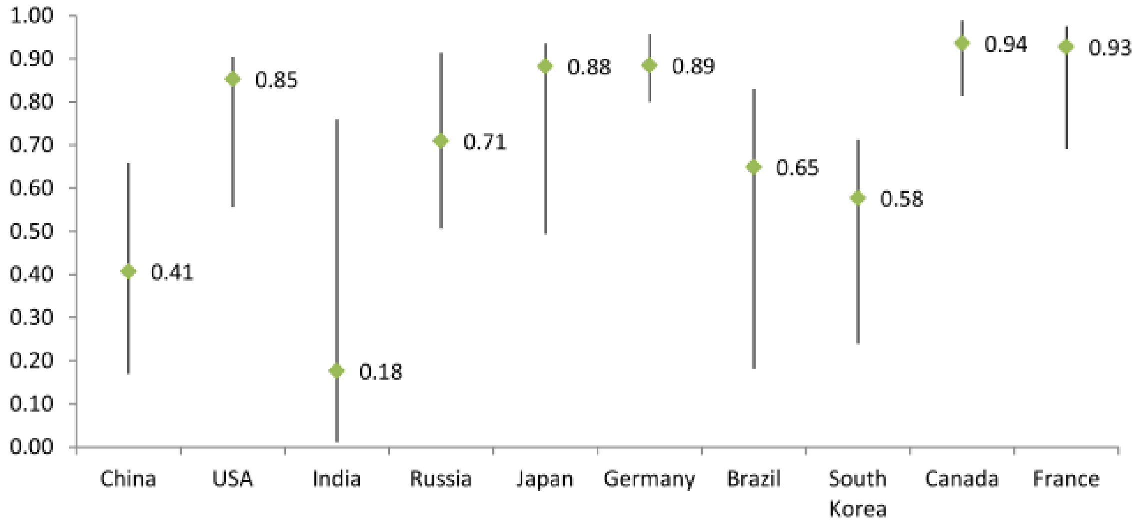

Fig 3.4: Range and median of country scores for different indices.

Conclusion

The essential need of energy for the natural maintenance of a society led energy security to be a contemporary problem, deeply discussed in the political agenda of many countries. Historically, the concept of energy security was related to the availability of oil supply. In this sense the idea of equivalence between fossil resources and energy has represented an indivisible binomial for a long time. Therefore, when the first energetic crisis took place in the '70s, mainly caused by unavailability of oil , the awareness of an energetic problem started rising. Afterwards, the concept of energy security itself has been revised and partially changed from its original meaning, becoming a multifaceted topic, especially because of climate change issues, the decreasing of fossil resources use and the strong energy market competition after the rising of new highly energy-consuming countries.

In this work the need to analyse how the meaning of energy security evolved over times was immediately evident and to determine which of the large number of definitions is the most functional as a starting point for the next assessments seemed to be of primary importance. Results obtained considering most of the publications in this field, show that besides the well-known dimensions of energy price, energy physical availability and infrastructures reliability, new dimensions have started to be recurring in the past decade: the environmental issue, social effects and the role of governance and energy efficiency. Following considerations revealed how important is not to confuse the solutions with the problem itself, in the energy security definition. Therefore, what concluded from this research is that energy efficiency and governance are not adequate parameters. Furthermore it is necessary not to confuse the role of social and environmental sustainability with the concept of energy security itself, as often done especially in the recent past. In order to define and quantify the energy security problem, considerations about environmental issues or social consequences are pointless. Clearly, once defined the energy security level of the examined system and identified areas of improvement, it is important to think also about the sustainability of the different alternatives. Hence, after these considerations, the definition to use as reference in the following evaluations needs to be linked only to the first three mentioned aspects. The most appropriate definition was provided by the IEA, which defined energy security as "the availability of reliable energy flows at an affordable price".

From this definition is pretty clear that the economic value of energy security is strictly linked to price reasonableness and energy flows physical availability. This thesis aimed to identify the best monitoring tools of these two aspects, in order to provide an effective help to policy makers, in trying to define the area of improvement. Since the topic is really complex and studied, a large number of definitions of energy security can be found in literature, also because it is not completely obvious what energy security is, but in our opinion many of them are not suitable tools in the evaluation of the energy security level of a country.

