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Doctoral Dissertation
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A framework for integrity assessment of multiscale energy infrastructures

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Summary

The climate change phenomena represent a global issue that could significantly impact on world economic and social systems. During last decades, several international bodies and institutions (like the IPCC) developed scientific techniques to analyse the causes and effects of these phenomena, their evolution over time and possible future scenarios. According to these studies, in order to face climate change and air pollutant emissions issues several targets have been hypothesized and proposed. In particular, the ones related to the Paris Agreement (COP21) can be mentioned. These goals require, in the mid/long-term, significant changes in the structure of the energy systems at global level, aiming at achieving their substantial decarbonisation through the so-called "energy transition". The implementation of this transition could be obtained by means of different pathways. In particular, two extreme options can be identified. On one side, a wide electrification of final uses, coupled with power generation from renewables and long-distance transmission through global interconnections. On the other, small-scale energy systems based on electricity, heat and gas produced by renewables sources, characterized by power generation from wind, solar photovoltaic and small hydro and with a relevant role played by storage systems. It can be expected that the future configuration of the global energy systems will be a mix of these extreme solutions. In every case, however, a crucial role will be played by the infrastructures for supplying, transmitting and distributing energy. For this reason, the integrity of these infrastructures – at all spatial levels (transnational gas and oil pipelines, maritime routes, power lines, district heating networks, etc.) – is a key factor for ensuring the long-term energy transition strategies. The integrity measures the capability of a given infrastructure to perform its function according to what is requested and to be properly managed from several points of view, including safety, environmental protection, maintainability, productivity, etc. Therefore, it is a concept more general than “security”, as it is multi-dimensional. Furthermore, the integrity is directly related to the development of infrastructures. The evolution of the current energy systems in the sense of the energy transition needs to plan the infrastructures architecture according to criteria that have to be not only technological, but also able to consider all the possible issues that can threat their integrity. In a long-term perspective, these issues should not be investigated through ex-post analyses, but they should be taken into account as much as possible in the design phase. Starting from this, the main goal of the doctoral project has been the identification of a multiscale approach for assessing the integrity of energy infrastructures. A two-dimensional scheme has been proposed, considering different spatial scales (energy corridors, transmission/distribution infrastructures, local networks) and kind of threats (natural, accidental, intentional), for assessing the impacts on the integrity dimensions (technological, geopolitical, environmental, economic). In particular, five case studies have been considered, covering all the considered spatial scales with respect to different integrity dimensions and threats. They focused on the geopolitical supply security, the resilience of distribution infrastructures, the effects of renewables penetration, the reliability of district heating networks and the impact of innovative vectors on the security. The obtained results showed that this multidimensional approach can be useful in defining guidelines for the integrity assessment and the development of energy infrastructure under a holistic perspective, in order to support the policy decision-making about strategical investments and their prioritization, planning, management, and identification and ranking of criticalities.

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To my parents, for their endless support and encouragement throughout my entire life.

To Federica, for trusting and believing in me more than I do.

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Chapter 1

Introduction

During last decades, many scientific evidences highlighted the relevance of **climate change phenomena** and shoed how they can represent a global issue that could significantly impact on world economic and social systems.

The analysis of the causes and effects of these phenomena has been systematically carried out by different **international institutions**, like the IPCC, whose activity is mainly related to the publication of the "Assessment Reports", which contain the state of the art on climate change under the scientific and technical perspective.

These studies, in particular, allowed to put into evidence the significance in the increase of the **global temperature** (+0.85 °C with respect to the pre-industrial era) and the consequent effect on the natural environment, that is:

- The reduction in the Artic sea-ice extent
- The increase in the global mean sea level.

Figure 1 shows, in particular, the increase in land e ocean surface temperature and the increase in the average sea level.

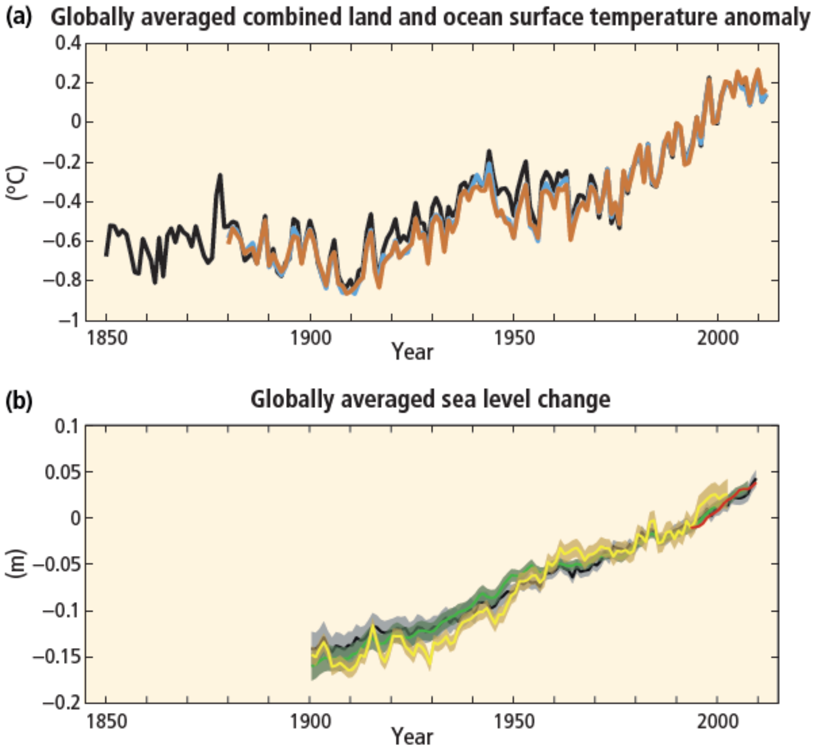


Figure 1: Global temperature and sea level changes **[1]**

The causes of these changes are related to the enhancement in **anthropogenic GHG emissions** in comparison with the pre-industrial era, which has led to atmospheric concentrations of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) that have not been reached during the last 800000 years. Figure 2 put into evidence the increase in global anthropogenic GHG emissions during the most recent decades, highlighting the relevant contribution provided by the fossil fuel combustion and industrial processes.

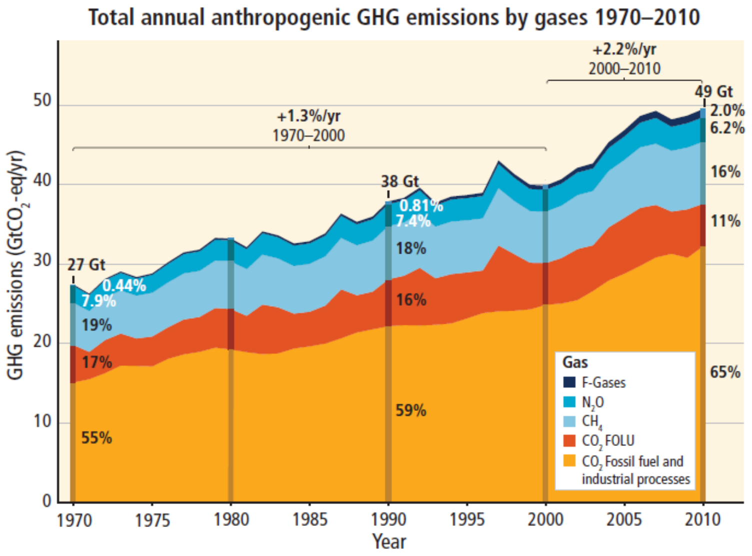


Figure 2: Trend of global anthropogenic GHG emissions **[1]**

Besides GHG emissions, another relevant aspect correlated to the combustion of fossil fuels is represented by **air pollutant emissions** (sulphur oxides, nitrogen oxides, particulate matter, volatile organic compounds, carbon monoxide, ammonia, etc.).

These emissions in turn can cause negative effects on health (mostly associated to the respiratory tract) and economy (related mostly to the heath economic costs and to the costs deriving from the impacts on the agriculture), whose severity depends on the concentration of the emissions and on the exposure duration.

As for the GHG emissions, the majority of these emissions – with the exception of the ammonia – arises from the **energy sector** (Figure 3).

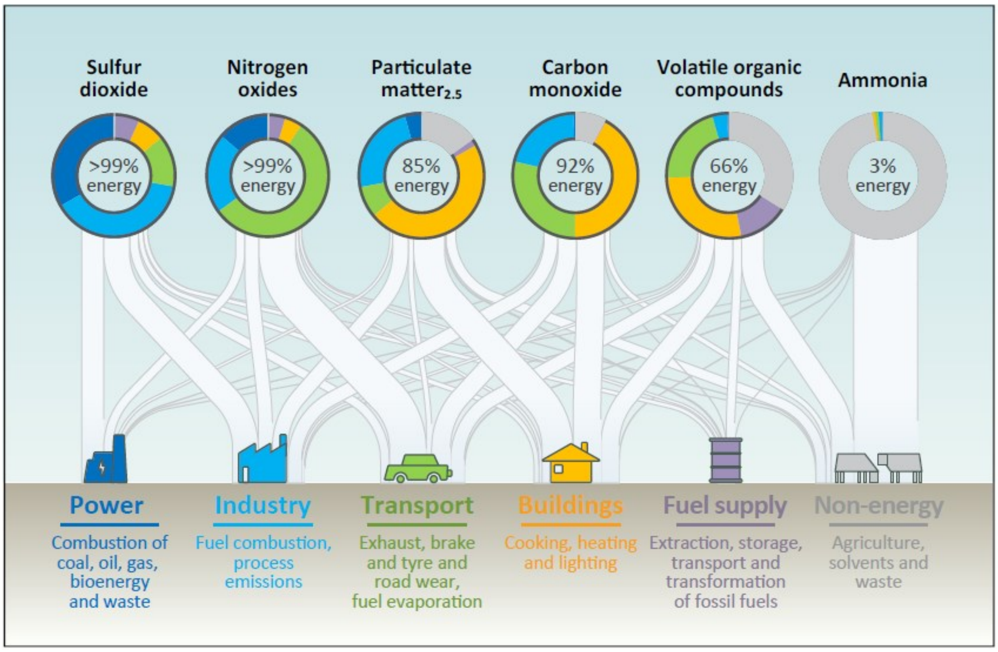


Figure 3: Air pollutant emission from the energy sector **[2]**

For these reasons, in order to counteract climate change phenomena and negative effects of air pollution emissions, measures directly acting on the global structure of the energy chain (from production to final uses) are requested. In particular, regarding GHG emissions, their strong limitation is a necessary need for allowing a **reduction of the global average temperature** rise with respect to the pre-industrial era below 2 °C, or better 1.5 °C, by the end of this Century.

Among the international political and regulatory frameworks related to the climate change, the most significant is represented by United Nations Framework Convention on Climate Change (**UNFCCC**), whose main goal is to ensure the stabilisation of GHG emissions concentration in order to “prevent dangerous anthropogenic (human induced) interference with the climate system”. For reaching this purpose, the most developed and industrialised countries have been requested to reduce their own emissions and to support actions for limiting climate change phenomena in developing countries, not only through funding measures, but also by sharing advanced technological solutions.

An annual meeting of the Parties that ratified the UNFCCC – the "Conference Of the Parties" (COP) – has been established since 1995; these conferences allowed to define different environmental and climatic agreements.

The most recent one, in particular, is the **2015 Paris Agreement**, introduced in the framework of the COP21. It entered into force on 4 November 2016, and it has as its main goal the reduction of global warming, aiming at reducing the global average temperature increase well below 2°C in comparison with the pre-industrial era by the end of the current Century, making all the efforts to reduce this temperature rise below 1.5 °C.

According to the Agreement, each country that has ratified it has to define an emissions reduction target, through voluntary pledges and without penalties in the case of failure in achieving the proposed goals. These pledges have been collected in the so-called Intended Nationally Determined Contributions (INDCs), before and during the Conference, and has to be transformed into the **Nationally Determined Contribution** (NDC) by the single countries. These pledges are particularly significant for the six countries that are responsible for the largest part of CO_2 emissions due to fossil fuel combustion (68.4% in 2014), i.e. China, the United States, the European Union, India, Russia and Japan (Figure 4):

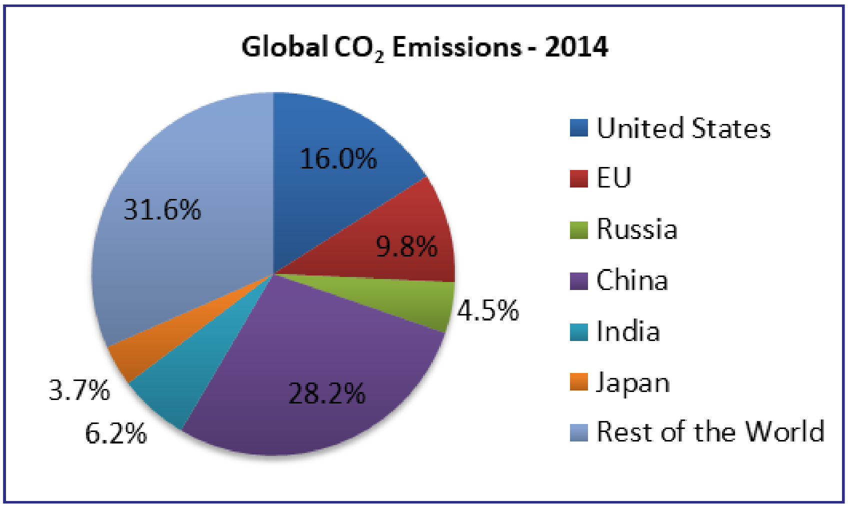


Figure 4: Global CO2 emissions by country in 2014

Table 1 shows the main pledges of these Countries proposed in the framework of the Paris Agreement. It has however to be underlined that the current administration planned the withdrawal of the U.S. from this agreement, and for this reason it is not clear which could be the effective long-term environmental strategy of the U.S. and the effects on the country energy mix.

Table 1: Main international pledges related to the COP21 Paris Agreement

Party	Main NDC / INDC target
China	Peaking of CO_2 emissions around 2030, possibly early Lower carbon intensity by 60÷65% from 2005 level Increase the share of non-fossil fuels in primary energy consumption to ~20% Increase the forest stock volume by ~4.5 bcm on 2005 level
EU	At least -40% GHG emissions by 2030 from 1990 level
India	-33÷35% carbon intensity by 2030 from 2005 level ~40% cumulative electric power installed capacity from non-fossil fuel by 2030 +2.5÷3 billion tons of CO_2 eq. carbon sink through forest coverage by 2030
Japan	-26% GHG emissions by 2030 from 2013 level
Russia	-25÷30% GHG emissions by 2030 from 1990 level
U.S.	-26÷28% GHG emissions by 2025 from 2005 level (efforts to achieve -28%)

In general, these targets underline the need for a strong modification of the energy system at global level, reducing the dependency from fossil fuels and increasing, on the opposite, the relevance of renewables. This structural change is encompassed in the so-called “energy transition” towards decarbonised energy systems.

In order to implement it, several **strategies** can be adopted, and different countries and world macro-areas already defined possible roadmaps and policy actions. In general, however, **two extreme pathways** can be identified, that can be summarised as follows:

- A **wide-scale electrification** of energy end-uses, coupled with power generation from renewables (up to 100%) and long-distance transmission through global ultra high voltage interconnections.
- **Small scale energy systems** based on electricity, heat and gas produced by renewables (up to 100%), with power generation from wind, solar photovoltaic and small hydro. A relevant role is played by storage systems (including pumped hydroelectric storage, batteries and power-to-gas systems).

Referring to the **first option**, on one side it requires the modification of the end-use sectors (residential, industry, commerce and services, transport, agriculture) in the sense of a high penetration of **electricity-based technologies**. These technologies are used for the fulfilment of the so-called “services demands”, like space heating and cooling, water heating, cooking, lighting in the residential sector, mobility of passengers and goods in the transport sector, industrial production, etc. On the other side, this option requests the implementation of a **global energy interconnection** system, based on Ultra High Voltage (UHV) transmission technologies, mainly Direct Current (DC), aiming at defining a backbone for redistributing over large areas electricity produced from renewable sources in some specific world zones. In particular, the main productive areas could be

- the **Artic** region for wind and
- the **deserts** in the Equatorial area for solar.

These areas should then be connected to the large world consumption areas or countries (as the European Union, the U.S., Asian countries like China, etc.) through the above-mentioned UHV-DC super-grid.

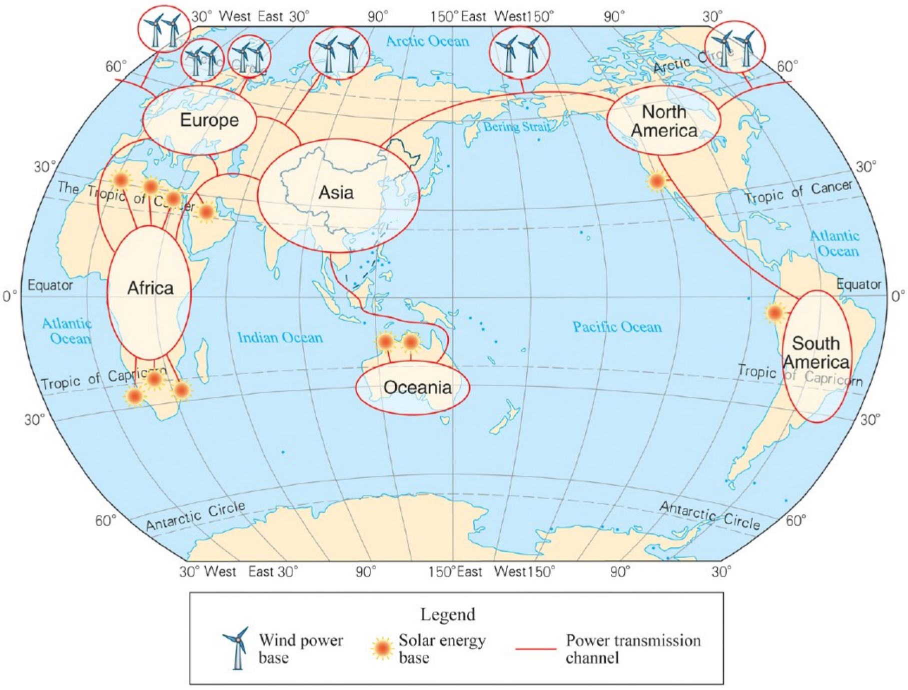


Figure 5: Graphical representation of the global interconnection option **[3]**

The **second option** is related to a local/regional scale and it relies on three main energy commodities:

- electricity
- gas
- heat.

Electricity is supposed to be produced by

- three renewable sources (wind, solar and hydro) and by
- Combined Heat and Power (CHP) plants.

Furthermore, two options for **storing** it are considered:

- Pumped Hydroelectric Storage (PHS) and
- Lithium-ion (Li-ion) batteries.

The available electricity is used not only to satisfy the demand of the considered area, but it is also used as commodity input to other elements of the energy system, like the power-to-gas system and power-to-heat processes.

Power-to-gas, in particular, allows to produce synthetic natural gas through the adoption of electrolysis and methanation processes, starting from the excess of electricity generated. The produced methane can be then fed into the existing gas network, thus representing a form of energy storage for the system. These microgrids are locally controlled distinct miniature energy system, able to operate in parallel with or isolated from the main network, and allow affordable, reliable and secure energy by exploiting distributed and locally available energy sources and by including distributed storage systems, demand response, etc. Due to the proximity to the loads, the microgrids do not have a transmission layer and allow the possibility of being operated in an isolated and autonomous mode. This makes them more flexible, especially during emergencies, avoiding that the failure will propagate to other grids, thus limiting its impacts.

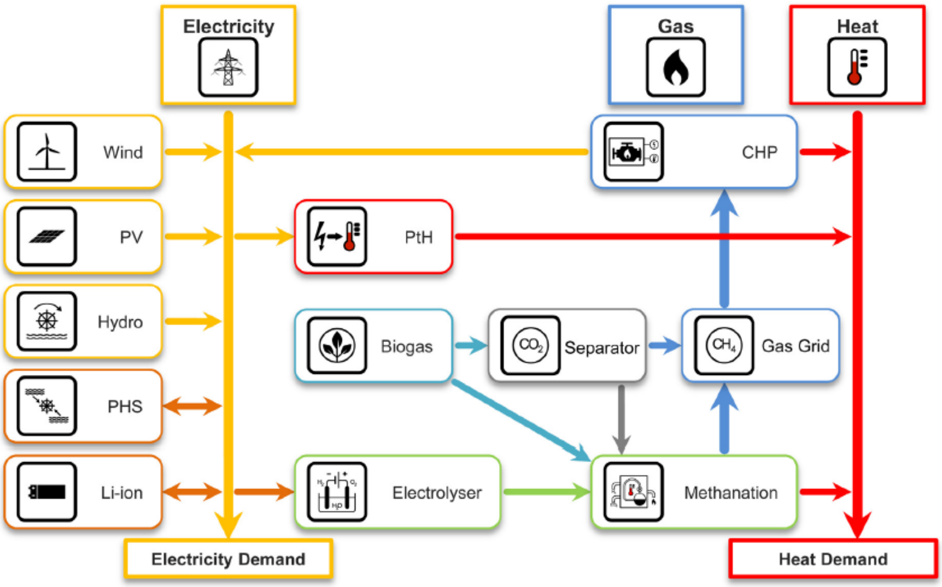


Figure 6: Graphical representation of a micro-grid system **[4]**

Different **scenario** analyses can be performed for comparing the perspectives and the effects of these decarbonisation solutions with respect to more traditional pathways. In general, however, it can be expected that the future configuration of the global energy systems will be not fully coherent with one of the two extreme solutions above mentioned, but will be probably a mix of them.

In every case, in this energy transition framework, a key role will be played by the **infrastructures** for the supply, transmission and distribution of energy, like oil and gas pipelines, power lines, maritime routes, district heating networks, etc. In particular, their **integrity** – at all spatial scales – is a crucial element for guaranteeing the effectiveness of the decarbonisation strategies that can be defined and implemented.

In fact, the integrity of a given infrastructure is an attribute that refers to the capability of:

- Performing its function according to what is requested

- Being properly managed under various points of view, including safety, environmental protection, maintainability, productivity, etc.

The integrity concept is also related to the **development** of energy infrastructures, as it should be embedded in the design of the infrastructures architecture, especially taking into account the possible evolution of the energy systems that can be determined by the energy transition.

To consider integrity thus means to take into account in the planning phase several **dimensions** not always considered and issues that are usually investigated only during ex-post analyses applied to infrastructures already designed and/or existing.

According to this purpose, new design and sizing procedures should be developed and existing ones should be adapted for integrating assessments that have been historically implemented in a stand-alone way.

Starting from these considerations, the main **aim** of the doctoral project has been the identification of a possible **multiscale and multidimensional approach** useful in assessing the integrity of energy infrastructures taking into consideration its different perspectives.

In particular, in order to build this multiscale approach, a two-dimensional scheme has been adopted, simultaneously considering different dimensions related to the spatial scale and the kind of threats. On these two axes, the single items have been collocated. The considered items are the following ones:

- Spatial scale:
    - Energy corridors
    - Transmission / distribution infrastructures
    - Local distribution networks

- Kind of threats:
    - Natural
    - Accidental
    - Intentional

The proposed scheme (graphically represented in Figure 7) thus allows to identify 9 possible **combinations** of the assumed dimensions.

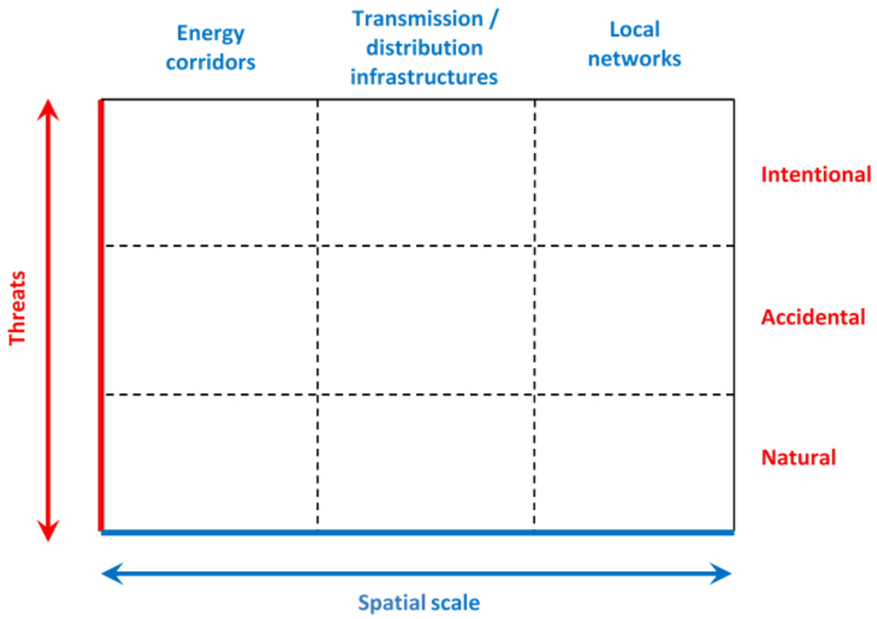


Figure 7: Scheme of the adopted multi-dimensional approach

The adopted approach allows to evaluate the impacts of those combinations of threats and spatial scales on the different levels of the infrastructure integrity, that can be summarized as follows:

- Kind of integrity:
    - Technological:
      Related to the technical aspects involved in the operation of the considered infrastructures and, consequently, to the capability of performing their function from the technical point of view. It involves the assessment of how technical failures can affect the infrastructure functioning and service quality.
    - Geopolitical:
      Related to the political status of the countries involved in the energy supply and on the impact that political tensions, instabilities and presence of antagonistic groups can have on the security, costs and availability of energy commodities, and on the strategical planning of new infrastructures.
    - Environmental:
      Related to environmental aspects to be considered with respect to energy infrastructures, like the impact that natural events can have on them and the sustainability goals to be achieved through structural modifications of the energy systems.
    - Economic:
      Related to the consequences of a loss of energy infrastructures integrity on the economic system of a country, to the cost-benefits of

protective/mitigation countermeasures implemented against several kinds of threats and to the investments priorities according to the criticality status of the infrastructures.

Furthermore, these dimensions can be respectively related to the four main attributes of the energy transition, namely:

- Energy efficiency:
  Energy efficiency improvements can be defined as the capability of ensuring the same services by reducing the amount of energy used in input. Energy efficiency mostly involves end-use technologies, and its growth is fundamental in decarbonisation strategies. In fact, it allows to decrease the fossil fuel consumption – thus also reducing the costs related to the fulfilment of final users demands – or to avoid a further increase in their use in the mid-long term to satisfy higher energy services demands (as it can be expected at global scale, unless global economic crises are hypothesised).

- Energy security:
  Energy security can be defined as the capability of ensuring the availability of energy commodities in the quantities needed for the fulfilment of services demands, through local production or import via energy corridors (oil and gas pipelines, open sea routes, power lines, etc.). Energy security is fundamental especially for countries characterised by a high level of import dependency, due to the fact that this dependency involves geopolitical situations that could impact on the effective supply of the requested commodities. There is a close relation between security and decarbonisation, because an increase in renewables and a simultaneous reduction in fossil fuel consumption could easily lead to improvements in energy security. On the opposite, however, high penetration rates of renewables in power generation could lead to grid instabilities, thus resulting potentially critical for the security of the whole system.

- Environmental sustainability:
  Sustainability is a key aspect correlated to decarbonisation. The sustainability for renewable sources can be assured if the harvesting rate is lower than the regeneration rate. For fossil sources, instead, the resource depletion has to be balanced by a corresponding suitable development of alternative renewables, and for environmental pollution the generation rate of wastes has to be lower than the environmental absorption capacity. As a consequence, under a low-carbon perspective, sustainability is mainly related to resource availability, to the penetration of renewables and to the related impact on pollutant emissions, especially CO_2.

- Economic affordability:
  In economic terms the affordability is the level to which customers are able to pay (economic affordability) and are willing to pay (willingness to pay) a certain price for a given product. If this definition is applied and adapted to the decarbonisation, the affordability represents the economic sustainability, from the final users perspective, of the strategies, measures and actions to be defined and implemented for supporting the transition from fossil to renewable commodities in energy systems. It also involves subsidies and taxations that can be introduced to respectively making renewables competitive form the market point of view and penalising, by means of carbon pricing mechanisms, the use of fossil fuels.

The proposed multidimensional approach can be useful in defining **guidelines** for the integrity assessment and the development of energy infrastructures under a holistic perspective, in order to support the policy decision-making about strategical investments and their prioritization, planning, management, identification and ranking of criticalities. Of course, for effectively developing such guidelines, the complete set of combination should be analysed, by developing/testing new and existing ad hoc analysis techniques.

During the project, **five** of these **combinations** have been explored, covering all the considered spatial scales with respect to various threats. Each of these case studies (i.e. each of the "cells" of the two-dimensional scheme illustrated in Figure 7) thus represents a specific integrity assessment procedure for evaluating a different aspect – such as reliability, supply security, resilience – related to the above-mentioned integrity dimensions.

In particular, the proposed case studies can be collocated on the diagram according to Figure 8, which shows that the considered analyses – even if not able to fully describe the entire set of configurations – allow to cover all the spatial scales and all the kinds of threats.

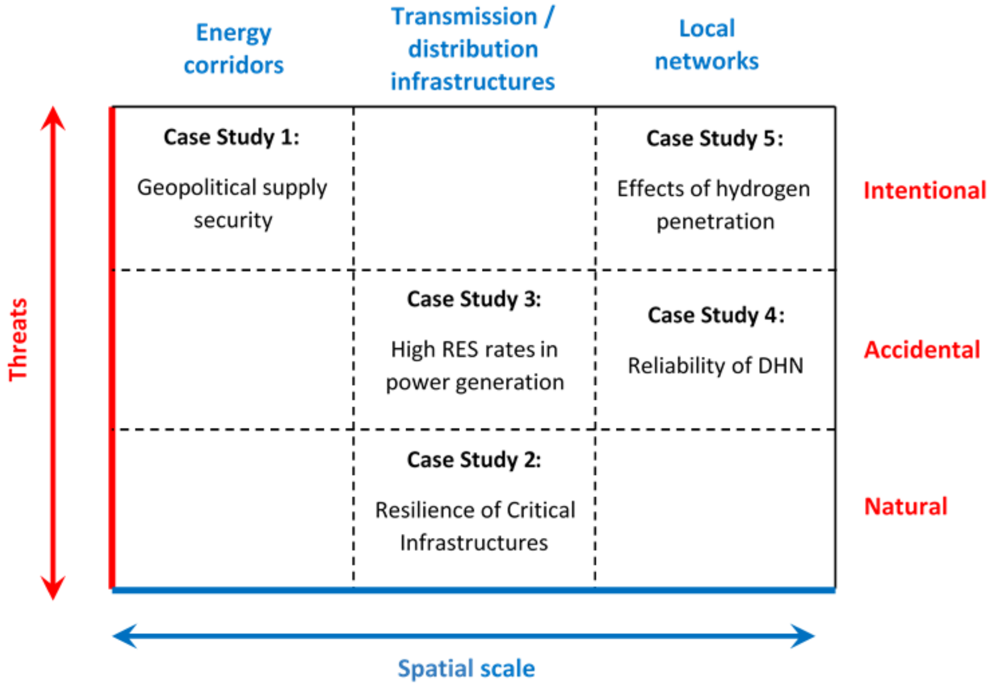


Figure 8: Scheme of the adopted multi-dimensional approach

The output of the proposed methodological approaches defined for the case studies is represented by the integrity assessment for the assumed infrastructures and with respect to a specific dimension. Namely:

- Case study 1:
  Security of energy supply → geopolitical and economic dimensions
- Case study 2:
  Resilience of distribution infrastructures → technological, economic and environmental dimensions
- Case study 3:
  Power grid issues related to high renewables penetration rates in electricity generation → technological and environmental dimensions
- Case study 4:
  Reliability and service quality in district heating networks → technological dimension
- Case study 5:
  Effects on energy security of hydrogen penetration → geopolitical and economic dimensions

Referring to the single procedures for the integrity assessment, the **Case study 1 – Geopolitical Supply Security** is related to the **security of energy supply** under the geopolitical perspective. For this reason, large transnational energy corridors (oil and gas pipelines, maritime routes, etc.) have been considered and the possible political scenarios that could cause a disruption in their integrity (thus leading to relevant effects on the availability of the required energy commodities) have been analysed.

In this context, energy security is the capability of ensuring the availability of primary and secondary energy commodities for the fulfilment of the end-uses, where they are needed, in the required quantities and over short, mid and long-term time horizons. The geopolitical security of energy supply is especially relevant in countries characterized by a high level of import dependency, like the EU28 and, in particular, Italy, which has been the focus of the scenarios implemented for testing the proposed methodology.

In order to quantify the risk related to the energy supply, this methodology couples the adaptation of the classical approach used in the **risk analyses** performed in the industrial sector to the geopolitical dimension and the spatial characterisation of the energy corridors, thus embedding their physical dimension in the analysis. Furthermore, it associates to each country involved in the national energy supply chain a numerical **risk index**, in order to quantify the risk related to each corridor and to quantitatively compare the outcomes of different supply scenarios.

This perspective can be thus considered a supporting tool for the decision-making process, as it allows to highlight and rank the criticalities of the studied energy system and to compare different possible strategical options regarding energy imports and infrastructure development.

The **Case study 2 – Resilience of Critical Infrastructures** analysed in the thesis is related to a spatial mesoscale of critical energy infrastructures and focuses on the evaluation of their **resilience**. Even if the methodology has been generically developed for energy corridors, it can find a valuable application in the case of transmission and distribution networks. The starting point of the analysis is represented by the definitions of “critical infrastructures” and “resilience”.

According to the definition provided by the European Community in 2004, critical infrastructures are crucial systems, facilities, networks or assets whose disruption would lead to relevant impacts on the socio-economic condition and development of a Member State (MS). The United Nations International Strategy for Disaster Reduction (UNISDR) defined instead the resilience as “the ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions”, and this general statement applies also to the critical infrastructures. The reduction in the vulnerability to all the possible hazards (in many cases unpredictable) that could damage critical infrastructures by improving the level of their protection and by increasing their resilience is one of the main goals of the European Union.

A methodological approach for the evaluation of a **criticality index**, related to the failure of an energy infrastructure caused by an extreme natural hazard (as earthquakes, floods, storms, landslides and wildfires) has been proposed. This index can be useful for assessing the criticality level of each section of the infrastructure itself – thus taking into account its spatial dimension – with respect to the socio-economic damage (measured in economic unit) produced by the failure. Moreover, the possibility to evaluate the distance from the criticality status even in case of non-critical scenarios and to compare the criticality condition with a risk acceptability criterion could provide a support in prioritising investments and in defining ad hoc countermeasures and protective actions.

The **Case study 3 – High RES rates in power generation** refers again to transmission and distribution infrastructures, in this case mainly considered under a technological perspective. In fact, the analysis focuses on the issues that can arise from **high penetration levels of non-programmable renewable sources** in the energy systems and, in particular, in the power generation systems. These issues are related to the structure of the traditional power systems and their management, mainly based on conventional (and almost uninterruptable) large plants for the base load and adjustable smaller plants for the peak coverage. This leads to an inflexibility of the systems themselves and to the need for additional solutions in order to allow large penetration rates avoiding relevant excess of non-programmable renewable sources production.

A methodology has been proposed focusing on the Italian power system. It aims at evaluating the percentage of **electricity** produced by non-programmable renewable sources **that cannot be immediately consumed** because it exceeds the instantaneous flexibility of the system, i.e. the difference between the instantaneous load and the minimum output power of the other plants belonging to the analysed system. This minimum power is defined **inflexibility** and corresponds to the threshold below which the production of the base load plants has to be modified, often causing the shutdown of certain units in order to avoid damages. If the net load is lower than the inflexibility, the surplus of electricity generated by non-programmable renewable source plants cannot be instantaneously consumed: if storage systems are available, it could used later, otherwise some of these plants have to be disconnected from the grid. In the analysis, different renewables penetration rates have been assumed in order to verify the sensitivity of the national system.

The **Case study 4 – Reliability of DHN** is related to the local scale, and in particular to the analysis of **district heating networks**. It starts from the consideration that usually design approaches for district heating networks are based on functional and thermo-fluid dynamic considerations, without embedding **reliability** aspects, which are commonly object of ex-post analyses.

The proposed case study aim to put into evidence the relevance of introducing these aspects in the network design phase and, in particular, of developing a supporting tool for DHNs design. The developed approach couples a thermo-fluid dynamic module for the simulation of the **physical behaviour** of the considered network, and a Monte Carlo module for the management of the failure and repair processes of the grid. This methodology can be useful in optimising the layout and maintainability of the network, in particular by defining the best position and size of possible centralised and distributed **thermal heat storage systems**, by comparing the effects on the service quality (measured through ad hoc parameters) in the case of different grid configurations. The case study can thus help in identifying and quantifying the role that thermal heat storage systems could play in the management of the network and of the installed power capacities, in the decoupling between heat production and demand and in the enhancement of the network reliability.

The aim of this approach is thus to support planners and designers in the definition of optimal network architectures by firstly proposing an integrated approach able to link technical and economic analyses with reliability techniques.

The **Case study 5 – Effects of hydrogen penetration** is related to the analysis of the penetration of alternative energy vectors, in particular **hydrogen**, with reference to local decarbonised energy systems (as the transport sector, both urban and intercity).

This study, performed through a global **optimisation forecasting** energy model able to also quantify the security of energy supply, allows to evaluate the impact of a modification of the energy mix at local scale on the energy security at wider scale (national or European). The model can use the hydrogen commodity to fulfil demands in different sectors (transport, residential, industrial, commercial and agricultural) and it is able to describe the end-use technologies with a high level of detail.

Particularly interesting is the mobility application, which could be a key entry option for the success of hydrogen economy. The **urban or suburban dimension** of hydrogen penetration in the transport sector is influenced by the range vehicles fuelled by hydrogen that, even if growing, still remains lower than the one of internal combustion engine vehicles. Furthermore, the difficulty in building a diffused refuelling infrastructure, limits the hydrogen applications to urban areas.

This approach, by means of scenario analyses, can thus be useful in understanding how actions at local scale (cities, urban areas) and the integration of local smart networks with the main distribution networks can help in reaching targets like those related to environmental and energy security issues.

Chapter 2 describes the climate change issues and the correlation between them and the energy sector. Chapter 3 discusses the possible extreme energy strategies for implementing the energy transition towards decarbonised systems. Chapter 4 investigates the role of energy infrastructure with respect to the energy transition and, in particular, the role played by their integrity. Furthermore, it illustrates the multidimensional approach adopted in the doctoral project. Chapter 5 proposes the considered case studies with reference to different spatial, threats and integrity dimensions. Finally, Chapter 6 analyses the obtained results related to the general framework proposed and the possible future developments.