After having identified the suitable indicators, able to satisfy the need to provide complex information in the most effective way, they were grossly classified, distinguishing simple metrics, i.e. objective statistics, and complex indexes, i.e. a synthetic expression derived from the aggregation, through different methods, of several simple metrics, related to different aspects. The research first focused on these methods and the resulting complex indexes. The classification involved 60 studies and was meant to point out the aforementioned dimensions of energy security, to evaluate the number of indicators used in the composition of each model, to define if the study focused on the comparison between countries or the evaluation of performances over time of one or more countries and finally to shortly present the construction method of the complex indexes. The results of this classification are briefly presented below:

-the average number of indicators used in each model is about 20. This number seems to be adequate, since 15-20 is a significant range to mediate, when one or more parameters change, between the effects of excessive instability and insensitivity.

-the most adressed specific focus areas are those linked to economic aspects and to the concept of 4AS, with an important role held by those areas specifically developed for a certain study.

-the number of spatial and temporal studies is basically the same.

-there is not a construction method preferable over the others, but applying together the Min-Max methodology in the normalization process and the equally weighting of indicators seem to be the most used approach. This is probably due to the fact that this method is easy to apply, and not because it is actually better than the others.

After this classification, it was not possible to individuate one model better than the others, mainly because many dimensions are taken into account in the composition of an aggregate index, not all equally important in energy security assessment. Therefore it was decided to analyse in more detail, each metric used in each method. Among them, a distinction between those useless in energy security quantification, as defined in this study, and those that provide useful information (and more in specific the ones really effective in evaluating price variations and possible physical blackout of energy flows) was made. To determine which are the parameters that are truly significant, the main causes of energy insecurity were critically analysed: extreme events (weather events, acts of terrorism, large scale accidents and strikes), the inadequacy of the energy market (insufficient investments in new infrastructures and problems related to the supply-demand balancing in the electric sector), the issue of the concentration of energy resources in certain regions and fossil resources depletion. It was pointed out that the most important aspects for the maintenance of energy security are related to: the supply chain flexibility, in terms of supply flexibility, defined as the physical ability of a given energy market to compensate for the supply shortfall, and in terms of resilience (use of storage facilities and reserves); the infrastructure market share of the affected sector; the capacity-margin in balancing fluctuations between supply and demand; the infrastructure reliability; the differentiation of economic partners in imports; the availability of a liquid energy market, where buyer and sellers can easily undertake transactions. Afterwards the role of demand-side in energy security was investigated, concluding that all the parameters related to how efficiently the energy is used (efficiency in end use sectors and energy intensity) are not significant in quantifying the energy security level, while those linked to demand elasticity over price and to absolute level of demand, even if less directly, could be included in the useful metrics.

Tables in Section 3.2 give an overview of which metrics are more or less significant, among the 150 analysed, for each aspect mentioned before. Hence, almost the whole number of metrics collected in dependency, diversification, energy market and price stability, infrastructure and reliability, resilience and adaptive capacity and, to a lesser extent, also in security of supply, are significant in the identification of impacts in energy price and energy flow availability.

This thesis ended with some recommendations on the correct use of indicators. In a few words, the absolute value of several complex indicators matters not at all, since it strongly depends and varies according to the method used to construct the index. Nevertheless, analysing one country, in case of a good level of energy security, the values of complex indexes of different models (built up in a similar way but with different metrics), are generally high and not so different from one another. On the other hand, countries with a low energy security level present indexes with a low average value and an high standard deviation. Always analysing one single country, comparing different models it is possible to evaluate if the trend over time is positive or negative, i.e. if the country is improving or getting worse its performances, respectively. Finally, in the comparison of different countries, it would be better to compare those countries that present similar energy systems (homogeneous in terms of resource concentration, economic profiles, size, geographic and weather conditions and stages of industrialization) and not just classifying considering the exact value of the complex index. The preferred solution might be to organize together countries that fall within a range of scores.

Summarizing, the aim of this thesis was to define in a clear way the concept of energy security through a critic analysis of previous literature and to provide tools to help quantifying it. More in specific the metrics linked to price reasonableness and flow physical availability were object of study, as key aspects, according to the chosen definition of energy security.