Chapter 2

Energy and Climate Change

2.1 Climate changes: effects, causes and the role of the energy sector

Climate change phenomena represent a global issue able to have significant impacts on world economic and social systems. During last decades, several international bodies and institutions developed scientific techniques to analyse the causes and effects of these phenomena, their evolution over time and possible future scenarios.

Among them, the Intergovernmental Panel on Climate Change (**IPCC**) can be mentioned.

The IPCC is structured into three Working Groups (I, II and III) and a Task Force: the activity of the Working Groups respectively focuses on

- the physical principles of climate change,
- the environmental and socio-economic impacts of climate change and
- the possible countermeasures to be set for mitigation purposes,

while the Task Force aims at developing shared methodological approaches for the assessment of greenhouse gas (GHG) emissions at national level.

The activity of the IPCC mainly leads to the publication of the so-called **"Assessment Reports"**, which comprise the state of the art on climate change from the scientific and technical point of view; the Fifth Assessment Report [1] is the lastly published, as the Sixth Assessment Synthesis Report is planned by April 2022.

According to this report, the increase in the global temperature and the related climatic effects since the mid of the 20th century are clearly observable and not negligible. In particular, three main interdependent consequences have been identified:

- The first one is the increase in the global land and ocean **surface temperature**, whose average growth from the pre-industrial era (i.e. over the period 1880-2012) is equal to 0.85 [0.65÷1.06] °C.
- The second one is the reduction in the **Artic sea-ice extent**, whose decay rate in 1979-2012 ranged between 3.5% and 4.1%.
- The third one is the change in the global **mean sea level**, which increased by 0.19 [0.17÷0.21] m over the period 1901-2010.

The square bracket values identify the range corresponding to a 90% probability of including the average estimated value.

The most relevant results obtained by the IPCC are shown in Figure 9.

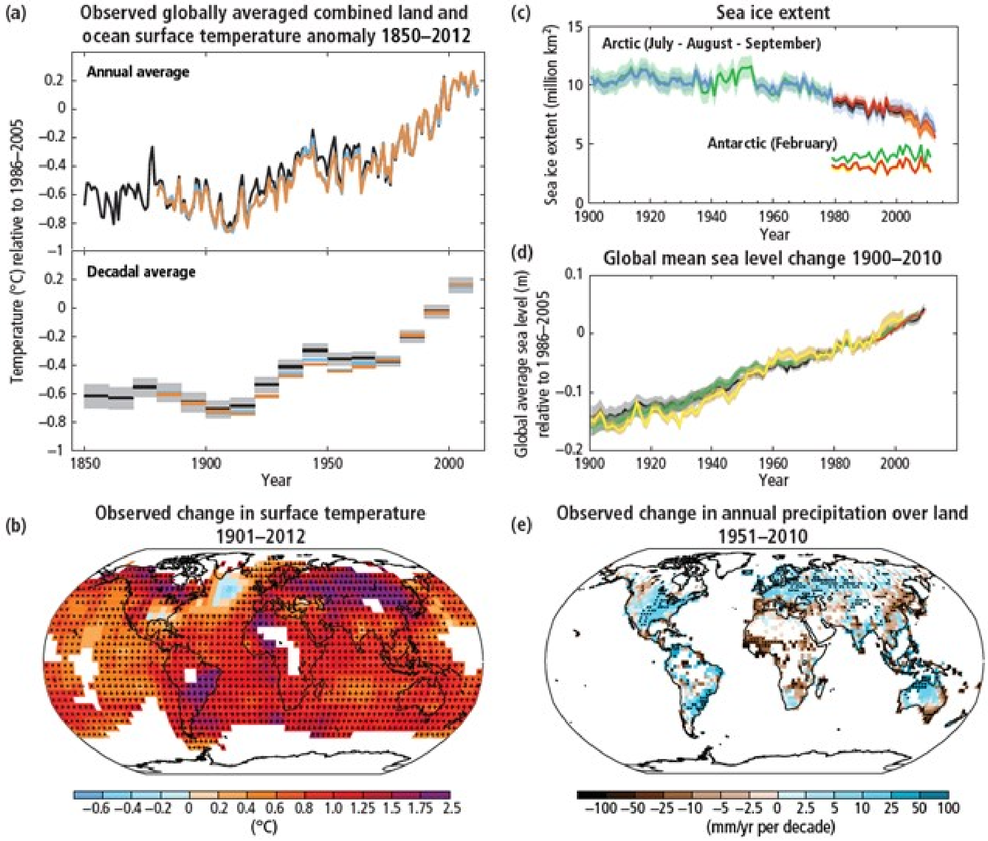


Figure 9: Main IPCC observations on climate change phenomena **[1]**

The **causes** of these changes are related to the strong increase in the anthropogenic GHG emissions with respect to the pre-industrial era, that has led to atmospheric concentrations of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) that have not been reached in the last 800000 years. About 30% of the anthropogenic emissions have been absorbed by oceans, causing their acidification, while about 40% of the emissions remained in the atmosphere. Industrial processes and fossil fuels combustion caused about 78% of the overall increase in GHG emissions in the period 1970-2010 (Figure 10).

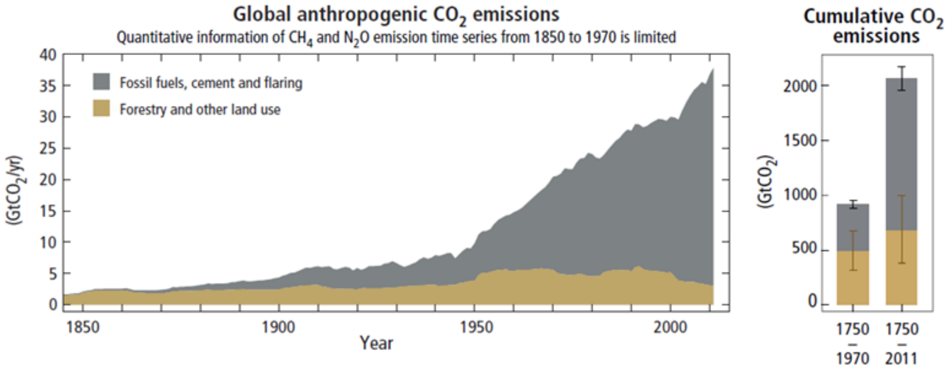


Figure 10: Historical trend of global anthropogenic CO_2 emissions **[1]**

As a consequence, the IPCC report underlines that is "extremely likely" that more than 50% of the growth in global average temperature in the period 1951-2010 has been due to the **anthropogenic GHG** emission plus other anthropogenic forcings (Figure 11).

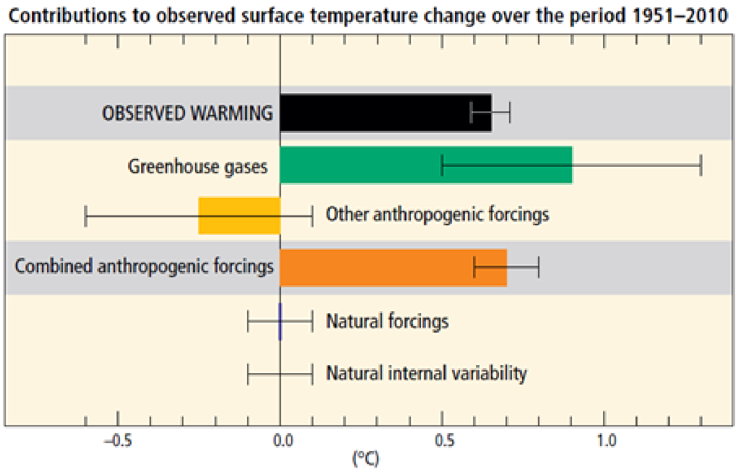


Figure 11: Contribution of anthropogenic GHG emissions to the global temperature increase **[1]**

Furthermore, the analyses of the available climate models performed by the IPCC shows that experimental data are coherent with **model results** only if anthropogenic forcings are considered (Figure 12).

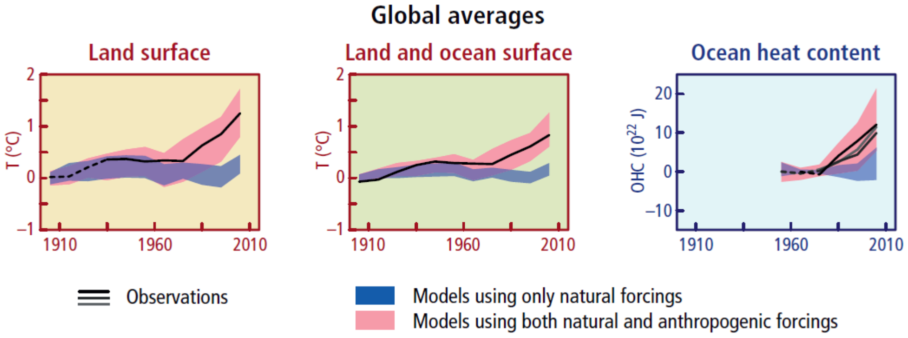


Figure 12: Coherence between empirical observation and model results related to climate change phenomena **[1]**

GHG emissions have a crucial role in determining climate changes. Among them, CO_2 is the most relevant one, with a contribution significantly larger than the one given by other gases like methane (CH_4) and nitrous dioxide (N_2O), which are characterised by a persistence in the atmosphere lower but by a global warming potential (**GWP**) higher than the CO_2 one (which is assumed equal to 1, while the GWP ranges between 28 and 36 for CH_4 and between 265 and 298 for N_2O over a 100-years period [5])

According to the statistical data provided by the International Energy Agency [5], **global CO_2 emissions** in 2014 due to fossil fuel combustion were equal to 32.4 Gt, with an increase by 57.9% with respect to the 1990 value. The majority of these emissions was due to few countries (Figure 13). In particular, six countries or world macro-areas were responsible for 68.4% of them:

- China (28.2%),
- the United States (16.0%),
- the European Union (9.8%),
- India (6.2%),
- Russian Federation (4.5%) and
- Japan (3.7%).

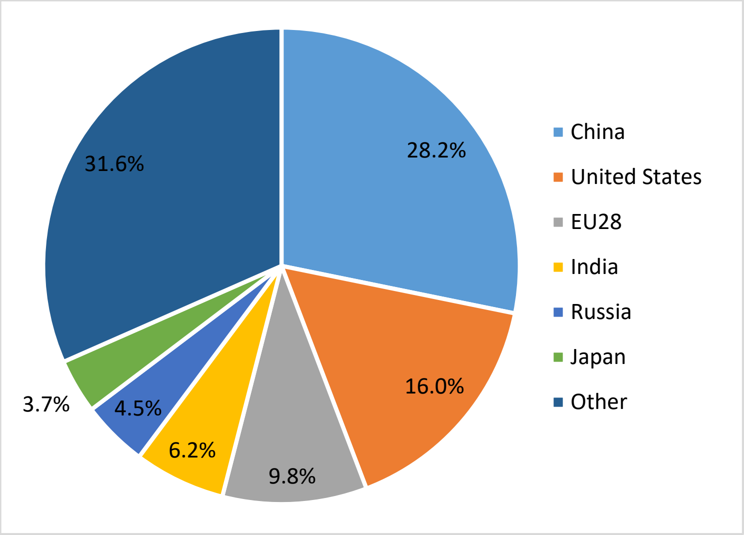


Figure 13: Percentage global CO_2 emissions by country in 2014

Focusing on the single commodities, it can be observed that coal and oil are the most relevant contributors, accounting respectively for 45.9% and 33.9% of the total. This is mainly due to the relevant role that they play in different countries, especially in the power generation and in the transport sectors.

In order to highlight this relevance, the country **energy balances** can be considered, analysing specifically three of the balance items:

- The Gross Inland Consumption (**GIC**; also named Total Primary Energy Supply, TPES), which corresponds to the overall energy needs of a country and, on the basis of the definition provided by Eurostat [6], can be defined as

$$GIC = local\ production\ of\ energy\ commodities + recovered\ products \\ + net\ imports\ +\ variations\ of\ stocks - bunkers$$

- The transformation **input to power generation**, which identifies the energy content of primary commodities (as coal, oil products, natural gas) used to produce electricity.
- The **final energy consumption**, which represents the amount of energy consumed to satisfy the so-called "services demands" (space heating and cooling, water heating, lighting, cooking, use of electrical appliances, industrial production, mobility of passengers and goods, etc.) in the end-use sectors by the different technologies (like heating systems, stoves, air conditioners, boilers, lamps, industrial machineries and equipment, cars, trucks, trains, etc.).

Referring to these items, it can be observed that, for example, in **China** (i.e. the major emitting country) in 2014 coal accounted for about

- 65.9% of the GIC,
- 83.4% of the fuel input to electricity generation plant and
- 36.5% of the final energy consumption.

These values are significantly higher than the average corresponding ones at **global** level, which are equal to

- 28.6% (GIC),
- 48.6% (transformation input for power generation) and
- 11.4% (final uses).

This large use of coal, historically justified by the local availability of this resource (in 2014 the local production covered 93.9% of the Chinese GIC), coupled with the relevant economic growth that characterised China during last decades put into evidence the need for a change in the country fuel mix in order to positively impact on the global emissions level.

In fact, analysing the historical trends of the cumulative CO_2 emissions [5], it is possible to observe that the importance of the United States and of the European Union, which up to 1980 together accounted for the majority of world emissions, progressively slowed down in the last 35 years and that the role of leading country has been assumed by China (Figure 14). Moreover, focusing on the last years, the average annual growth rate of CO_2 emissions since the beginning of the 21st century has been equal to 2.3% (almost double in comparison with the one in the period 1990-2000, which was equal to 1.2%). In particular, this increase has been driven by the power sector (especially in developing countries like China), which doubled its emissions (and China was responsible for about two-thirds of this growth).

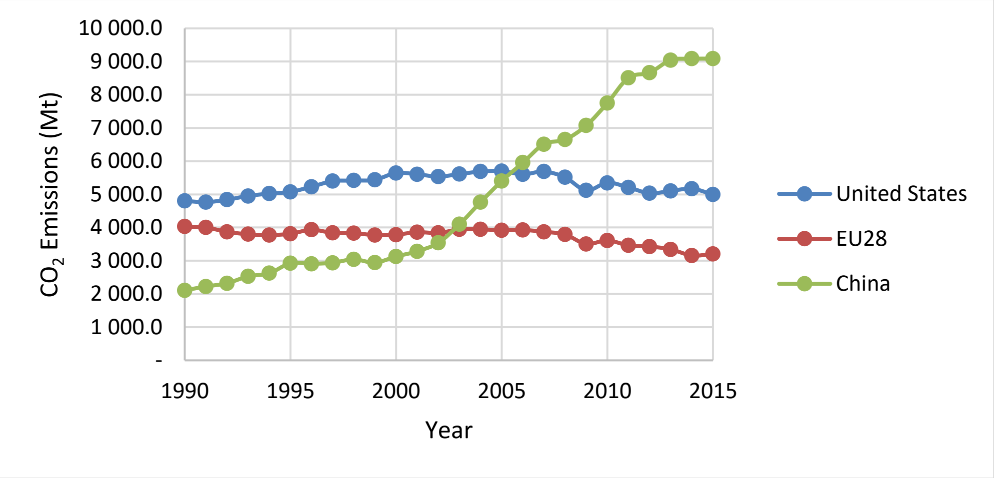


Figure 14: Trend of CO2 emissions from fuel combustion in U.S., EU28 and China from 1990 to 2015

Furthermore, considering the role played by energy in the overall increase of GHG emissions, it has to be noticed that the IEA Energy and Climate Change Special Report [7] underlines that the GHG emissions (whose largest part is represented by CO_2) related to the **energy sector**, which identifies

- energy supply,
- transformation (including the power generation) and
- energy consuming end-use sectors (like the agriculture, industrial, residential and transport ones),

account for about two thirds of the overall anthropogenic GHG emissions.

In particular, as mentioned before, the **power sector** is responsible for more than 40% of CO_2 emissions of the energy sector, thus becoming one of the most relevant sectors to act on in order to define and implement effective decarbonisation policies.

One of the most significant indicators that can be adopted to compare the relevance of CO_2 emissions among different areas is the **carbon intensity** *CI*, which can be calculated as the ratio between the amount of CO_2 emitted by a given country and its GDP, according to the following relationship:

$$CI = \frac{CO_2 \; emissions}{GDP} \qquad [CI] = \frac{kg}{\$}$$

On the basis of the statistical data available, with reference to 2014 and assuming the GDP based on the purchasing power parity (PPP) expressed in 2010 $ and the CO_2 emissions expressed in kg, Figure 15 reports a comparison among some of the most relevant world areas in terms of carbon intensity:

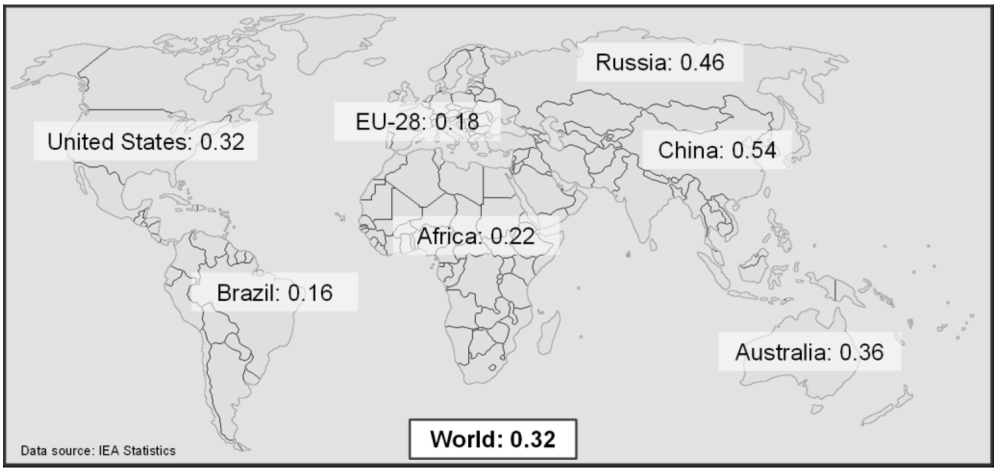


Figure 15: Comparison among carbon intensity in different world areas

It can be observed that the countries like China and Russia are characterised by a carbon intensity significantly higher than other countries like the European Union and even higher than the global average value. This means that each unit of GDP generated (i.e. the production of the internal richness of the country) requires a higher amount of energy with respect to other areas. This can be related to the fact that in these countries – especially in China – the economic system is mostly based on energy intensive industries (like those for cement and iron and steel production), in turn relying on fossil fuels like coal. During last decades, China showed a relevant reduction trend for the carbon intensity, starting from the value reached at the end of Seventies (about 2 kg of CO_2 per $), but additional structural changes in the industrial technologies, processes and fuel mix are needed to further reduce it.

A positive aspect to underline is instead represented by the signal of a progressive **decoupling** between global economic growth and CO_2 emissions that arose during last years. Focusing, in fact, on the most recently available data published by the IEA [8], it can be observed that world energy-related CO_2 emissions remained quite stable in 2015 and 2016 with respect to 2014, in spite of an overall economic growth.

Figure 16 shows the historical evolution of the CO_2 emissions and GDP annual growth rates from 1971 to 2016, highlighting the past link between these two variables and the decoupling in the most recent years; GDP data (based on constant 2010 $) are taken from the World Bank DataBank [9], while the CO_2 emissions data are from the IEA statistics (2015 and 2016 values have to be considered provisional data).