The limit of this report is related to the arbitrary choice of the definition of energy security, since the whole development of the work and following considerations depended on that. Furthermore, the suggested metrics can only describe and present an overview of the current situation, without giving information about what will happen during or after a price increasing or a energy flow blackout, but just focusing in the identification of the possible area of improvement to get an higher energy security level. Finally, it is important to remember that, in line with what already said about the diversity of energy systems, this work does not provide an absolute reference level under/over which the country would be characterized by energy insecurity/security, in the analysed sector. It only gives an objective overview to take as a starting point for other considerations.

Concerning future developments, it would be interesting to conduct a detailed analysis of those models that try to forecast the economic consequences of an energy insecurity situation, in order to have a complete evaluation, starting from the possible causes to the effects on economy, in general. Furthermore, it could be investigated if the parameters could be used in the evaluation of which of the policies or actions suggested to improve a risky aspect are more effective. At the moment, this use of the indicators, that involves also the inclusion of metrics related to environmental and social sustainability, seems no to give significant results. In case of positive results, this approach could substitute the more accurate (but also more complex) cost-benefit analysis in the assessment of the effectiveness of a certain policy adoption.

APPENDIX A

[Table A1] shows some definitions of energy security taken from **(Winzer 2010 [80])**, while **[TableA2]** is the survey taken from **(Ang, Choong and Ng 2014 [138])** used reference for considerations in chapter 1.

Table A1: Energy security definitions

Author (year)	Title	Energy Security Definition
Andrews (2005) [9]	**Energy security as a rationale for governmental action**	*''I use Yergin's definition: ''The objective of energy security is to assure adequate, reliable supplies of energy at reasonable prices and in ways that do not jeopardize major national values and objectives.''*
Bazilian et al. (2007) [27]	**Security of supply in Ireland**	*''A broad definition of SOS in used in this series of reports. Based on international experience to date, a country's energy security policy generally comprises measures taken to reduce the risks of supply disruptions below a certain tolerable level. Such measures should be balanced to ensure that a supply of affordable energy is available to meet demand. Security of energy supply thus encompasses both issues of quantity and price. However, time is also a key parameter, as a sudden price hike will have very different effects on both society and the economy compared to those of a long-term price increase. Insecurity in energy supply originates in the risks related to the scarcity and uneven geographical distribution of primary fuels and to the operational reliability of energy systems that ensure services are delivered to end users.''*
Bohi and Toman (1993) [114]	**Energy security: externalities and policies**	*''Energy insecurity can be defined as the loss of welfare that may occur as the result of a change in price or availability of energy.''*
Checchi et al. (2009) [115]	**Long-term energy security risks for Europe: a sector-specific approach**	*''The literature is divided between those who interpret energy security from an economic perspective and those who stress its political and strategic side. The literature is further divided between those who see the security of supply as exclusively related to energy and those who like to couple it with the environmental dimension. Although there is no common interpretation, it is possible to identify a number of features that are always included, namely physical availability and prices.''*

Creti and Fabra (2007) [116]	**Supply security and short-run capacity markets for electricity**	*'' In the short-term, supply security requires the readiness of existing capacity to meet the actual load; supply adequacy, instead, refers to the ''long-run performance attributes of the system in attracting investment in generation, transmission, distribution, metering, and control capacity so as to minimize the costs of power supplies.''*
Doorman et al. (2006) [13]	**Vulnerability analysis of the nordic power system**	*''System vulnerability, which is defined as the system's inadequate ability to withstand and unwanted situation.''*
Department of Trade and Industry (DTI) (2002) [3]	**Joint energy security of supply working group (JESS) first report**	*''Insecurity of energy supply, in the form of sudden physical shortages, can disrupt the economic performance and social welfare of the country in the event of supply interruptions and/or large, unexpected short-term price increases. Supply interruptions to the gas system are also hazardous in terms of risk of gas inhalation and explosions. No energy form and no source of supply can offer absolute security, so improving security of supply means reducing the likelihood of sudden shortages and having contingency arrangements in place to limit the impact of any which do occur.''*
European Commission (EC) (2001) [1]	**Green Paper— towards a European strategy for the security of energy supply**	*''Strategy for energy supply security must be geared to ensuring, for the well-being of its citizens and the proper functioning of the economy, the uninterrupted physical availability of energy products on the market, at a price which is affordable for all consumers (private and industrial), while respecting environmental concerns and looking towards sustainable development."*
Grubb et al. (2006) [14]	**Diversity and security in UK electricity generation: The influence of low-carbon objectives**	*''Security of supply, for the purposes of this paper it can be defined as a system's ability to provide a flow of energy to meet demand in an economy in a manner and price that does not disrupt the course of the economy. Symptoms of a non-secure system can include sharp energy price rises, reduction in quality (e.g. brown-outs), sudden supply interruptions and long-term disruptions of supply.''*
Hoogeveen and Perlot (2007) [19]	**The EU's Policies of Security of Energy Supply Towards the Middle East and Caspian Region: Major Power Politics?**	*''Security of supply is a general term to indicate the access to and availability of energy at all times. Supply can be disrupted for a number of reasons, for, example, owing to physical, economic, social, and environmental risks. The most important crises that have been instrumental in shaping the EU's security of supply policy are of a social and economic nature and were all crises in the GME region.''*