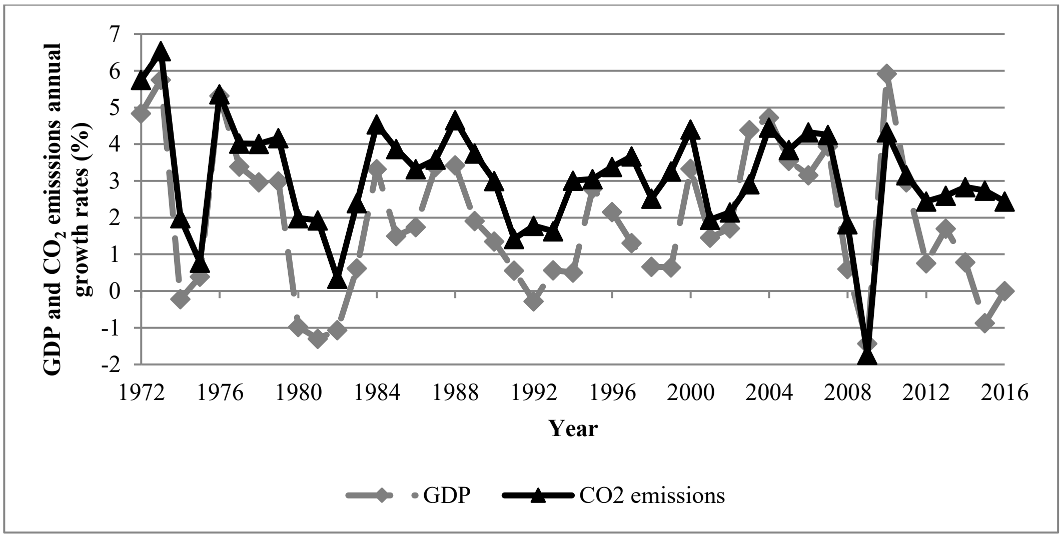


Figure 16: Historical trend of GDP and CO2 emissions annual growth rates (data source: IEA Statistics, World Bank DataBank)

The main reasons of this decoupling are related to the increase in the energy efficiency and in the technological advancements, that allow to satisfy the same services demands with a lower input of energy commodities, together with a global trend of increase in the renewable penetration in the power generation sector, driven in turn by the environmental concerns and the related policies.

In particular, the IEA reports that in the United States in 2016 the economic increase was equal to 1.6%, while the CO_2 emissions reduced by 3.0%, mainly due to an increase in the use of shale gas and in an increasing penetration of renewables for power generation with respect to coal, leading to an electricity production from natural gas higher than the one from coal. Furthermore, due to the availability of local shale gas reserves the U.S. could become during next years natural gas net exporters to European and Asian countries via LNG (Liquefied Natural Gas) maritime routes. According to these preliminary data, also China experienced during last year a decoupling phenomenon, with simultaneous a reduction in CO_2 emissions by 1.0% with respect to 2015 and a GDP increase by 6.7%, mostly driven by the growing role played by renewables, natural gas and also nuclear in the power sector (even if, as previously mentioned, coal still absolutely remains the dominant energy commodity for the electricity production): referring to the nuclear generation, China in 2016 increased the electricity production from nuclear by about 24% in comparison with 2015, with 5 new plants entered into operation and 213 TWh produced (3.6% of the total generation); moreover, 20 plants are under construction, with a capacity equal to 22.0 GW and 40 plants are planned, with a capacity equal to 46.7 GW [10]. Another key factor in enabling this decoupling in the Chinese energy and economic system has been represented by the increase in the role of natural gas in the residential and industrial sectors, supported by policies aiming at promoting GHG and pollutant emissions reduction.

However, besides the GHG emissions, an additional relevant aspect related to the combustion of fossil fuels is represented by the emission of **air pollutants**. Air pollutants can be divided into primary and secondary: primary air pollutants have a natural origin (f.i. from wildfires and volcanoes) or are the direct output of anthropic activities; secondary air pollutants derive from the primary ones through reactions that can happen in the atmosphere. Among the primary ones, the following can be mentioned:

- sulphur oxides (SOX), and in particular sulphur dioxide (SO_2);
- nitrogen oxides (NOX);
- particulate matter (PM), a mixture of liquid droplets and particles, further classified according to their dimensions in coarse;
- volatile organic compounds (VOC);
- carbon monoxide (CO), deriving from incomplete combustion processes;
- ammonia (NH_3).

Among the secondary ones, instead,

- ozone (O_3), produced by the reaction between hydrocarbons and NOX in the presence of sunlight

can be cited. It has to be underlined that – with the exception of the ammonia – the majority of primary air pollutant emissions are **energy-related**, and the main sources are represented by combustion of fossil fuels and bioenergy, mining activities (like coal extraction), oil refining, coal processing and transportation, non-exhaust emissions related to the transport sector (like the road and brake wear), etc. The percentage contribution of the energy consumption to the emissions of the different typologies of pollutants and the sectors that mainly are responsible for them are reported in Table 2, built on the basis of the data available in the IEA Energy and Air Pollution Special Report [2] and graphically synthetized in Figure 17, directly taken from the same report.

Table 2: Contribution of the energy sector to air pollutant emissions and most impacting sectors

Air pollutant	Energy-related emissions (%)	Major contributing sectors
SO_X	>99%	Power
NO_X	>99%	Industry
CO	92%	Residential
PM2.5	85%	Transport
VOC	66%	Energy supply
NH3	3%	Non-energy

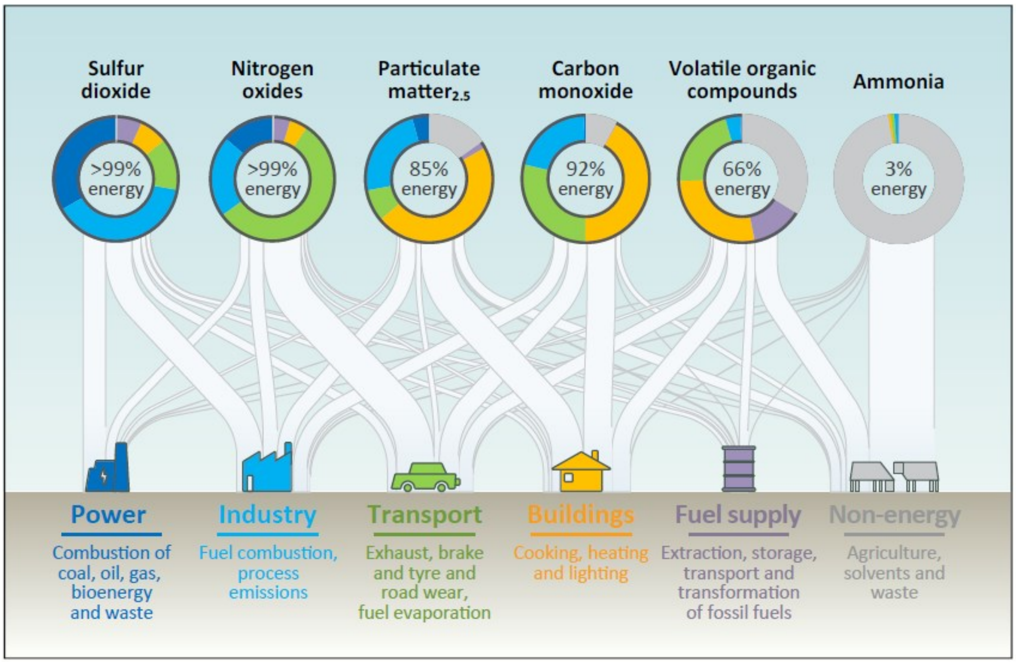


Figure 17: Role played by single sectors of the energy chain in air pollutant emissions **[2]**

It can be thus observed that the whole energy chain – from the supply (i.e. production of energy commodities) to the final uses, passing through the transformation from primary to secondary commodities (like in the case of power generation) – is involved in the emission process.

This aspect underlines the need for considering measures and action spread over the entire energy systems (and not limited to specific areas, like single end-use sectors or single kind of technologies) when energy and environmental policies aiming at counteracting pollutant emissions are defined and implemented.

The effects of the air pollutant emissions are twofold:

- **health** impacts and
- **economic** impacts.

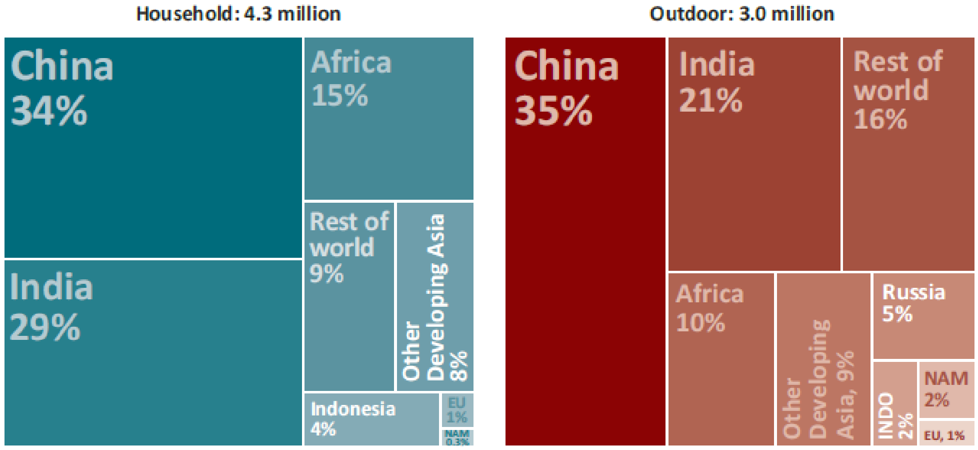
Their severity is related to the concentration level of the emissions and to the duration of the exposure.

Regarding the **health effects**, they are mostly associated to the respiratory tract, including bronchial and lung diseases, asthma (mainly from SO_X and NO_X), throat cancer, lung cancer (especially from PM) and various chronic lung illnesses.

In particular, the World Health Organization (WHO) demonstrated that about 500000 annual deaths of children from 0 to 5 years old and that more than 4 million premature deaths in 2012 are related to diseases like pneumonia caused by residential air pollutant emissions.

These emissions, in turn, are due to a wide use of solid biomass and kerosene for cooking, heating and lighting, and are largely concentrated in low- or middle-income countries, like the Asian ones. In fact, the number of deaths due to indoor air pollution has been quantified in about 1.5 million people in China and in 1.25 million people in India [11]. Furthermore, the WHO highlighted that China and India are also the countries mostly affected by premature deaths caused by outdoor air pollutant emissions, especially the PM ones, with about 1 million people and 620000 people deaths in 2012, mainly due to the large role played by coal in the energy mix.

Figure 18 shows the geographical distribution at global scale of deaths that can be due to household and outdoor air pollution.



Notes: EU = European Union; NAM = North America; INDO = Indonesia.

Figure 18: Global distribution of deaths related to household and outdoor air pollution **[2]**

Referring to the **economic impact**, the most relevant costs are those related to the health effects caused by air pollution. Also in this case, China and India have been identified as the two countries that mostly suffer from this economic effect. In particular, the cost per person in 2012 has been estimated equal to about 1600 USD PPP for China and 800 USD PPP for India, while the overall cost has been estimated equal to more than $2100 \cdot 10^9$ USD PPP for China and more than $900 \cdot 10^9$ USD PPP for India.

It has to be observed that, even if the overall cost is almost negligible in comparison with the one of the two Asian countries, the per capita value in high-income countries like Germany and Italy is between 1000 and 1200 USD PPP, thus resulting higher than the Indian one.

As mentioned before, in the low- and middle-income countries, the residential, industry and power sectors are the main responsible for pollutant emissions, so they can be considered as the most impacting sectors in terms of heath economic costs. On the opposite, in high-income countries, the transport sector is most relevant one, as it is responsible for about 50% of the economic health costs related to air pollution.

Another significant economic impact is the one on the agriculture, namely on the crops production, mainly related to the concentration of ozone (which is generated by the reaction between NO_X and VOC, CH_4 or CO in presence of sunlight) at ground level. This negative impact mostly affect developing countries, which are characterised by a high level of air pollutant emissions and simultaneously by a significant importance of the agriculture sector, with relevant production volumes of crops.

Furthermore, pollutants like SO_2, NO_X and NH_3 can cause acid rain, that in turn can impact on water and soil. Finally, a low air quality and high concentration of pollutants lead to uncomfortable environments, which determine a negative effect on the promotion of tourism in the affected areas, thus leading to additional indirect economical losses.

All these aspects underline the need for a strong **decarbonisation pathway**, able to progressively reduce the incidence of fossil fuels (in particular, of the sources characterised by the highest emission levels, like solid fuels and oil) in the world energy mix.

2.2 International agreements and strategies

In order to face climate change and air pollutant emissions issues, several strategies have been analysed and proposed. In particular, as mentioned in the fifth Assessment Report of the IPCC, one of the key elements to counteract the most relevant climate change phenomena (like the increase in the average sea level and the reduction of the Arctic ice coverage) is represented by the limitation of **global warming**. To obtain this result, the global average temperature rise with respect to the pre-industrial era should be maintained below 2°C (or better 1.5°C) by the end of the current century. In turn, this goal requires a significant reduction of GHG emissions, leading to zero or nearly-zero emissions by the end of the Century.

As mentioned in Chapter 1, among the international political and regulatory frameworks related to the climate change, the most relevant is represented by United Nations Framework Convention on Climate Change (**UNFCCC**) [12]. The main goal of the UNFCCC is to ensure the stabilisation of GHG emissions concentration in order to “prevent dangerous anthropogenic (human induced) interference with the climate system”. To do this, the most developed and industrialised countries have been requested to reduce their own emissions and to support the actions aiming at limiting climate change phenomena in developing countries not only from the economic point of view (through funding measures), but also by sharing advanced technological solutions.

This general purpose aims to take into account that in developing countries the coupling between the need for the economic growth (and the related social development) and the investments requested by an effective long-term strategy against climate changes could not be easy to achieve, even if the fact that these countries pursue environmental sustainability pathways as much as possible is one of the crucial aspects to reach the overall goal at global level.

An annual meeting of the Parties of UNFCCC – the so-called Conference Of the Parties (**COP**) – has been established since 1995. Amon the main treaty and agreements set by these conferences, the following can be mentioned:

- The Kyoto Protocol (1997):

  It was defined in the COP3 and it stated, for the developed countries, a GHG emissions reduction by at least 5% with respect to 1990 values during the period 2008-2012 [13]. This protocol was ratified only in 2005 (after that Russia signed it), due to the fact that the signature of at least 55 countries responsible for at least 55% of the global emissions was requested. The United States, instead, did not ratified the protocol. The Kyoto Protocol considered three different mechanism for reaching the expected targets:

  - Joint Implementation (JI):

    It identifies the joint achievement of the duties through the cooperation among countries, that can decide to share the reduction constraints, provided to ensure the total emission reduction deriving from the achievement of the single national constraints.

  - Clean Development Mechanism (CDM):

    Developed countries can promote and implement projects allowing an emission reduction in developing or not developed countries, thus obtaining emission credits (Certified Emissions Reductions, CERs) and – as a consequence – the possibility to reduce the amount of their emission reduction burden.

  - International Emissions Trading (IET):

    It is the possibility that a country able to reach an emission reduction level higher than the requested one could sell (under a market mechanism) emission credits (Assigned Amount Units, AAUs) to other countries that did not achieve their emission reduction goals.

  All these mechanisms aimed to prioritise the achievement of the targets at global scale with respect to the achievements of the ones at single country level.

- The Copenaghen Accord (2009):

  In this Accord [14] it had been firstly introduced the need for limiting the global average temperature increase below 2°C, even if the reference year for this increase was not identified. Only after the definition of the Copenhagen Accord, the reference was set by the UNFCCC to the pre-industrial era. However, no practical indications about the way in which this limitation should be implemented were provided. Furthermore, the delegates of the

Conference Of the Parties only “took note” of the Accord and did not formally adopt it, which remains not binding from a legal point of view.

- The Paris Agreement (2015):

  The Paris Agreement was defined in the framework of the COP21 [15] and its main goal is the reduction of the global average temperature increase well below 2°C with respect to the pre-industrial era by the end of the current Century, making all the efforts to reduce this temperature rise below 1.5 °C (Article 2.1(a)).

  Furthermore, the Paris Agreement promotes actions (in terms of both financial flows and technological sharing) to support developing countries in pursuing decarbonisation pathways. It entered into force on 4 November 2016 and currently more than 170 Parties (over 197) have ratified it.

  According to the Agreement, each country that has ratified it has to define an emissions reduction target, through voluntary pledges and without penalties in the case of failure in achieving the proposed goals. These national pledges have been collected in the so-called Intended Nationally Determined Contributions (INDCs), before and during the Conference. For each country, the INDCs has been transformed into the Nationally Determined Contribution (NDC) when the country itself ratified the Agreement, unless it submitted a new NDC in coincidence with the ratification.

All these protocols and treaty share a common factor, i.e. the attention devoted to the decarbonisation of economic and energy systems, which in turn correspond to a decrease in carbon intensity, which quantifies the amount of CO_2 emissions per unit of Gross Domestic Product generated). It has to be underlined that actions and regulations promoting decarbonisation currently are not inserted into a unique global framework, but single countries or areas (like the EU) adopt different approaches.

As mentioned in Chapter 1, **six countries**/areas are responsible for more than 68% of the total GHG emissions. For this reason, the main climate policies and emissions reduction targets of these countries are now discussed, starting from the EU, which historically paid a significant attention to environmental issues and policies.

In particular, considering the more recent years, in 2011 the **EU** published the **“Energy Roadmap 2050”** [16]. This document introduced an emission reduction target by 2050 that ranges between 80% and 95% with respect to the 1990 value; 80% of this reduction should be obtained only through internal measures, i.e. without the use of international credits (financial systems that correspond to one t of CO_2 removed by means of an emission reduction project).

In accordance with the Strategic Energy Technology **(SET) Plan** [17], [18], [19], the constriction of nearly zero energy buildings (NZEB), the implementation of smart grids, the diffusion of carbon capture and storage systems and the enhancement of the renewables penetration in the energy mix are recognised as crucial elements for reaching the long-term decarbonisation targets. Furthermore, beyond these elements, carbon price is identified as another relevant factor to be considered in the definition of decarbonisation strategies. It corresponds to the amount of money that has to be paid as a tax, for each tonne of CO_2 produced, by emitters, and it represents the base of carbon taxation systems. This mechanism, and in particular an increase in carbon price, is considered more effective in a low-carbon perspective than an increase in fossil fuel costs, due to the fact that the carbon pricing revenues could be used, in several ways, by the internal economic system. For instance, they can be used for supporting households or productive sectors, for reducing other taxes, for reducing the public debt or for financing the implementation of other environmental and climate policies.

Focusing on the single sectors, according to the Energy Roadmap 2050 the power generation system could be almost totally decarbonised (96÷99% of electricity generated without using fossil sources) by 2050. Moreover, the role of electrification in final energy uses should significantly increase during next decades: it could fulfil 36÷39% of the European final energy demand by 2050, covering about 65% of the energy demand for light duty vehicles and passenger cars. The transport sector, however, is expected to reach a decarbonisation level (less than 70%) by 2050 lower than other sectors. The same for the agriculture sector, which is expected to reach a decarbonisation level lower than 50% by 2050.

Considering instead the Nationally Determined Contribution (**NDC**) to the 2015 Paris Climate Agreement, the EU pledged a binding domestic reduction in GHG emissions of at least 40%, with respect to 1990 level by 2030, to be reached jointly, without the use of international credits [20]. In the EU NDC planning process, it is further underlined the proposal to implement the **2030 Climate and Energy Framework**. This strategy is characterised by three main targets for 2030:

- 40% GHG emissions reduction with respect to 1990 value (i.e. the main goal of the NDC),
- at least 27% renewable penetration in the energy consumption,
- at least 27% energy savings in comparison with the business-as-usual scenario (i.e. with the continuation of the current trend).