Intharak et al. (2007) [22]	**A quest for energy security in the 21st century**	*''This study defines energy security as the ability of an economy to guarantee the availability of energy resource supply in a sustainable and timely manner with the energy price being at a level that will not adversely affect the economic performance of the economy.'' Following the above definition, there are 3 fundamental elements of energy security that will be discussed in this study: (1) PHYSICAL energy security, the availability and accessibility of supply sources; (2) ECONOMIC energy security, the affordability of resource acquisition and energy infrastructure development; and (3) ENVIRONMENTAL SUSTAINABILITY, the sustainable development and use of energy resources that ''meets the needs of the present without compromising the ability of future generations to meet their own needs.*
Jamasb and Pollitt (2008) [37]	**Security of supply and regulation of energy networks**	*''Security of supply. often discussed in terms of physical availability of energy sources and their commodity price risk."*
Jansen and Seebregts (2010) [53]	**Long-term energy services security: What is it and how can it be measured and valued?**	*''Energy (supply) security'' can be considered as a proxy of the certainty level at which the population in a defined area has uninterrupted access to fossil fuels and fossil-fuel based energy carriers in the absence of undue exposure to supply-side market power over a period ahead of 10 years or longer."*
Joode et al. (2004) [7]	**Energy policies and risks on energy markets; a cost-benefit analysis**	*''What is meant by 'securing the supply of energy'? According to politicians, it is guaranteeing a stable supply of energy at an 'affordable' price, no matter what the circumstances. From an economic point of view, however, the concept of security of supply is less clear. In general economic terms, energy security refers to ''the loss of welfare that may occur as the result of a change in price or availability of energy'' (Bohi et al., 1996). [121]"*
Joskow (2005) [117]	**Supply security in competitive electricity and natural gas markets**	*''….what it is that I think policymakers mean when they express concerns about ''supply security'' in liberalized electricity and gas markets. First, they are concerned about ''involuntary rationing" of demand. Second, policymakers are also concerned about high prices, or at least sudden increases in prices. Although perhaps an oversimplification, it is useful to group ''supply security'' concerns into two categories: (a) short run system operating reliability and (b) long run resource adequacy.''*
Jun et al. (2009) [48]	**The analysis of security cost for different energy sources**	*''Energy security can be defined as a reliable and uninterrupted supply of energy sufficient to meet the needs of the economy at the same time, coming at a reasonable price.''*