In order to achieve these goals, three main policy schemes have been proposed by the European Commission:

- security and competitiveness of the energy systems through supply diversification, interconnection among European countries and price differences with the main partners;
- a new governance founded on national energy plans, in turn based on a common and homogenous methodology for all the Member States;
- the reform of the Emissions Trading Scheme (ETS).

Referring to **China**, in 2009 – in the framework of the **Copenhagen Accord** – it pledged a carbon intensity reduction by 40-45% by 2020 with respect to 2005 value, and an increase of the contribution given by non-fossil fuels to the primary energy consumption to 15% by 2020 [21].

Moreover, in the Paris Agreement **NDC**, it planned to make efforts in order to

- achieve the CO_2 peak before 2030,
- reduce carbon intensity by 60÷65% by 2030 in comparison with the 2005 value,
- reach a penetration of non-fossil fuels in the primary energy mix equal to about 20%
- increase the forest stock by $4.5 \cdot 10^9$ m^3 with respect to the 2005 level [22].

Furthermore, in the **13th Five-Year-Plan**, approved in 2016, new goals have been defined. These targets include

- an energy intensity reduction by 15% by 2020 with respect to the 2005 value,
- a renewables penetration share in the primary energy consumption by 2020 equal to 15%,
- a carbon intensity reduction by 18% by 2020 with respect to the 2015 value (which is higher than the 2009 target)
- an energy consumption cap by 2020 equal to $5 \cdot 10^9$ tce per year [23].

India introduced its first plan on climate change, called National Action Plan on Climate Change (**NAPCC**), in 2008. It defined a set of policies aiming at mitigating GHG emissions through the enhancement of energy efficiency, renewables penetration, nuclear plants and mass transport [24].

In the framework of the **Copenhagen Accord**, in 2009, India pledged a reduction in the emissions intensity of its GDP by 20÷25% by 2020 in comparison with the 2005 value [25].

Moreover, in the Paris Agreement **NDC** in 2015 [26], it planned to

- reduce the emissions intensity by 33÷35% with respect to the 2005 level by 2030,
- reach about 40% of cumulative power generation capacity from renewables by 2030,
- enhance the forest coverage in order to create an additional carbon sink of $2.5 \div 3.0 \cdot 10^9$ t of CO_2 equivalent by 2030,
- make investments (also by means of funds from developed countries) for climate changes adaptation and mitigation actions in sectors particularly exposed to the negative effects (like agriculture) and for supporting research cooperation for the development of new technologies.

Referring to **Russia**, in the **Copenhagen Accord**, it pledged a GHG emissions reduction by 15÷25% by 2020 with respect to the 1990 value [27].

In 2014, with the **Decree No. 504-p**, a new emissions reduction target by 75% of the 1990 level by 2020, consistent with the range defined in the Copenhagen Accord, was set [28].

In the 2015 Paris Agreement **INDC**, Russia slightly modified this goal, setting the reduction in anthropogenic GHG emissions to 70÷75% of the 1990 value by 2030, "subject to the maximum possible account of absorbing capacity of forests" [29]. Moreover, in this document, Russia underlined that a complete decoupling between the economic growth and the GHG emissions can be obtained by means of the achievement of the previously mentioned targets. It also stated that if the contribution given by forests is taken into consideration, the emissions constraints do not determine obstacles to the socio-economic advancement of the country.

During las decade, **Japan** firstly introduced in 2012 the fourth **Basic Environment Plan**, in which a decrease in GHG emissions by 80% with respect to the 1990 value by 2050 was defined [30]. According to the document, this main target should be achieved by means of an increase in renewables penetration in the energy mix and in energy efficiency.

In its Paris Agreement **NDC**, Japan planned instead a 26% GHG emissions reduction by 2030 in comparison with the 2013 level (which corresponds to a decrease by 25.4% with respect to the 2005 value), as feasible target considering the current national energy mix [31].

Moreover, in 2016 the **Plan for Global Warming Countermeasures** [32] was introduced by the Ministry of the Environment. The goal of this plan is to constitute a general policy framework for the achievement of the mid-term (-26% by 2030) and the long-term (-80% by 2050) reduction targets related to GHG emissions and introduced by the Basic Environment Plan and by the 2015 NDC. In particular, this document identifies the main actions and measures to be implemented by both National and Local Government: a particular attention is paid to the energy conversion, to the main end-use sectors (residential, commerce and services, industry and transport), and to the Land Use, Land-Use Change and Forestry (LULUCF) sector.

Finally, considering the **U.S.**, it has to be underlined that they did not ratified the Kyoto protocol. More recently, in the framework of the **Copenhagen Accord**, they pledged a GHG emissions decrease by 17% by 2020 in comparison with the 2005 value (including the LULUCF sector) [33].

Furthermore, in the Paris Climate Agreement **NDC**, the U.S. defined a target of 26÷28% GHG emissions reduction by 2025 in comparison with the 2005 level (including LULUCF), highlighting the need for making efforts to reach the -28% goal. In particular, the U.S. planned to achieve this goal without using international market mechanism but only by means of domestic regulations, actions and measures [34].

Moreover, in 2015, under the Obama administration, the **Clean Power Plan** [35] has been introduced by the U.S. Environmental Protection Agency (EPA). Its main target is the decrease of CO_2 emissions by 32% by 2030 with respect to the 2005 level in the power sector.

However, it has to be noticed that the current Trump administration planned the withdrawal of the U.S. from the Paris Agreement: due to this reason, it is not clear which could be the effective long-term environmental strategy of the country and which could be the effects on the national energy mix.

Figure 19 synthetises the historical trend of **GHG emissions** for the six main emitting countries above mentioned, considering 3 milestone years (1990, 2005 and 2012) and the **forecasted valued** according to the future pledges previously described. All the values have been normalised with respect to the 1990, assumed as reference year for the comparison of the different trends.

It has to be observed that China and India did not defined targets related to the overall amount of GHG emitted, but they set only quantitative goals respectively for carbon intensity and emissions intensity. These targets could be easier to be reached for developing countries, as they are related to a ratio in which the GDP represents the denominator and tends to structurally increase along time, thus reducing the value of the considered indicator.

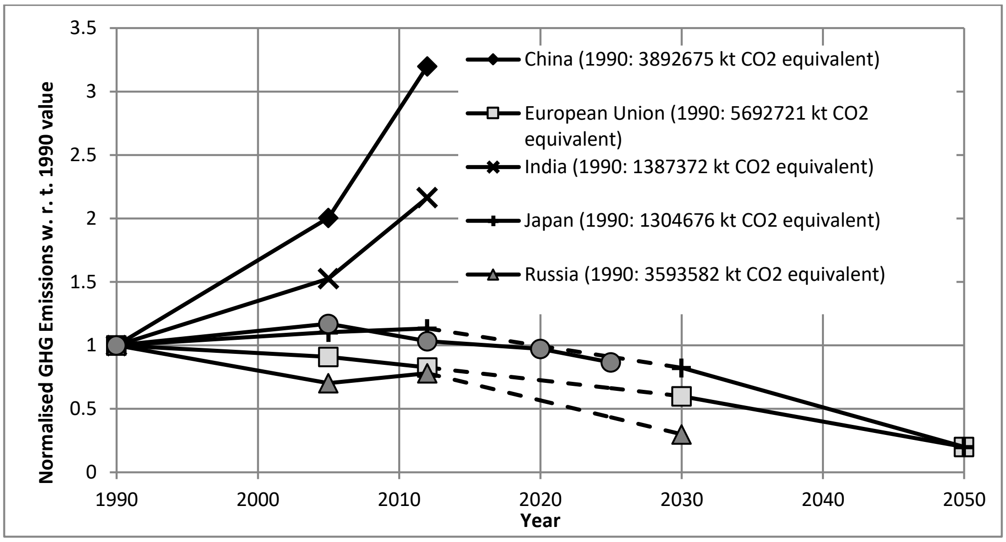


Figure 19: Historical trends and main GHG emissions targets for the six most emitting countries analysed

Chapter 3

Future energy and CO_2 outlooks

3.1 Scientific literature on long-term policies

In order to analyse the mid/long-term effects of targets and policies and, in particular, to quantitatively assess and compare the effectiveness of decarbonisation pathways, several forecasting scenario studies based on **energy and climate models** have been performed during last years, many of them related to the **European Union**.

Considering the scientific literature, among these studies, the one carried out by Capros et al. [36] can be firstly mentioned. It is based on evaluation of the needed modifications in the European energy systems configuration and of the related costs in order to achieve the decarbonisation targets defined in the EU Roadmap 2050. This analysis has been perfomerd by means of the use of seven energy and econometric models. The characteristics of these models have been deeply described by the authors in an ad hoc study [37]. Capros et al. [38] used the PRIMES energy system model [39] also to demonstrate that the 2050 European decarbonisation targets can be achieved without hypothesising new breakthrough technologies but simply through an improvement in the presently available technologies if significant modifications in the energy supply and demand are implemented. In particular, a relevant role for all decarbonisation strategies is the one played by electricity, produced by renewables and widely used in the final energy uses in place of fossil fuels, which is coupled to an increase in energy efficiency.

Considering the EU NDC, also Fragkos et al. [40] emphasised the importance of the electrification of the energy end-use (particularly in the transport sector) and of the energy efficiency in reaching the defined targets. The decarbonisation goals introduced by the Roadmap 2050 have been also analysed by Hübler et al. [41] through an econometric Computable General Equilibrium (CGE) approach; in particular, the authors underlined the need for deeply considering the interdependencies among policy design, sectoral policy effects and technological options, in order to achieve the planned targets. Böhringer et al. [42] instead studied the costs associated to the implementation of the EU climate policies, highlighting the need for a better definition of targets and strategies to be adopted for pursuing GHG emissions reduction, in order to assure the cost-effectiveness of the proposed policies and to avoid excess costs.

Referring to **non-European countries**, a lower number of studies is available. Among these, the ones carried out by Chen [43] and Chen et al. [44], Li et al. [45], can be mentioned. In particular, the last one focuses on the assessment of the impacts produced by decarbonisation pathways on the Chinese cement sector by using the bottom-up optimisation China TIMES [46] energy model. The results obtained by the authors show the importance of improving energy efficiency in the short/mid-term and in enhancing the penetration of alternative, non-fossil fuels in the long-term as more efficient policy options for achieving the proposed GHG emissions reduction targets.

Sakamoto et al. [47] used instead an econometric energy model for the assessment of the Japanese energy demand by 2030. The results show a reduction in CO_2 emissions related to the energy sector equal to 14.8% at the end of the analysed time horizon. This decrease is not sufficient according to the Japanese emissions reduction goals, and it is mainly due to the increase in energy intensity in the residential and in the commerce and services sectors. This study thus underlines the need for more effective policies.

The U.S. historically are characterised by a lack in unique clean-energy policy frameworks at Federal level. Despite this, during last decades several single states defined and introduced actions and measures aiming at decarbonising the power sector and at reducing GHG emissions. Among the studies devoted to the analysis of the effects of these policies, the one performed by Yi [48] can be mentioned. The author considered the historical data series for 48 states over the period 1990-2008, in order to assess the effects on the carbon intensity, on the total CO_2 emissions and on the electricity consumption. In particular, he suggested, according to the obtained results, the implementation of more aggressive strategies, able to effectively promote a high penetration rate of renewables in the power generation sector. At country scale, a study carried out by the U.S. Energy Information Administration (EIA) [49], based on the use of the National Energy Modeling System (NEMS), an economic model for long-term analyses [50], quantified instead the impacts of the Clean Power Plan.

3.2 The transition towards decarbonized energy systems

The above-mentioned **decarbonisation** strategies and pathways can be collocated in the more general framework of the so-called "**energy transition**", i.e. the mid/long-term evolution of the energy systems towards scenarios characterised by a relevant increase in the penetration of **renewables** sources (mainly hydro, wind, solar, geothermal, biomass and other less diffused alternatives like tidal).

Among decarbonisation options it could be included also the **nuclear** one. However, according to several definitions, nuclear can be considered “clean”, because it allows to reduce to zero the GHG emissions in the power generation, but not “green”, because it does not have a zero (or minimum) environmental impact, especially in the long-term. Furthermore, it is characterised by a very low social acceptability, mostly conditioned by the few accidents occurred during the last decades, as those of Chernobyl in 1986 and Fukushima in 2011. For this reason, the nuclear option is often not included in the strategical decarbonisation plants of many countries.

In order to implement this transition, various **strategies** can be defined and implemented. However, a common element to almost all of them is represented by the increase in the **energy efficiency** of the single end-use technologies (like, for instance, productive machineries for industry, heating and cooling technologies and electrical appliances for residential and commerce and services sectors, cars and trucks for passengers and goods mobility) and of buildings. The enhancement of efficiency, in fact, could ensure the fulfilment of the same services demands (as production, space heating and cooling, mobility) with a lower energy consumption. Moreover, the increase in the energy efficiency should ensure a significant decoupling between the economic growth and the energy consumption, according to the trend already observed in 2015 and 2016 at global level.

Three main **goals** – that has to be reached in the framework of the decarbonisation transition – should associated to the evolution of the energy systems:

- **Security**:

  Security can be defined as the possibility to ensure the amount of energy required for the fulfilment of the end-uses where it is needed and in accordance with the requested demand profiles. It is mainly related to the import of energy commodities trough energy corridors (like oil and gas pipelines, maritime routes, power lines) and to their transmission/distribution inside a country. Energy security is characterised by different dimensions:

  - Geopolitical:

    It is correlated to the political instabilities that can affect the energy supply

  - Technological/operational:

    It is correlated to events (like technical failures or particular system configurations) that can impact on the possibility to guarantee the quantities of energy needed for the satisfaction of the final uses.

- Market:

    It is correlated to competitive mechanisms and to the risks associated to market operations.

- Environmental:

    It is correlated to the effects that climatic changes can have on energy infrastructures.

- **Affordability**:

  Affordability is mostly related to the economic dimension and it can be defined as the possibility to acquire on the market (and at market prices) the amount of energy needed to fulfil the end-uses of consumers.

- **Sustainability**:

  Sustainability is related to the environmental dimension and it identifies the assurance that energy production, distribution and use are able to satisfy current and future needs without impacting on people's quality of life and on the future availability of fundamental resources, allowing, at the same time, economic efficiency and social equity.

These objectives are needed, as mentioned, in each decarbonisation strategy. However, according to the chosen pathway, they can be **convergent or conflicting** each other, i.e. the achievement of one of them can be coherent with the achievement of both the remaining two or, on the opposite, the achievement of one of them can lead to the impossibility to reach the other two. This fact can be explained with reference to one of the most relevant elements of the commonly proposed decarbonisation strategies: the enhancement of the renewables penetration.

Referring to the **convergence** among objective, the increase in renewables through the implementation of local micro-grids can determine benefits in terms of sustainability, as it allows the deployment of locally available resources and the consequent reduction in energy imports, thus enhancing energy security.

Considering instead the possible **conflicts**, the case of implementation of large electrical interconnections at trans-continental scale, in order to maximise the power generation from renewables by concentrating the electricity generation in the world areas characterised by the highest potential, can be cited. In fact, these super-grids are certainly beneficial from the environmental sustainability point of view, but can be affected by instabilities due to geopolitical reasons or by intentional threats, with a negative effect on the energy security. These threats can be both physical, with attacks to a given infrastructure (for instance, a strategical natural gas pipeline) able to compromise their operational state and the related energy flow, and cyber, with the intrusion into the informatics systems for the management of a certain infrastructure (like a power grid) in order to put in out of operation (causing, for instance, a large scale black-out).

Furthermore, a relevant increase in non-programmable renewables penetration (whose availability depends on climatic and meteorological conditions) could lead to instabilities of the electrical systems, due to the decrease in the system inertia and to the difficulty in balancing production and demand. This can thus determine an additional negative impact on the energy security (considered, in this case, not from the geopolitical point of view, but from the technical and operational one).

Finally, a high renewables penetration could also impact on the adequacy of the electrical grids, i.e. the capability of a system to cover the loads in normal conditions, with a suitable reserve margin, which is one of the key elements of energy security. In fact, particular climatic conditions (like solar eclipses, cloudy and sultry days, etc.) can significantly reduce the available capacity. This requires ad hoc countermeasures, as the availability of back-up plants feed by fossil fuels, demand-response strategies able to modify the load curves (thus acting on the demand side), or the implementation of storage systems.

These examples show the relevance of simultaneously considering the different objectives and their **interdependencies** when possible future energy transition scenarios are considered, for instance through analytic methodologies.

3.3 Comparison of future scenarios under the energy transition perspective

As previously said, the energy transition towards decarbonised energy systems requires an increasing contribution from renewables for satisfying the final energy demands. According to this, several possible pathways can be hypothesised and implemented. Among them, **two extreme solutions** can be identified and analysed. These two approaches could be probably coexist in the future configuration of energy systems, with a proper mix of the two.

3.3.1 Electrification and global interconnections

One of these two extreme options is represented by a wide **electrification of final uses**, coupled with **power generation from renewables** (up to 100%) and long-distance transmission through global interconnections.

Considering, in particular, the energy **end uses**, it can be observed that industry, residential and transport sectors were responsible together for about 78% of the global CO_2 emissions in 2014, if the emissions related to electricity and heat production are allocated to the consuming sectors proportionally to the amount of electricity and heat consumed by each sector. If the power and heat generation is instead assumed as a single sector (independent from the others), it can be noticed that, in 2014, it was responsible for 42.1% of the overall CO_2 emissions, followed by transport (23.3%), industry (9.6%) and residential (5.7%) sectors [51].

Considering the technological mix for the single end-use sectors (i.e. the set of technologies that are used in these sectors to satisfy the services demands), it can be put into evidence that the transition towards decarbonisation requests different strategies and policies and, in particular, the enhancement of the penetration of different technologies.

Referring to the **industrial sector**, the large scale electrification of the productive processes is an option still relatively unexplored but which could be potentially feasible from a technical point of view in the next decades. Among the studies available in the scientific literature and related to this topic, the one carried out by Lechtenböhmer et al. [52] can be mentioned. The authors analysed, through "what if" scenarios and over a long-term time horizon (i.e. up to 2050), the applicability and the impacts of electrification option with reference to energy intensive industries that produce basic materials. They focused on the European Union and, in particular, on some of the most consuming industrial subsectors, as the iron and steel, chemical (which includes the production of chlorine, ammonia and petrochemical products) and non-metallic minerals (which includes the production of glass, cement and lime) ones. For each of these subsectors, they assumed the complete electrification by means of the introduction and the implementation of ad hoc technologies and processes. For instance, among them the use of high temperature electro-thermal processes for non-minerals production, the adoption of electrowinning in the steel production, the Haber-Bosch process with hydrogen from water electrolysis for the ammonia production and the use, in petrochemicals production, of synthetic gases obtained by means of electricity from renewables can be cited.

In the **residential sector** the shift from an energy consumption based on fossil fuels to one based on electricity is relatively simple with respect to other sectors (as industry, above described). This is due to the fact that the available technologies can already allow this modification in the end-use energy mix, in particular in developed countries. Considering the main services demands of this sector – i.e. space heating and cooling, water heating, cooking, lighting and use of electrical appliances [53] – it can be observed that some of them are almost fully electrified (namely space cooling, lighting and use of electrical appliances). Furthermore, the remaining ones can be satisfied, even nowadays, by technologies fed by electricity, like electrical heat pumps for space heating and cooling, electric stoves for space heating, electric boilers for water heating, electric hot plates, electric ovens, radiant and inductive cooktops for cooking. Due to this reason, ad hoc policies and measures (as subsidies) for supporting the penetration of these technologies coupled to a decrease in the electricity costs for final users could lead to a significant increase of electrification in the sector, even in a short time period. The same considerations can be applied to the commerce and services sector, whose services demands are the same of the residential one.

Considering the **transport sector**, it can be highlighted that it is historically almost totally relying on fossil fuels, especially regarding the road transport of passengers and goods, which accounted for 73.5% of the CO_2 emissions of the transport sector at global level in 2014 [51]. Nevertheless, during last years it progressively moved along a decarbonisation pathways based not only on alternative fuels like biofuels – both traditional and advanced, as those obtained from algae and wastes, which do not compete with food crops (as set, for instance, by the EU Directive 2015/1513 [54]), but also on electricity. In the European Union, for instance, the use of electricity for the fulfilment of passengers mobility demand is expected to significantly contribute to the achievement of the CO_2 emission target of 95 g/km for the new car fleet [55], [56]. Several technological options has been explored by car makers in the last years: among them, a specific attention has been devoted to the development of electric vehicles, i.e. Battery Electric Vehicles (BEVs) and Plug-in Hybrid-Electric Vehicles (PHEVs). Both these options can relevantly contribute to lower the carbon emissions. However, in a decarbonisation pathway aiming at maximise the electrification, BEVs could be, in particular, considered the best choice. Their diffusion can be supported by the expected simultaneous reduction in battery costs and enhancement of battery performances (i.e. the increase in energy density, which allows to cover longer distances, which in some cases are already higher than 300 km) that can be already observed analysing the trends of the last years [57]. Focusing on the battery cost, several forecasting studies have been carried out to estimate the possible price evolution over the next decade. The majority of them hypothesise a significant reduction, leading to values of about 100-120 $/kWh by 2030, starting from the 2017 average cost of 209 $/kWh for Lithium-ion batteries and following the decreasing trend observed during last years [58]. These studies usually set the cost threshold to make electric vehicles competitive with respect to the internal combustion engine vehicles at 150 $/kWh [57], [59], [60]. The current focus is mainly on the electrification of passenger mobility, but projects for electric trucks, for satisfying the mobility demand of goods, have been recently proposed, given the increase in batteries performance.

As previously said, one of the options to reach this wide electrification of the end-uses is to implement an “extreme” paradigm based on the so-called **global interconnection**. The global energy interconnection is based on Ultra High Voltage (UHV) transmission technologies, mainly Direct Current (DC), aiming at building a backbone system for redistributing over large areas electricity produced from renewable sources. In particular, the main productive areas could be the Artic region for wind and the deserts in the Equatorial area for solar. These areas should then be connected to the large world consumption areas or countries (as the European Union, the U.S., Asian countries like China, etc.) through the above mentioned UHV-DC super-grid.

The starting point of this system is thus represented by the electricity generation from renewables, in particular wind and solar, whose theoretical availability is largely sufficient to cover present and future energy demands. In order to evaluate the technical and economic **potential** of these sources, various studies (using different methodological approaches and tools) have been carried out [61]. Their comparative analysis shows that different results have been obtained, according to the main assumptions and to different level of detail of the models that have been used.

For instance, Moriarty et al. [62] reported a global potential of 3900000 EJ/y for solar, 28400 EJ/y for wind, 3000 EJ/y for biomass, 1300 EJ/y for geothermal, 700 EJ/y for ocean and 130÷160 EJ/y for hydro. The authors also compared the numerical results obtained by different studies related to the quantification of the renewables technical potential available in the scientific literature, highlighting in turn the significant differences among them, which are equal even to two or more orders of magnitude.

However, the relevance of these studies is the demonstration that the theoretical potentials, anyway calculated, are significantly higher than the amount of energy requested to fulfil the global annual demand, taking into account that the Total Primary Energy Supply (TPES) at global level in 2014 has been equal to 573.6 EJ [5], i.e. to 159320.8 TWh.

The global interconnection option for the energy transition can be collocated inside the concept of **“electricity triangle”** (Figure 20).

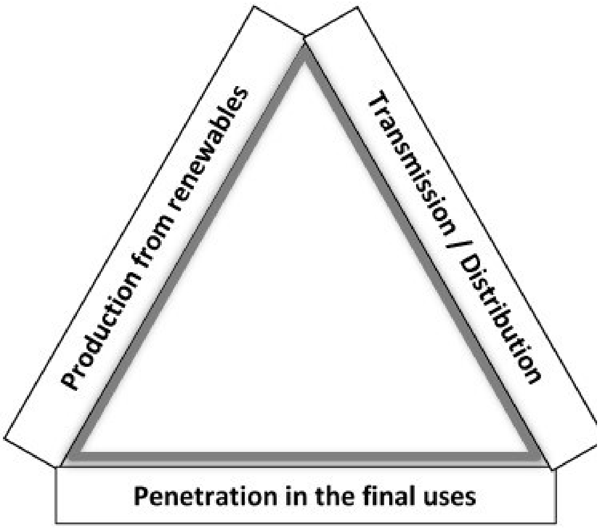


Figure 20: The “electricity triangle” in the framework of the energy transition

This triangle is characterised by three elements:

- Electricity generation from renewable energy sources (mainly wind and solar at large scale), avoiding thermoelectric production.
- Transmission and distribution of energy by means of the electricity vector, i.e. with power lines intended to become the most relevant energy infrastructures with respect to other “more traditional” ones, like oil and gas pipelines and marine routes, rails and roads.

- Strong increase in the electrification of final uses, according to what previously described.

As a consequence, the global interconnection can be considered the vertex between production from renewables and transmission / distribution of energy.

Among renewable sources, wind and solar shown the highest increase in penetration during last years.

The annual installed capacity for **wind** grew from 3.7 GW in 2000 to 63.5 GW in 2015; in the same year the global cumulative installed capacity reached 432 GW, i.e. about 25 times the value in 2000 (17 GW) [63]. In addition, the capacity of the single units increased over time: for instance, referring to off-shore plants, it passes from 0.5÷1 MW in 2000 to 8 MW in 2014 [3]. The enhancement in the performances of wind plants has been supported by the implementation of advanced control techniques of the blades, including variable-speed constant-frequency and variable-speed variable-pitch turbines controllers. Nevertheless, since the large deployment of wind source in the global interconnection perspective should mainly involve the Arctic region, further technological improvements are expected, especially regarding insulation techniques, automatic unfreezing of blades and development of materials able to resist in extremely cold climatic conditions.

Referring instead to **solar**, the global annual installed capacity of photovoltaic plants reached 40 GW in 2014, while in the same year the cumulative installed capacity was equal to 178 GW. From the technological point of view, also the photovoltaic plants experienced a significant evolution during last years. For instance, considering the adopted materials, the conversion efficiency of the thin film solar cells (like the Gallium Arsenide – GaAs – ones) achieved a value of 28.8% efficiency, with an annual growth rate of 1÷1.5%, while the conversion efficiency of crystalline silicon cells reached a value equal to 26.3%, with an annual growth rate of about 0.5% [64]. Furthermore, also the solar tracking systems improved along time. For instance, the single axis tracking system can currently reach 30÷40% higher power gain from the radiation, while the double axis tracking allows efficiency values up to 80% higher with respect to fixed panels [65].

Finally, considering the **transmission grid**, the ultra-high voltage transmission lines can be developed according to two different technical options, i.e. alternate current (HVAC) or direct current HVDC), whose main technological and economic characteristics are compared in Table 3.

Table 3: Comparison of different UHV transmission technologies [3]

UHV Transmission technologies	Technical-economic characteristics				
	Transmission capacity (GW)	**Economic transmission distance (km)**	**Loss (%/km)**	**Footprint overhead line (m/MW)**	**Costs (€/MW·km)**
500kV AC (double-circuit)	2-2.4	250-800	0.46-0.69	0.029-0.035	280
1000kV AC (double-circuit)	8-9	500-2000	0.17-0.21	0.008-0.009	194.5
±500kV DC	3	800	0.28	0.013	137.6
±800kV DC	8-10	1100-2500	0.19	0.01	95.4
±1000kV DC	8-12	2300-5000	0.09	0.007	90.8

According to the previously listed characteristics, it can be noticed that for large-scale interconnections, like those hypothesised in the global interconnection vision – ranging between 2000 km and 5000 km – the UHV-DC at ±800kV or ±1000kV seems to represent the best option.

The approximated distances among the main world areas for electricity production from renewables and the main global consumption areas, the related capacities of the possible UHV-DC connections are shown in Figure 21. Furthermore, the same Figure reports a possible configuration of the generation systems, with the annual production and installed capacity under the assumption that the generation factors for wind and solar are about 30% (for the U.S. they were equal respectively to 34.7% and 27.2% in 2016 [66]).

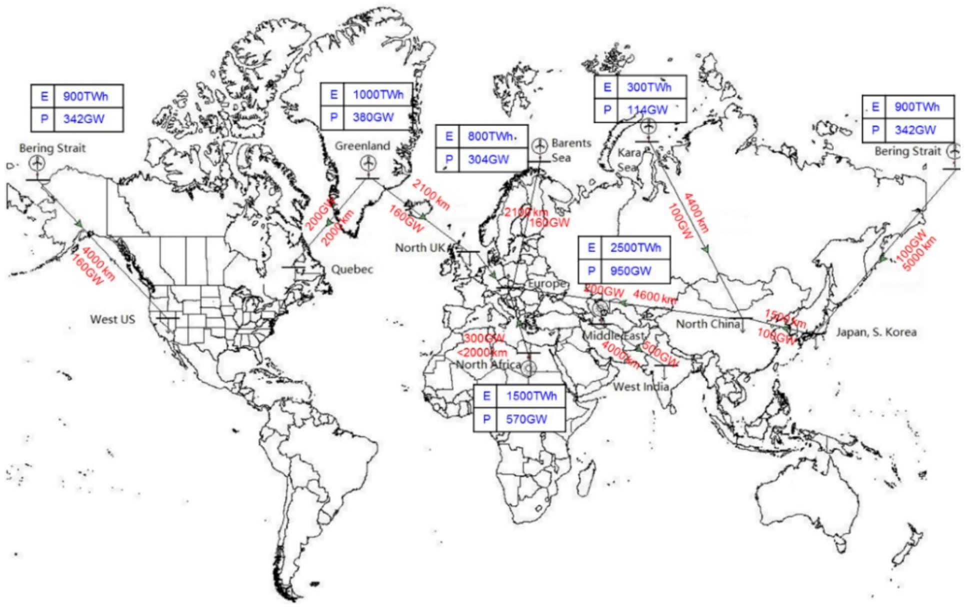


Figure 21: Distance between production and consumption areas and related possible configuration of the generation and transmission system in terms of electricity produce and installed capacity

Considering the intensity of energy fluxes to be transmitted by means of these interconnections over long distances, the global interconnection requires the adoption of effective control systems – including voltage and frequency stability controls, implementation of synthetic inertia, automatic recovery, localisation and fast recovery after failures – coupled with advanced Wide Area Monitoring Systems (WAMS). WAMS, in particular, are large-scale monitoring technologies based on the measurement systems called Phasor Measurement Unit (PMU), which in turn use GPS signals to synchronise the measures of voltage and current phasors in different most relevant nodes of the grid, thus allowing a more efficient control of the grid itself.

The implementation of the global interconnection strategy can be considered an extreme but theoretically feasible solution in the framework of the energy transition. However, it has to be underlined that – even if the feasibility from a purely technical point of view could be ensured – several non-negligible **issues** subsist from other perspectives that has to be considered if a practical implementation of this option is decided.

- Financial issues:

  Because of relevant investments are needed in order to implement the global interconnection, it has to be firstly defined how them should be divided among the involved countries. In fact, for instance, they could be in charge of the single local governments or to be covered by international bodies and institutions, like the European Union or the World Bank. Furthermore, they could be divided proportionally to the length of the branch for each crossed country or to equally distributed among the countries that receive benefits from the global interconnection option.

- Market issues:

  Currently a large variety of electricity market schemes exists at global level. These markets are commonly national or regional markets, governed by specific (and different) regulations and policies, and should be harmonised in order to make this option really feasible and constitute a single world market. Moreover, since global interconnections are totally based on renewables, an essentially zero marginal cost configuration can be hypothesised and new market clearing mechanisms should be identified.

- Social issues:

  The change in paradigm from fossil to renewables can lead to a modification in the global wealth distribution, from countries characterised by a high availability of fossil resources to countries having a high renewables potential. Furthermore, based on the global interconnection scheme, a different access to energy can be hypothesised, especially for countries that currently suffers energy poverty. This will require, however, strong investments in distribution infrastructures, in particular in areas that presently have not access to electricity and that have not large financial possibilities.

- Geopolitical issues:

  The implementation of the global interconnection option could determine relevant impacts also from the political point of view at world scale, due to the fact that a common governance of this global system is needed. As a consequence, it should be necessary to define if this governance has to be hierarchical or horizontal, and if the control sovereignty has to be proportional to the investments, to the geographic size of each country or to the level of involvement of each country in the global network coverage.

3.3.2 **Small local systems and microgrids**

The second extreme option for the implementation of the energy transition is represented by the definition of **small scale** energy systems based on electricity, heat and gas produced by **renewables** sources. These systems are fully based on renewables (up to 100%) and – as in the global interconnection option – are characterised by power generation from wind, solar photovoltaic and small hydro. A relevant role is played by **storage** systems, including pumped hydroelectric storage, batteries and power-to-gas systems.

These systems are local or regional grids. A good representation of them is proposed by Kötter et al. [4], which focused on the definition of an optimisation model simulating the implementation of a small local energy system – fully based on renewables – in a German region, coherently with the so-called "Energiewende" policy strategy. In such a system, a special attention has been devoted to the storage options and, in particular, to the Power-to-Gas technology. The authors used the P2IONEER [67], an energy flow simulator characterised by a time resolution equal to 15 minutes, to perform a scenario analysis over a mid-term time horizon (up to 2030) and considering a penetration of renewable sources reaching 100% at the end of the assumed time period. Even if specifically developed for a specific case study, this modelling approach can be generalised and assumed as a paradigm of the small renewables-based energy systems described in this section.

The overall reference energy system scheme of this approach is summarised in Figure 22.

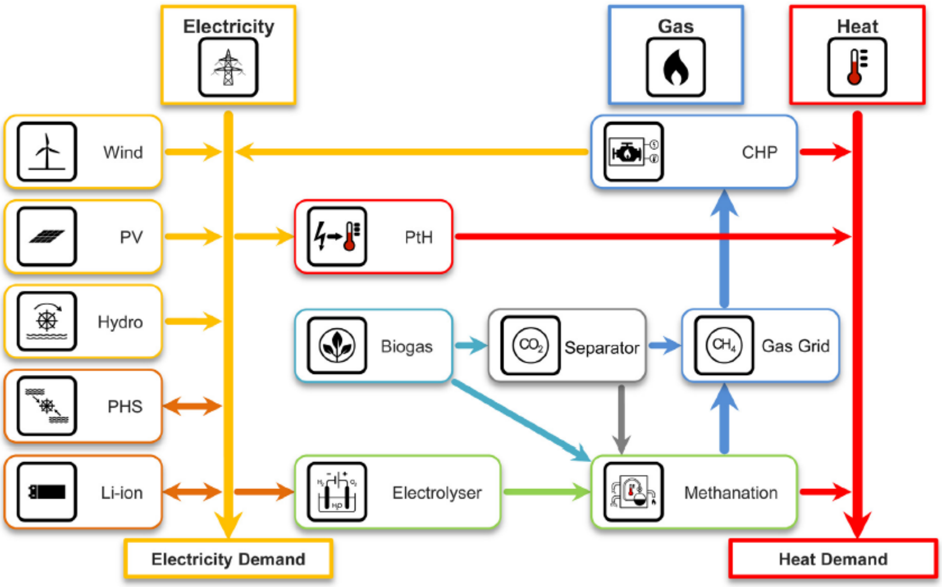


Figure 22: General reference energy system scheme for the hypothesised modelling of small-scale local/regional systems **[4]**

This scheme relies on three main energy commodities:

- electricity
- gas
- heat.

Electricity is supposed to be produced by three main renewable sources (wind, solar and hydro) and by Combined Heat and Power (CHP) plants.

Furthermore, two options for storing it are considered:

- Pumped Hydroelectric Storage (PHS) and
- Lithium-ion (Li-ion) batteries.

In the **PHS** systems water is moved between two reservoirs at different level. When a surplus of electricity is available, water is pumped to the higher reservoir and thus energy is stored as potential energy. When additional electricity is requested, the water is moved back from the higher to the lower reservoir through a turbine, thus producing electricity.

The **Li-ion batteries** are instead assumed as a representative form of the electrochemical storage. In these batteries, positive Lithium ions flow from the negative electrode (anode, which is generally made by graphite or by Lithium titanate) to the positive electrode (cathode, which can be made, for instance, by phosphates or lithiated metal oxides) through the electrolyte (which allows the ions movement and that is commonly liquid and made by lithium salts – like $LiPF_6$ or $LiBF_4$ – in an organic solvent, like ethylene carbonate) in the case of discharge. The Lithium ions flow instead in the opposite direction (from the cathode to the anode) in the case of charge, when an over-voltage is applied, and they are stored in the porous structure of the negative electrode in a higher energy state, thus allowing the energy storage.

The available electricity is used not only to satisfy the demand of the considered region/area, but it is also used as commodity input to other elements of the energy system, namely the

- power-to-gas system and
- power-to-heat processes.

Power-to-gas allows to produce synthetic natural gas through the adoption of electrolysis and methanation processes, starting from the excess of electricity produced. In particular, the electrolysis of water – which can be carried out by means of different technological solutions, like polymer electrolyte membranes (PEM), solid oxide electrolysis (SOEC) and alkaline electrolysis (AEL) [68] – let firstly to produce hydrogen. The next step is represented by methanation, which can be performed though different kinds of reactors (catalytic or biological) and which allows to use the produced hydrogen from electrolysis and the CO_2 from a CO_2 separation process from biogas. The exothermic reaction among them leads to the generation of synthetic methane (CH_4), H_2O and heat.

$$4\,H_2(g) + CO_2(g) \rightleftharpoons CH_4(g) + 2\,H_2O(g) \tag{1}$$

The produced CH_4 can be then fed into the existing gas network, thus representing a form of energy storage for the analysed energy system.

Furthermore, also the biogas can be converted into synthetic natural gas by means of the above mentioned separation process (which separates CH_4 from CO_2) or of the methanation. The produced gas can be in turn feed in the grid, as the one produced starting from electricity.

The third commodity considered in this general scheme, i.e. heat, can be produced in three different ways. The first one is the previously described methanation process, in which heat represents a secondary output (together with water, which is a reaction product). Referring to this point, it has to be highlighted that biological methanation has a lower capability of waste heat utilisation with respect to catalytic methnantion, due to its low temperature (which is below 70 °C) [68]. The second one is through the CHP plants. The last on is instead constituted by the **power-to-heat** process, according to which a part of the possible electricity overproduction that cannot be consumed or directly stored can be converted into thermal energy, usable to cover a portion of the heat demand of the region.

The potential feasibility of these integrated small-scale renewables-based solutions has been analysed in different studies available in the scientific literature. Among them, the already cited one carried out by Kötter et al. performed an optimisation modelling exercise applied to a German region. The authors demonstrated that the development of an energy system fully based on renewables is possible both including or not the power-to-gas option in the technological mix. Nevertheless, the power-to-gas system allows, in the long term, to reduce the levelised cost of electricity (LCOE) of the energy system; in particular, they showed a correlation among the capital expenditure in power-to-gas systems, the installed capacity and the obtained LCOE.