Keppler (2007) [25]	**International relations and security of energy supply: risks to continuity and geopolitical risks**	*''Traditional definitions of energy supply security combine a short-term notion of the continuity of physical supplies with long-terms notion of ''affordable'' prices, ''competitive'' prices'' or ''adequate prices''. The risk management approach to the security of energy supplies argues that supply security s an issue dependent on the risk-adverseness of consumers. Its focus is thus not the absolute level of energy prices but the size and impact of changes in energy prices.''*
Kruyt et al. (2009) [49]	**Indicators for energy security**	*''...elements relating to SOS: availability – or elements relating to geological existence. Accessibility – or geopolitical elements. Affordability – or economical elements. Acceptability – or environmental and societal elements.''*
Le Coq and Paltseva (2009) [50]	**Measuring the security of external energy supply in the European Union**	*''Supply security, usually defined as a continuous availability of energy at affordable prices.''*
Lefevre (2010) [54]	**Measuring the energy security implications of fossil fuel resource concentration**	*''Energy insecurity can be defined as the loss of welfare that may occur as a result of a change in the price or availability of energy.''*
Lesbirel (2004) [8]	**Diversification and energy security risks: the Japanese case**	*''Energy security, like the concept of security itself is a contestable concept. Rather than seeking to define energy security comprehensively and while acknowledging different conceptions of it, I stress the notion of insurance against risks. An important aspect of energy security is the relative ability to insure against the risks of harmful energy import disruptions in order to ensure adequate access to energy sources to sustain acceptable levels of social and economic welfare and state power both nationally and internationally.''*
Lieb-Doczy et al. (2003) [15]	**Who Secures the Security of Supply? European perspectives on security, competition, and liability. Indicators of energy security in industrialized countries**	*''Security of supply is fundamentally about risk. More secure systems are those with lower risks of system interruption.''*

Mabro (2008) [39]	**On the security of oil supplies, oil weapons, oil nationalism and all that.**	*''Security is impaired when supplies are reduced or interrupted in some places to an extent that causes a sudden, significant and sustained increase in prevailing prices.''*
McCarthy et al. (2007) [118]	**Assessing reliability in energy supply systems.**	*''Security includes the dynamic response of the system to unexpected interruptions, and its ability to endure them. Adequacy refers to the ability of the system to supply customer requirements under normal operating conditions.''*
Mulder et al. (2007) [119]	**The economics of promoting security of energy supply.**	*''From a political viewpoint, ensuring security of supply often means that a stable supply of energy needs to be guaranteed at 'affordable' prices, regardless of the circumstances. From an economic viewpoint, however, the concept of security of supply is related to the efficiency of providing energy to consumers. In this paper, we approach the issue of security of supply from the economic perspective.*
Newbery (1996) [120]	**Development of natural gas trade between east and west**	*''Security in turn requires an analysis of the possible shocks that might disturb the original equilibrium''*
Noel and Findlater (2010) [56]	**Gas supply security in the baltic states: a qualitative assessment**	*''For the purpose of this article ''security of supply'' (or gas supply security) refers to the ability of a country's energy supply system to meet final contracted energy demand in the event of a gas supply disruption.''*
Nuttall and Manz (2008) [40]	**A new energy security paradigm for the twenty-first century**	*''Interruption of the energy supply has been identified by many as the primary threat that faces global energy security.''*
Olz et al. (2007) [26]	**Contribution of renewables to energy security**	*''This study defines energy security risk as being the degree of probability of disruption to energy supply occurring. A forthcoming IEA report on the interactions between energy security and climate change policy uses an analogous definition of energy insecurity as ''the loss of economic welfare that may occur as a result of a change in the price and availability of energy.''*
Patterson (2008) [42]	**Managing energy wrong**	*''The energy security that worries politicians concerns supplies of imported oil and natural gas, not the secure delivery of energy services, such as keeping the lights on.''*
Rutherford et al. (2007) [28]	**Linking consumer energy efficiency with security of supply**	*''In the context of this paper, we will use the term energy security to refer to a generally low business risk related to energy with ready access to a stable supply of electricity/energy at a predicable price without threat of disruption from major price spikes, brown-outs or externally imposed limits.''*

Scheepers et al. (2007) [29]	**EU standards for security of supply**	*''A security of supply risk refers to a shortage in energy supply, either a relative shortage, i.e. a mismatch in supply and demand inducing price increases, or a partial or complete disruption of energy supplies. A secure energy supply implies the continuous uninterrupted availability of energy at the consumer's site.''*
Stern (2002) [4]	**Security of European natural gas supplies**	*''Security is measured as resources to consumption ratio (R:C).''*
Turton and Barreto (2006) [15]	**Long-term security of energy supply and climate change. Security of energy supply: comparing scenarios from a European perspective**	*''Energy security is defined as the availability of a regular supply of energy at an affordable price (IEA, 2001 [122]). The definition has physical, economic, social and environmental dimensions (European Commission (EC), 2001 [1]); and long and short term dimensions.''*
Wright (2005) [11]	**Liberalization and the security of gas supply in the UK.**	*''Security of gas supply'': ''an insurance against the risk of an interruption of external supplies.''*
Spanjer (2007) [30]	**Russian gas price reform and the EU–Russia gas relationship: Incentives, consequences and European security of supply**	*''Security of supply can broadly be divided into two parts: system security—the extent to which consumers can be guaranteed, within foreseeable circumstances, of gas supply—and quantity security—guaranteeing an adequate supply of gas now as well as in the future. This comprises not only gas volumes, but also price and diversification of gas supplies.'' In a short paper there is limited space for a methodological definition of gas security.3 Perhaps the briefest way to deal with definitions is to say that this paper deals with the threats of supply and price disruptions arising from risks associated with the sources of gas supplies, the transit of gas supplies and the facilities through which gas is delivered. There are two major dimensions of these risks: short-term supply availability versus long-term adequacy of supply and the infrastructure for delivering this supply to markets; operational security of gas markets, i.e. daily and seasonal stresses and strains of extreme weather and other operational problems versus strategic security, i.e. catastrophic failure of major supply sources and facilities.*

Table A2: List of energy security studies, where themes in energy security definition are energy availability(A), infrastructure(B), energy prices(C), societal effects(D), environment(E), governance(F) and efficiency(G).

Source	Year	Country/region	Publication type			Energy security definition given	Energy security indicators or index provided	Themes in energy security definition						
			Journal paper	Official report	Others			A	B	C	D	E	F	G
EC [1]	2001	Europe			x	x		X	X		x	x		
Bielecki [2]	2002	N/A	x			x		X	X	X				
DTI [3]	2002	Britain		x		x	x	X	X	X	x		x	
Stern [4]	2002	Europe			x	x		X	X					
Lieb-Dóczy et al. [5]	2003	Europe	x			x		x	x					
Blyth and Lefevre [6]	2004	Australia, Italy, UK and US		x		x	x	x	x	x	x			
de Joode et al. [7]	2004	Netherlands			x	x		x	x	x	x			
Lesbirel [8]	2004	Japan	x			x		x	x		x			
Andrews [9]	2005	US	x			x		x	x		x			
Onamics [10]	2005	Central/Eastern Europe			x	x	x	x	x					
Wright [11]	2005	UK	x			x		x						

Department of Energy and Climate Change [12]	2006	UK			x	x			x	x	x	x	x	x
Doorman et al. [13]	2006	Nordic Countries	x			x		x	x					
Grubb et al. [14]	2006	UK	x			x		x	x	x				
Turton and Barreto [15]	2006	Europe	x			x		x						
Yergin [16]	2006	US	x			x		x	x	x			x	
Sovacool and Brown [17]	2007	US	x			x	x	x		x	x	x		
Costantini et al. [18]	2007	EU	x			x		x		x	x	x		
Hoogeveen and Perlot [19]	2007	EU	x			x		x	x		x	x		
IAEA [20]	2007	7 countries		x			x							
IEA [21]	2007	OECD countries		x			x							
Intharak et al. [22]	2007	Asia-Pacific countries		x		x	x	x	x	x		x		
Wu and Morisson [23]	2007	Selected AsiaPacific economies and EU			x		x							
Kemmler and Spreng [24]	2007	Developing Countries	x			x		x			x	x		x

Keppler [25]	2007	Europe			x	x		x	x	x				
Ölz et al. [26]	2007	IEA countries			x	x		x	x	x		x		
O'Leary et al. [27]	2007	Ireland			x	x		x	x	x			x	
Rutherford et al. [28]	2007	New Zealand	x			x		x	x	x				
Scheepers et al. [29]	2007	EU-27		x		x	x	x	x					
Spanjer [30]	2007	Europe	x			x		x		x				
Streimikiene et al. [31]	2007	Lithuania, Latvia,Estonia	x				x							
Center for Energy Economics [32]	2008	South Asia	x			x		x	x	x	x			x
ESCAP [33]	2008	Asia-Pacific countries			x	x		x		x				
Frondel and Schmidt [34]	2008	Germany and US			x		x							
Gnansounou [35]	2008	37 industrialised countries	x			x	x	x	x					
Gupta [36]	2008	26 net oilimporting countries	x				x							
Jamasb and Pollitt [37]	2008	UK and Europe	x			x		x		x				
Kessels et al. [38]	2008	N/A			x	x		x	x	x			x	x