Moeller et al. [69] analysed instead feasibility and affordability of high renewables penetration rates in the power generation system of the Berlin-Brandenburg region. However, they pointed out that the increase in renewables is not the only element to be considered in an effective transformation strategy of the energy system. A significant role is played, in fact, by the storage systems: among them, methanation can show interesting perspectives.

Among the technical options, Götz et al. explored in particular the power-to-gas one. They underlined the relevant role that this solution for storing the electrical energy from renewables can play, but also put into evidence the need for overcoming some economic and technical issues in order to enhance its effective penetration in future small-scale energy systems. Among them, the authors mentioned several key aspects related to the single elements of the process. Referring to the electrolysis, they highlighted the need for improving the process and for reducing its cost; they also identified the alkaline option as the one currently most reliable and economically feasible, exploring however the potential for the SOEC and PEM solutions. Regarding the catalytic methanation, they showed that this process is characterised by a higher efficiency with respect to the biological one and it needs smaller reactors to handle the same gas flows. In general, the possibility to use the heat obtained from methanation allows to enhance the overall efficiency of the power-to-gas system.

To conclude, it is possible to underline that a microgrid is a locally controlled distinct miniature energy system, able to operate in parallel with or isolated from the main network in order to ensure affordable, reliable and secure energy. Because of the proximity to the loads, a microgrid does not have a transmission layer and allows to exploit distributed and locally available energy sources, including renewable resources, distributed storage systems, demand response, etc. Moreover, it gives the opportunity of integrating small-size generators, which usually cannot be easily connected to the traditional power systems, like small hydro, on-roof PV, micro-wind turbines and diesel CHP. The possibility of being operated in an isolated and autonomous mode makes microgrids more flexible, especially during emergency situations, as they allow to avoid that the failure will propagate to other grids, thus limiting its impacts.

3.4 The global interconnection option: a scenario comparison

With respect to the two extreme alternatives described in the previous sections, in this thesis, a specific analysis of the global interconnection option has been carried out. In particular, this configuration has been analysed in a scenario perspective, comparing it with the main outcomes of other scenarios available in the scientific literature.

3.4.1 Reference energy attributes for driving the energy transition

In general, in order to comparatively assess the effects of different visions and policy actions aiming at promoting low-carbon pathways, a multilayer approach can be adopted (as made by Han et al. [70] for evaluating the impact of smart energy policies on the energy systems). This approach is based on the analysis of the impact of specific energy attributes on different stages of the energy chain and on other non-energy domains (hereafter called *layers*).

In particular, four **attributes** can be considered:

- economic affordability,
- energy security,
- environmental sustainability and
- energy efficiency.

They are related to the goals to be achieved in the decarbonisation framework, described in the previous section, and are able to capture the most relevant dimensions and effects of decarbonisation itself; they can thus be assumed as drivers for the energy transition.

Figure 23 shows, in a conceptual way, the interaction between this four attributes, the energy chain (which, in turn, includes the production and import of primary commodities, the transformation in secondary commodities, the distribution and the end-use) and the three main layers that can be considered, i.e. the economic, environmental and geopolitical ones.

In fact, the effects of these attributes spread not only over the macro-sectors of the energy system, but also involves different **domains**. In particular, the environment is influenced by sustainability policies and by the implementation of energy efficiency improving measures (due to the above mentioned reduction in energy consumption for satisfying the same demand). The economy is affected by the affordability (due to the effects that taxation and subsidies could have on the energy bill and, more generally, on the economic system), by the energy security (as the loss of a given supply has a negative impact on the GDP of a country) and by the energy efficiency improvements (because of the reduction in the total energy system costs). The geopolitical layer is obviously related to the security of supply issues.

Referring to the main four sections of the energy chain,

- the affordability impacts on all of them, as the economic aspects involves every aspect, from production to final uses of energy;
- the sustainability is widely related to the availability of resources, thus involving both local production and import of energy commodities;

- the security mainly affects the energy imports, but also their internal distribution, due to the fact that the related infrastructures could be subject to malicious attacks or natural hazards;
- the energy efficiency mostly concerns the final uses, because it is mainly associated to the improvements in end-use technologies (like heating and cooling systems and electrical appliances in the residential and service sectors, vehicles for mobility of passengers and goods, industrial equipment, etc.).

All these interactions do not cover the entire spectrum, but can be considered representative of the most relevant effects that decarbonisation strategies could determine. For this reason, they are useful in comparing different future options and scenarios, in particular the one based on fully electrification of energy final uses through global interconnections and other more traditional ones.

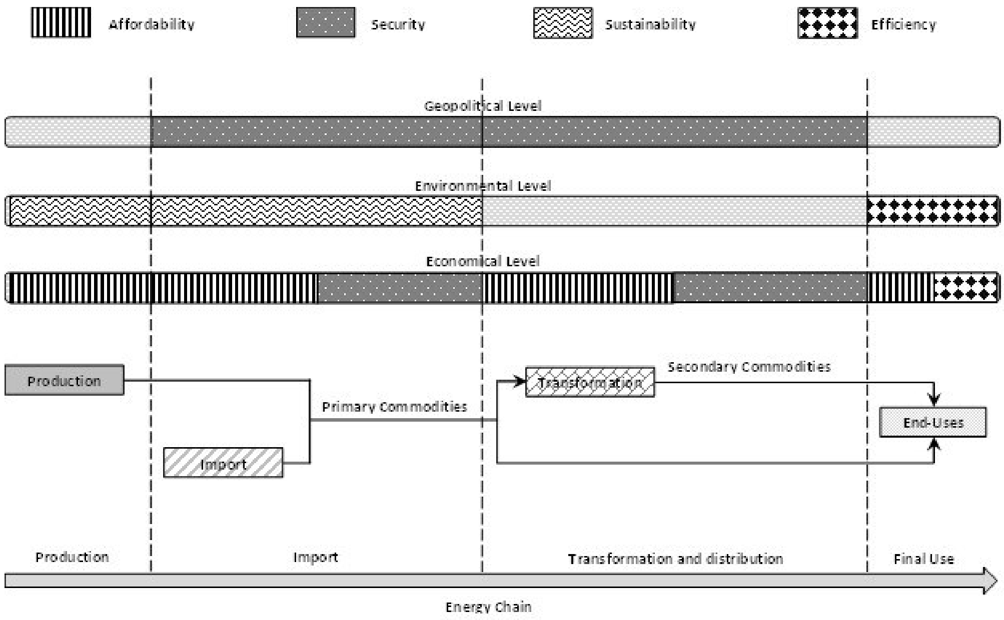


Figure 23: Scheme of the interaction among the energy attributes, the different sections of the energy chain and the three main layers

For quantitatively assessing the attributes, ad hoc metrics and **indicators** have to be chosen and estimated.

The main **criteria** adopted for selecting the indicators for the choice have been the following:

- The indicators have to be quantitative
- The indicators have to be commonly calculated and used in the scenario analyses available in the international scientific literature

According to the above-mentioned criteria, **five metrics** have been considered, each of them affecting one or more attributes:

- Primary energy intensity (I_p):

  It is the ratio between the total primary energy supply (*TPES*, defined as *S* in the following relationships) and the *GDP* (*G*) and it impacts on affordability, sustainability and energy efficiency:

$$I_p = \frac{S}{G} \qquad [\mathrm{Mtoe/T\$}] \tag{2}$$

- Final energy intensity (I_f):

  It is the ratio between the final energy consumption (*F*) and the *GDP* (*G*) and it impacts on affordability, sustainability and energy efficiency:

$$I_f = \frac{F}{G} \qquad [\mathrm{Mtoe/T\$}] \tag{3}$$

- Final energy consumption per capita (F_{pc}):

  It is the ratio between the final energy consumption and the population *P* and it impacts on sustainability and energy efficiency

$$F_{pc} = \frac{F}{P} \qquad [\mathrm{Mtoe/MPersons}] \tag{4}$$

- Emissions per unit of energy consumed (*E*):

  It is the ratio between the CO_2 emissions (*C*) and the *TPES* (*S*) and it impacts on sustainability

$$E = \frac{C}{S} \qquad [\mathrm{Mt\ CO_2/Mtoe}] \tag{5}$$

- Ratio of renewables (*R*):

  It is the ratio between the gross inland consumption from renewables I_r and the *TPES* and it impacts on sustainability and security

$$R = \frac{I_r}{S} \qquad [\mathrm{Mtoe/Mtoe}] \tag{6}$$

Considering the relationship among the single parameters and the five metrics, the **energy intensities** (primary and final) I_p and I_f can be assumed representative of the energy efficiency. In fact, they link technological and economic perspectives, as a reduction in the amount of energy needed to produce a unit of GDP corresponds to a more efficient use of energy in the system, i.e. to the adoption of technologies characterised by a higher efficiency, coherently with policy strategies for the transition towards decarbonised (or at least low-carbon) energy systems.

Furthermore, energy intensities can be used as an indicator of the sustainability. This is due to the fact that, in a context of economic growth, a decrease in energy intensity corresponds to a reduction in energy consumption, which in turn corresponds to a lower environmental impact. The decoupling between the energy consumption and the economic growth can be considered a driver for decarbonisation and, to some extent, an indirect measure of economic affordability. In fact, if an economic system is able to produce the same amount of GDP by using a lower amount of energy (or, vice versa, it is able to increase its GDP without proportionally increasing the consumption of energy), this means that it is able to implement policies that are sustainable from the economic point of view and that end-users can bear. Regarding the decoupling, it has to be highlighted that non-unique consideration have been expressed in the studies available in the scientific literature. For example, the one performed by Jakob et al. [71] put into evidence the need for this decoupling, especially for developing countries, in order to achieve effective future decarbonisation. Instead, Csereklyei et al. [72] pointed out that forecasting scenarios should not hypothesise an increase in the GDP and a simultaneous decrease in energy consumption, and they should avoid to suppose that the decoupling between economy and energy will certainly happen. In particular, the authors stated that the energy intensity reduction in certain countries (like the U.S.) is probably due to an effect of convergence towards a global average value and so they could be difficultly repeated during next years or decades. Finally, Fiorito [73] focused on the usefulness limits of energy intensity as indicator to analyse decoupling phenomena, suggesting to deepen the description and characterisation of the economic systems without trying to aggregate information that refers to different domains (i.e. the energy and economic ones). It has to be further underlined that the final energy intensity only takes into account the consumption in end-use sectors and it does not consider the consumption and losses in the transformation sector, which are mainly related to the power generation. The comparison among the two energy intensities is interesting because it could be representative of the electrification level of the system and of the quality of this electrification. In fact, in the mid-long term and in presence of economic growth and efficiency improvements, an increase in the electrification (as the one expected with the implementation of the global interconnection scenario) generally leads to a decrease in the primary energy intensity I_p lower than the reduction in the final energy intensity I_f. This is due to the fact that the final energy intensity does not take into account the transformation losses (which are instead computed by the primary energy intensity), whose overall amount – in the case of traditional power generation mixes – usually increases with higher electrification rates. However, a high penetration of renewables (that – excluding biomass – are assumed to have no conversion losses in energy balances) in the power generation mix leads to a reduction rate of the primary energy intensity closer to the one of the final energy intensity.

As for the energy intensities, the **final energy consumption per capita** F_{pc} can be used for quantifying the evolution of the environmental sustainability and of the energy efficiency, because a reduction in this value corresponds to a lower use of energy for satisfying final uses. In particular, with respect to the energy intensities, the final energy consumption per capita is useful in better identifying the contribution of households. In fact, it has to be observed – according to the EEA [74] – that for industry, transport and services sectors the sectorial energy intensities are evaluated by dividing the sectoral final energy consumption by the GDP (for transport) or by the Gross Value Added (GVA; for industry and services). For the residential sector, instead, the energy intensity is calculated by dividing the household final energy consumption by the population.

The **emissions per unit of energy consumed** E can be used for measuring the sustainability, directly considering the pollutant emission content of the single unit of energy consumed. This indicator also reflects the composition of the energy mix, because higher penetration rates of renewables lead to lower values of the indicator itself.

Finally, the **ratio of renewables** R can be considered an indirect metric for evaluating the energy security, as an increase in its value corresponds to a reduction in the global trades of fossil fuels (which can be significantly affected by the international geopolitical tensions and crises), thus enhancing the level of the security of supply. Import dependency has instead not been considered as an indicator. In fact, it (together with the route of energy corridors and the mix of suppliers) is a relevant parameter for evaluating the energy security of a single country but it is not so significant and useful when both exporting countries (i.e. producers) and importing countries (i.e. consumers) are jointly considered in an overall world energy balance.

All the described parameters for the quantification of energy attributes have been quantitatively evaluated and compared for different forecasting energy scenarios, including the global interconnection one.

3.4.2 Comparative assessment of the global interconnection option

In order to comparatively analyse the possible impacts of the global electricity interconnection option on the future world energy system and the role that this scenario could play in the energy transition towards decarbonised systems, the forecasting **scenario analysis** to 2050 proposed by Liu [3] has been considered and compared to other scenarios available in the scientific literature.

Several studies, mostly based on models for energy planning, have been performed during last decades. Among them, the following can be mentioned:

- IEA World Energy Outlook [75]:
  It analyses three main scenarios:

  - Current Policy Scenario:
    It includes only policies and measures – related to the energy systems and, in particular, to the end-use sectors – that have been officially implemented until the mid of 2016. For this reason, this scenario does not include relevant future policies that have been already discussed at international level but that have been not yet formally implemented, like Nationally Determined Contributions (NDCs) to the Paris Agreement.

  - New Policy Scenario:
    It includes all the policies considered in the Current Policy Scenario, but also other measures that have been planned or discussed. Among them, a relevant role is played by the environmental policies, in particular the implementation of the NDCs pledged under the Paris Agreement in 2015. The hypotheses made by the authors regarding the time horizon of these possible future policies have been usually chosen according to a cautious perspective, in order to simulate the entire complex implementation process, which in turn depends on the political, social and economic conditions.

  - 450 Scenario:
    It includes all the policies considered in the New Policy scenario, plus a strong environmental focus on decarbonisation strategies. In particular, the simulated policies are designed in order to allow the limitation of the average global temperature rise by the end of this century to 2 °C above the pre-industrial levels. It has to be underlined that this goal is already included in the Paris Agreement targets (in which it is also highlighted that all the efforts have to be pursued in order to keep the temperature increase below 1.5 ºC, for effectively reducing the impact of climate changes). For this reason, it should be already embedded in the New Policy Scenario. However, the forecasting results obtained from the New Policy Scenario put into evidence that the pledged GHG emissions reduction is not sufficient to ensure the achievement of this long-term goal, thus requiring further policy actions.

- World Energy Scenarios of the World Energy Council [76]:
  It analyses three main scenarios:

  - Modern Jazz scenario:
    It is compliant with a low-carbon strategy and it is mainly driven by a competitive market perspective.

  - Unfinished Symphony scenario:
    Like the Modern Jazz scenario is focused on decarbonisation pathways but it is mostly devoted to the implementation of environmental policies driven by government actions.

  - Hard Rock scenario:
    It describes a world mainly based on a nationalistic approach to global challenges and paying a lower attention to climate change issues. It thus results still strongly relying on fossil fuels even in the future.

- EIA International Energy Outlook [77]:
  It presents five scenarios:

  - Reference case:
    It takes into account the situation of the world oil market up to the end of 2015 and it hypothesises an increase in oil prices by 2018.

  - High Economic Growth case:
    It assumes a higher economic development with respect to the Reference case.

  - Low Economic Growth case:
    It considers a lower economic increase with respect to the Reference case.

  - High Oil Price case:
    It hypothesises higher oil prices with respect to the Reference case.

  - Low Oil Price case:
    It assumes lower oil prices with respect to the Reference case.

- Shell Energy Scenarios to 2050 [78], [79]:
  It considers two scenarios:

  - Scramble scenario:
    Is suppose that the environmental issues will be deeply considered by policy makers only in the case of relevant climate effects.

  - Blueprints scenario:
    It is mainly focused on the clean energy penetration and on measures able to address not only the environmental but also the security and economic issues.

- MIT Food, Water, Energy & Climate Outlook [80]:

  It provides projections up to 2050, assuming emissions scenarios coherent with the achievement in 2030 (and the following keeping) of the targets defined in the framework of the Paris Agreement.

- BP Energy Outlook [81]:

  It provides projections up to 2035, assuming a most reasonable pathway, which takes into account a simultaneous increase in the energy consumption and the reduction in the carbon content of the energy systems.

- ExxonMobil Outlook for Energy [82]:

  It define forecasting trends up to 2040, taking into account the expected increase in energy demand and the change in the energy mix, driven by the increase in the electrification of the final uses and by the environmental policies to counteract climate change phenomena.

In order to perform the comparison among international scenarios and the global interconnection perspective, some of the above-mentioned studies have been selected. The main criteria adopted are the following:

- The completeness of information, i.e. the amount of available projected data, which has to be sufficient for allowing an evaluation of the indicators chosen to numerically evaluate the energy attributes.
- Wider time horizons have been preferred, avoiding those ending before 2040.

Table 4 summarises, in a qualitative way and from a synoptic perspective, the main **hypotheses** that are at the basis of the considered scenarios.

These hypotheses are subdivided according to four domains related to the layers previously described (i.e. the geopolitical, the economic and the environmental layers plus the energy chain):

- socio-political,
- economic,
- environmental and
- energy.

It has to be observed that many of these hypotheses do not affect only the domain most directly related to each of them, but could spread over several of them. Furthermore, in the Table, the end of time horizon (EOH) for the whole set of considered scenarios has been put into evidence.

Table 4: Main hypotheses for the selected scenarios, according to four domains

Main Qualitative Scenario Hypotheses																
Scenario			GEI	EIA – Reference	EIA – High Economic Growth	EIA – Low Economic Growth	EIA – High Oil Price	EIA – Low Oil Price	ExxonMobil	IEA – Current Policy	IEA – New Policy	IEA – 450	MIT	WEC – Modern Jazz	WEC – Unfinished Symphony	WEC – Hard Rock
EOH			2050	2040	2040	2040	2040	2040	2040	2040	2040	2040	2050	2060	2060	2060
Domains	**Sociopolitical**	Population growth	H	H[1]	H[1]	H[1]	H[1]	H[1]	H	H[2]	H[2]	H[1]	H	H	H	H
		Cooperation mechanism	H													
		Impact of digitalisation on people's life and on global political systems												●		
		Increase in purchasing power							●							
		Expansion of the middle class							●							
		New political movements												●		
		Role played by media												●		
		Global socio-economic re-equilibrium													●	
		International governance													●	
		Increase in poverty and inequity														●
		Population ageing														●
		Nationalistic policies														●
	Economic	Economic growth	H	M[2]	H	L	H	L	H	H	H	H	L	H	M	L
		Technological improvements	H	M[1]	M[1]	M[1]	M[1]	M[1]	H					H[3]	M[4]	L[5]
		Technology learning and cost reduction implemented and dependent on the penetration level								●	●	●				
		Technological breakthrough not predicted								●	●	●				
	Environmental	Renewables penetration policies	H[6]													
		Only existing environmental policies		●	●	●	●	●		●						
		Targets promoting the increase in penetration of nuclear and renewables							●				●			
		Carbon pricing									●[7]	●[8]				●[9]
		Existing policies and relevant policy proposals									●					
		Policies consistent with a 50% probability of limiting the global temperature rise to 2 °C in 2100										●	●			
		COP21 targets											●			
		New business models and technological innovation for sustainability												●		
		Subsidies to enhance sustainability													●	
		Attention to climate change issues	H						M	L	M	H	H	H	M	L
	Energy	Electrification of the end-use	●[10]						●							
		Only existing energy policies		●	●	●	●	●		●						
		Existing policies and relevant policy proposals									●					
		No subsidies to fossil fuels									●[11]	●[12]				
		All the energy sources contribute to the demand coverage							●				●			
		Future policies coherent with decarbonisation pathways										●				
		Accessibility to energy												●		
		Improvements in the supply side, with cost reduction												●		
		Focus on energy sustainability and security													●	
		Reduction in energy demand													●	
		Focus on energy security														●
		Relevant role played by fossil fuels, hydro, nuclear														●
		Low resilience of the energy systems														●

Where:

L: low
M: medium
H: high
●: considered in the scenario
[1]: according to a business-as-usual trend
[2]: driven by non-OECD Countries
[3]: driven by the market
[4]: supported by the governments
[5]: driven by the availability of local resources
[6]: large renewable plants in Artic and Equatorial regions
[7]: implemented in Countries that already announced it
[8]: spread worldwide
[9]: implementation of emission trading systems
[10]: high electrification with fossil fuel replaced by renewables
[11]: in all net-importing Countries
[12]: in all the Countries except the Middle East

The **projections** to 2040 of the most relevant macro-economic drivers (namely the population and the GDP) are instead reported in Table 5. The 2040 has been selected as reference end year because it is the later common year of the time horizons of the different scenarios.