Mabro [39]	2008	N/A			x	x		x	x	x				
Nuttall and Manz [40]	2008	N/A	x			x		x	x					
Patlitzianas et al. [41]	2008	N/A	x			x		x	x					
Patterson [42]	2008	N/A			x	x		x	x					
Augutis et al. [43]	2009	Lithuania	x				x							
CNA [44]	2009	US			x	x		x	x					x
Greenleaf et al. [45]	2009	EU			x	x	x	x		x	x	x		
Hughes [46]	2009	N/A	x			x		x					x	x
Jansen [47]	2009	N/A			x	x	x	x		x		x		
Jun et al. [48]	2009	South Korea	x			x		x	x	x				
Kruyt et al. [49]	2009	Western (OECD) Europe	x			x		x	x	x		x		
Le Coq and Paltseva [50]	2009	EU	x			x	x	x	x	x				
Balat [51]	2010	Turkey	x			x		x	x	x			x	x
Cabalu [52]	2010	7 countries	x			x	x	x	x	x				
Jansen and Seebregts [53]	2010	N.A.	x			x		x	x	x				
Lefèvre [54]	2010	France, UK	x			x	x	x		x	x			

Löschel et al. [55]	2010	Germany, Netherlands, Spain and US	x			x	x				x			
Findlater and Noël [56]	2010	Baltic states	x			x		x	x					
Sovacool and Brown [57]	2010	OECD and US (22 Countries)	x			x	x	x		x		x		x
Vivoda [58]	2010	Asia-Pacific countries	x			x	x	x	x	x	x	x	x	x
Augutis et al. [59]	2011	Lithuania	x			x	x	x	x	x		x		
Bazilian et al. [60]	2011	South Africa	x			x		x	x	x	x			
Cohen et al. [61]	2011	OECD (26 for oil, 20 for gas)	x				x							
Ediger and Berk [62]	2011	Turkey	x				x							
Jewell [63]	2011	IEA countries		x			x							
Leung [64]	2011	China	x			x		x	x	x	x			
Sovacool [65]	2011	Asia-Pacific countries	x			x		x		x		x		x
Sovacool and Mukherjee [66]	2011	N/A	x			x		x		x		x	x	
Sovacool et al. [67]	2011	ASEAN, EU and 7 other countries	x			x	x	x	x	x	x	x	x	x

Angelis-Dimakis et al. [68]	2012	Greece	x				x	x		x	x			
Augutis et al. [69]	2012	Lithuania	x				x							
Dunn and Dunn [70]	2012	US			x		x							
ERIA [71]	2012	East Asian countries		x		x	x	x						
Goldthau and Sovacool [72]	2012	N/A	x			x		x	x	x	x	x	x	x
Hughes [73]	2012	Province of Prince Edward, Canada	x			x	x	x	x	x		x		
Institute for 21st Century Energy [74]	2012	US		x			x							
Institute for 21st Century Energy [75]	2012	OECD and large energy users		x			x							
Martchamadol and Kumar [76]	2012	Thailand	x			x	x	x		x	x	x		
Pasqualetti and Sovacool [77]	2012	N/A	x			x		x	x	x	x	x		x
Sheinbaum-Pardo et al. [78]	2012	Mexico	x				x							
Vivoda [79]	2012	Japan	x			x		x	x	x		x		

Winzer [80]	2012	Austria, Italy and Great Britain	x			x	x	x	x					
WEF [81]	2012	105 countries		x		x	x	x	x					
WEC [82]	2012	WEC countries		x		x	x	x	x				x	
Wu et al. [83]	2012	China	x			x	x	x	x	x				
Below [84]	2013	US	x			x	x	x	x					x
Chuang and Ma [85]	2013	Taiwan	x				x							
Escribano Francés et al. [86]	2013	EU	x			x		x	x	x	x	x	x	x
Ge and Fan [87]	2013	China	x			x		x	x	x				
Gunningham [88]	2013	Indonesia	x			x		x	x	x				
Knox-Hayes et al. [89]	2013	10 Countries	x			x		x	x	x	x	x	x	x
Selvakkumaran and Limmeechokchai [90]	2013	Sri Lanka, Thailand and Vietnam	x				x							
Sovacool [91]	2013	18 countries	x			x	x	x	x	x	x	x	x	x
Sovacool [92]	2013	Asia-Pacific countries	x			x	x	x		x		x	x	x
Zhang et al. [93]	2013	China	x				x							

Demski et al. [94]	2014	United Kingdom	x			x		x	x	x				
Jewell et al. [95]	2014	Global/regional	x			x	x	x	x	x				
Kamsamrong and Sorapipatana [96]	2014	Thailand	x				x							
Wu [97]	2014	China	x			x		x		x		x	x	
Odgaard and Delman [98]	2014	China	x			x		x	x	x			x	x
Portugal-Pereira and Esteban [99]	2014	Japan	x			x		x	x	x	x	x	x	x
Ranjan and Hughes [100]	2014	Multiple	x			x	x	x		x		x		
Sharifuddin [101]	2014	Malaysia	x				x							
Sun et al. [102]	2014	China	x			x		x	x	x				
Yao and Chang [103]	2014	China	x			x	x	x		x	x	x		
Zhao and Liu [104]	2014	China	x			x		x		x		x	x	

APPENDIX B

[Table B.1] shows in more details the construction of indexes used for the comparison in section 3.3.

Table B.1: Indicators and weights used for various indexes.

SES dimension	EAPI 2014	Wt	EAPI 2013	Wt	ESI 2013	Wt
Total indicators	18		29		23 (only 12 used for energy performance are comparable)	
Availability (Diversity)	Energy import dependence (net % energy use)	0.066/0.4125	Total energy import exposure	0.04	Ratio of total energy production to consumption	0.04175
	Diversity of total primary energy supply (Herfindahl index)	0.066	Electricity diversity	0.05	Diversity of electricity generation	0.04175
	Diversification of import counterparts (Herfindahl index)	0/0.04125	GDP per capita	0.04	Days of oil and oil product stocks	0.04175
	Electrification rate (% of population)	0.066	Security of world oil, gas, coal reserves	0.02 each		

	Percentage of population using solid fuels for cooking (%)	0.066	Security of world oil, gas, coal production	0.03, 0.03, 0.02		
	Quality of electricity supply (1-7)	0.066	Petroleum, gas, coal import exposure	0.03, 0.03, 0.02		
			Energy consumption per capita	0.04		
			Transportation energy per capita	0.03		
Affordability	Cost of energy imports (% GDP)	0.04125	Fossil fuel import expenditures per GDP	0.05	Net fuel imports/export sas a percentage of GDP	0.04175
			World oil refinery utilization	0.02		
	Degree of artificial distortion to gasoline pricing (index)	0.04125	Retail electricity prices	0.06	Affordability of retail gasoline	0.125
	Electricity prices for industry	0.0825	Energy expenditure volatility	0.04	Affordability and quality of electricity relative to access	0.125
	Degree of artificial distortion to diesel pricing (index)	0.04125	Crude oil price volatility	0.05	Five year CAGR of the ratio of TPEC to GDP	0.04175

	Value of energy exports(% GDP)	0.04125	Crude oil prices	0.07		
			Energy expenditures per capita	0.03		
Acceptability	Alternative and nuclear energy (% of total energy use)	0.066	Non-CO2 emitting share of electricity generation	0.02	CO2 intensity	0.0625
	CO2 emissions from electricity production	0.066	Energy-related carbon dioxide emissions intensity	0.02	CO2 emissions from electricity generation	0.0625
	Methane emissions in energy sector	0.04125	CO2 emissions trend	0.02	Effect of air and water pollution	0.0625
	Nitrous oxide emissions in energy sector	0.04125	Energy-related carbon dioxide emission per capita	0.02		
	PM10, country level	0.066				
Efficiency	Energy intensity	0.0825	Energy intensity	0.07	Total primary energy intensity	0.0625
	Average fuel economy for passenger cars	0.066	Transportation energy intensity	0.04	Distribution losses as a percentage of generation	0.04175

		Petroleum intensity	0.03		
		Energy expenditure intensity	0.04		
Total weight	1.00		1.00		1.00

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