Moreover, in order to make homogeneous and comparable the data for the analysed scenarios, some **assumptions** have been introduced. In particular:

- For the GEI scenario, in the absence of further details, the GDP and the population have been calculated by evaluating the Compound Average Growth Rate (CAGR), according to its definition:

$$CAGR = \left(\frac{V_f}{V_0}\right)^{\frac{1}{t_f - t_0}} - 1 \tag{7}$$

Where:

V_f is the value of the considerer parameter at the end of the time horizon
V_0 is the value of the considered parameter at the beginning of the time horizon
t_f is the last year of the time horizon
t_0 is the first year of the time horizon

V_0 has been chosen equal to the last statistical data available (72.909 trillion 2010$ in 2014 for the GDP [5] and 7.347 billion people in 2015 for the population [83]) and V_f has been assumed equal to the given projected value in 2050 (220 trillion $ and 9.550 billion people respectively).

Furthermore, the GDP has been multiplied by a corrective factor *F* in order to convert it in constant currency 2010$ at purchasing power parity (ppp). Due to the lack of information about the decomposition of the projected value at single country level, an approximate procedure has been adopted. For each year of the period 1990-2014 [5], *F* has been calculated as the ratio between the GDP ppp and the GDP: the obtained historical series has been interpolated through a polynomial best fit of the third order (that shows a good correlation level, with $R^2 = 0.9947$) and finally the *F* value in 2040 has been forecasted.

The above-described procedure can lead to uncertainties in the estimation of GDP, however it can be hypothesised that these uncertainties are comparable with those of the scenario projections and so that they do not significantly affect the proposed comparison.

- For the three WEC scenarios, for the ExxonMobil scenario and for the MIT scenario, the same corrective factor as for the GEI scenario has been applied to the GDP projection.

Table 5: Values of the main macro-economic drivers (GDP and population) for the analysed scenarios in 2040

Scenario	**EOH**	**Population (10^9 people)**	**GDP (10^{12} 2010$ ppp)**	**GDP per capita (2010$ ppp per person)**
GEI	2050	8.860	284.631	32125
EIA – Reference	2040	9.014	236.831	26274
EIA – High Economic Growth	2040	9.014	256.065	28407
EIA – Low Economic Growth	2040	9.014	215.409	23897
EIA – High Oil Price	2040	9.014	248.521	27571
EIA – Low Oil Price	2040	9.014	222.835	24721
ExxonMobil	2040	9.100	263.746	28983
IEA – Current Policy	2040	9.152	242.014	26444
IEA – New Policy	2040	9.152	242.014	26444
IEA – 450	2040	9.152	242.014	26444
MIT	2040	9.039	202.963	22454
WEC – Modern Jazz	2040	9.157	298.912	32643
WEC – Unfinished Symphony	2040	9.157	267.263	29187
WEC – Hard Rock	2040	9.157	193.414	21122
2014 Statistical Value	*2014*	*7.249*	*101.463*	*13997*

As it can be observed, the range of the projected values for the population is small: the GEI scenario is characterised by the lowest value, but the highest one (corresponding to the three WEC scenarios) is only 3.35% higher. On the opposite, the GDP projections show a larger variability. In particular, the WEC scenarios include the extreme values of the range: in comparison with the GEI scenario, in the Hard Rock scenario the GDP estimation is 5.02% higher, while in the Modern Jazz scenario the forecasted GDP value is 32.05% lower. However, a general homogeneity among the considered scenarios from the macro-economic point of view can be noticed, taking into account the different hypotheses that are at the basis of each scenario.

Considering the obtained GDP per capita (i.e. the ratio among the projected values of GDP and population), a significant increase in comparison with the 2014 values [84] can be observed for all the analysed scenarios. In particular, it is interesting to notice that this growth is more significant for those scenarios that mainly pushes towards the decarbonisation pathways, like the GEI and the WEC Modern Jazz ones.

For each scenario, the **indicators** previously introduced and described have been calculated, depending on the availability of primary data. The obtained values are listed in Table 6, together with the corresponding 2014 statistical values [84].

It has to be underlined that for the GEI scenario the emissions per unit of energy consumed E have been estimated on the basis of the CAGR approach applied to the CO_2 emissions trend, due to the lack of information. In particular, V_0 has been hypothesised equal to the statistical value in 2014 (32381.04 Mt of CO_2 [5]) and V_f equal to the forecasted value of 12000 Mt of CO_2.

Table 6: Comparison among the considered energy indicators for all the analysed scenarios in 2040

Scenario	**I_p** (Mtoe/T$)	**I_f** (Mtoe/T$)	**$EC_{f,pc}$** (Mtoe/MPers.)	**E** (Mt CO_2/Mtoe)	**R** (Mtoe/Mtoe)
GEI	69.8	38.0	1.22	0.80	0.51
EIA – Reference	86.8	62.5	1.64	2.10	0.22
EIA – High Economic Growth	84.9	-	-	-	-
EIA – Low Economic Growth	89.5	-	-	-	-
EIA – High Oil Price	85.9	-	-	-	-
EIA – Low Oil Price	89.5	-	-	-	-
ExxonMobil	67.0	31.4	0.90	2.06	0.22
IEA – Current Policy	81.1	56.1	1.48	2.23	0.21
IEA – New Policy	73.8	51.8	1.37	2.03	0.26
IEA – 450	61.5	44.2	1.17	1.24	0.42
MIT	83.4	-	-	2.32	0.21
WEC – Modern Jazz	55.7	41.5	1.35	2.05	0.25
WEC – Unfinished Symphony	56.9	43.2	1.26	1.70	0.34
WEC – Hard Rock	88.2	64.3	1.36	2.19	0.23
2014 Statistical Value	*135.0*	*92.9*	*1.30*	*2.36*	*0.19*

In order to compare more effectively the considered parameters, a normalization with respect to the values of the GEI scenario in 2040 has been performed. The obtained values are graphically shown in Figure 24.

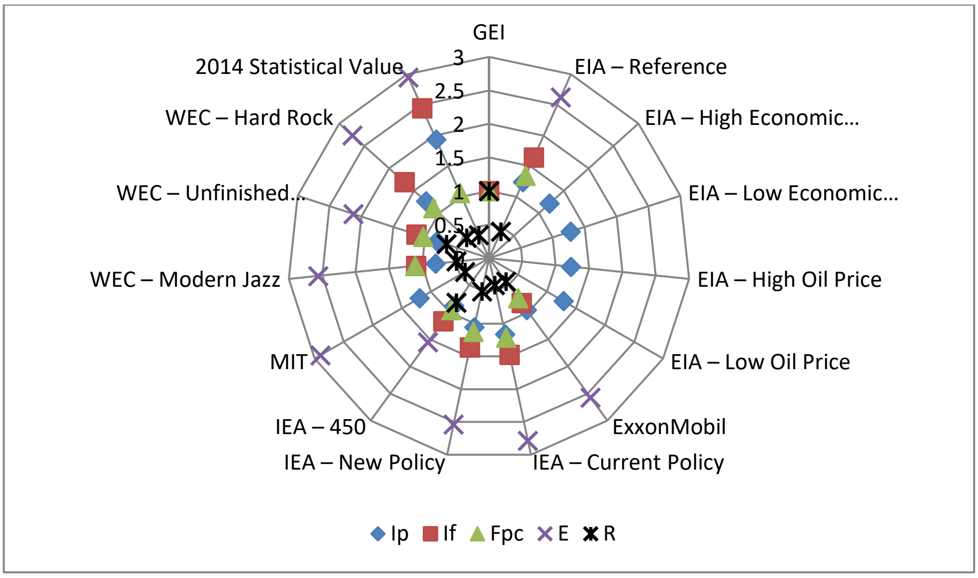


Figure 24: Values of the indicators normalised with respect to the GEI one for each scenario

Only for the **primary energy intensity** I_p a complete comparison among all the scenarios is possible. In all the cases, this parameter is significantly lower than the 2014 value, and comparable to the GEI scenario value. This decrease corresponds to a general increase in energy efficiency and sustainability, i.e. to a better and more rational use of energy, and (as previously said) it can be considered an indirect measure of a higher level of economic affordability, because to produce the same amount of GDP a lower amount of primary energy is needed. It can be further observed that scenarios which assume a relevant transition towards low carbon energy systems (as the GEI, the WEC Modern Jazz and Unfinished Symphony and the IEA 450 scenarios) show relatively low values of primary energy intensity.

The **final energy intensity** I_f also shows a significant decrease with respect to the 2014 level: like for the primary energy intensity, this is due to the more efficient use of energy in the end-use sectors. It can be underlined that the GEI scenario shows a stronger reduction in comparison to 2014 in the final energy intensity value (-59.1%) than in the primary energy intensity one (-48.3%), but with a discrepancy that it is not significantly large. This could be explained according to what previously mentioned, i.e. a combined effect of a relevant electrification (that enhances the divergence between the two energy intensities decrease rates) and of a high penetration of renewables in power generation (which makes the two rate values closer each other). Other more traditional scenarios like the IEA Current Policy and New Policy show decrease rates similar between the two energy intensities (-39.9% for I_p and -39.6% for I_f for the Current Policy scenario; -45.3% for I_p and -44.2% for I_f for the New Policy scenario).

For all the considered scenarios (with few exceptions, like the ExxonMobil scenario), the **final energy consumption per capita** $EC_{f,pc}$ is close to the value of the GEI scenario, and it is comparable to the current level. This means that, even if a more efficient and sustainable use of energy is promoted through ad hoc policies and measures and a relevant modification in the energy paradigm is set (with a transition towards low-carbon technological options and towards a strong electrification of the final uses of energy), the individual consumption remains almost unchanged. This could be caused to the concurrent increase in the world population and improvements in the economies of countries that are currently developing (as China and India) or not developed. In fact, this economic growth will probably correspond to an increase in the demand of energy services by people that presently have not (or have a limited) access to them.

The **emissions per unit of energy consumed** *E* shows instead a high variability across the scenarios. This reflects the different relevance of the environmental policies supposed to be implemented. For instance, it can be observed that the value of this parameter in the IEA 450 scenario (which mostly focuses on the decarbonisation) is 44.4% lower than the corresponding value for the IEA Current Policy scenario (which assume the continuation of current trends). Furthermore, it can be noticed that in the GEI scenario *E* is significantly lower than in all the other scenarios (-35.5% with respect to the IEA 450 scenario). This fact provides a quantitative measure of the weight of the environmental component in the GEI scenario and its impacts as possible decarbonisation pathway.

Focusing on the **ratio of renewables** *R*, it can be seen that it is lower for the scenarios based on the introduction of policies and technological choices oriented to the sustainability and having strong environmental effects, like the GEI, the WEC Unfinished Symphony and the IEA 450 scenario. On the opposite, it shows comparable values (which, in turn, are similar to the current value) for those scenarios characterised by more conservative and traditional hypotheses. As for the emissions per unit of energy consumed, the indicator *R* is significantly low in the case of the GEI scenario. This fact is another measure of the change in the energy framework that the global interconnections could determine, especially in comparison with the other possible transition pathways.

In general, the comparative analysis allows to highlight the effectiveness of global interconnections in representing a viable option to reach the main decarbonisation goals, particularly considering the positive impact on the environment. This aspect could be crucial in a world that is expected to increase its overall population and improve the quality level of life in countries characterised by high population densities: this is coherent with the high increase in the global GDP per capita foreseen by the GEI scenario, in comparison with other scenarios.

The GEI scenario involves a structural modification of the global energy system that spreads over the whole energy chain, affecting production (due to the intensive penetration of renewables), import, transformation (due to power generation mostly based on renewables) and end-use (because of the high level of electrification). Referring to the import, in particular, it has to be highlighted that the GEI paradigm could also have significant impact on the security of energy supply. In fact, from one side, the switch from fossil fuels to renewables could be beneficial because of the reduction in the energy dependency on few productive countries. From the other side, the expected geographical distribution of power generation from wind and solar could instead potentially lead to geopolitical implications that cannot be evaluated *a priori* and that need further studies. The analysis of the above described energy dimensions cannot allow an economic comparison of the long-term effects on the overall energy system cost, due to the different approaches, hypotheses and models adopted for the implementation of the considered scenarios. However, the analysis seems to suggest that this option could be sustainable from the economic point of view. In fact, even if relevant investments (which are higher than those expected in other more "traditional" scenarios) have to be made, the economic feedback in the long term could be positive, leading to a request of energy for generating the GDP lower than the other possible future trends.

The Global Energy Interconnection scenario is more "extreme" also from the point of view of the requested **policy actions**, because it assumes a large electrification of the end-uses, which – in turn – significantly impacts on the electricity demand and the corresponding exploitation of the renewable resources at global level. From the regulatory point of view, the definition of international standards is strictly required. In general, the policies related to this scenario should be shared among all the countries and designed in a cooperative framework.

These policies should involve 5 main aspects:

- Technical standards for the implementation and the operation of the UHVDC backbone
- Regulations for promoting a common electricity market
- Regulations for investments
- Regulations for a common governance
- Policies for promoting the security of supply

Besides the **technical** requirements (that should be unified), a special attention has to be devoted to the governance and to the market, which need common bases. Among the aspects to be addressed, the sovereignty, the identification of financers and the market schemes can be mentioned.

In particular, the proposed policies should be able to define **how to manage** the GEI among the various involved governments (defining, in particular, if the sovereignty for each country should be proportional to the investments or not) and TSOs, also identifying the kind of structure (horizontal or hierarchical) to adopt.

The several market dispatching schemes should be also harmonised, unifying the national or regional markets into a **global market**, and a new market clearing mechanism (taking into account the basically zero marginal cost configuration) should be introduced.

Furthermore, the policies should set rules for defining how to allocate the requested **investments** and share benefits among involved countries, also identifying the possible investors (national governments or transnational bodies and institutions) for building the needed new infrastructures and updating the existing country grids to make them compliant with the newly defined standards.

Among the needed investments, those for allowing the **access to energy** (namely to electricity) in country like several African ones has to be planned trough international cooperation agreements and support actions. The GEI scenario could in fact be useful in promoting a new paradigm against energy poverty in many world areas.

Eventually, ad hoc **security** policies should be set. They should be specifically designed for a new global energy system configuration, in which the overall UHVDC backbone has to be protected against both physical threats (e.g. terroristic attacks) and cyber threats. In fact, the GEI configuration could be, on one side, positive for the security of supply, as it allows to exploit renewable resources thus lowering the dependency of politically instable or unreliable fossil fuels production countries. On the other, to have a centralised system could lead to the above mentioned criticalities that have to be carefully prevented in order to avoid potential blackouts spreading over wide areas. In the same manner, emergency planning for facing possible natural hazards (like earthquakes, flooding, tsunami, etc.) impacting on the grid should be defined for all the areas/countries involved.

In general, it can be observed that the GEI scenario requires large-scale relevant changes, which in turn need common frameworks and cooperation among countries, overcoming geopolitical barriers that currently seem to be the most critical aspects for supposing a concrete future implementation of this kind of scenario.

Chapter 4

A multi-dimensional approach for assessing the integrity of energy infrastructures

Part of the activities described in this Chapter have been also already published in [85], [86], [87], [88]

4.1 The role of energy infrastructures and their integrity

According to the possible range of solution for implementing the energy transition towards decarbonisation, it can be observed that a crucial role is played by the infrastructures for supplying, transmitting and distributing energy. It can be expected that the future configuration of the global energy system will be a mix of the previously described extreme solutions.

However, in every case the **integrity** of these infrastructures – at all spatial levels (from gas and oil pipelines, to power lines, maritime routes, district heating networks, etc.) – is a necessary and key factor for ensuring such long-term strategies. The integrity can be considered an attribute that measures the capability of a given infrastructure to perform its function according to what is requested and to be properly managed from several points of view, including safety, environmental protection, maintainability, productivity, etc.

For this reason, "integrity" is a concept more general than "security", as it is **multi-dimensional**. This multi-dimensional aspect is fundamental in order to fully encompass all the aspects that can be involved in ensuring the operation of the energy systems, of which the energy infrastructures can represent the backbone.

Furthermore, the integrity is directly related to the **development** of infrastructures. The evolution of the current energy systems in the sense of the energy transition requires to plan the infrastructures architecture according to criteria that have to be not only technological, but able to consider all the possible issues that can threat their integrity. Currently, these issues are investigated and, in some cases, numerically evaluated through a sort of ex-post analysis, applied to infrastructures already designed and/or existing. In a long-term perspective, instead, they should be embedded as much as possible in the design phase, in order to guarantee a sort of self-integrity of the infrastructure itself. This requires the development of new design and sizing procedures or the adaptation of existing techniques, for integrating assessments that have been historically implemented in a stand-alone way.

Up to now, the integrity concept has been mainly adopted in the oil & gas sector in the framework of the so-called "Asset Integrity Management" (AIM) [89], [90], [91], [92]. According to the definition provided by the Health and Safety Executive (HSE) of the United Kingdom, the AIM identifies the way of guaranteeing that "… people, systems, processes and resources that deliver integrity are in place, in use and will perform when required over the whole lifecycle of the asset" [93]. This statement highlights that one of the main characteristics of the AIM is to cover the entire lifecycle of the considered infrastructure, which includes design, installation, commissioning, technical standard life of the asset, obsolescence and decommissioning.

More recently, this approach has been extended to other kind of infrastructures. An example is represented by the study carried out by Fuggini et al. [94], in which the AIM is applied to the transport sector. The authors proposed a performance-based methodology founded of a probabilistic approach in infrastructures design and retrofitting. They furthermore put into evidence the need for a different approach with respect to the oil & gas one, due the fact that this sector can be assumed quasi-static (because the processes undergo to a slow variability in time), while the transport one (and consequently the involved infrastructures) shows faster dynamics.

Ossai et al. [95] proposed instead to apply the AIM approach to the renewables power generation plants (wind, solar PV, biomass, hydro, geothermal, tidal). According to their findings, this methodology could allow to reduce issues like low productivity, high downtime and relevant maintenance costs. The authors also underlined that the implementation of an AIM could also lead to an enhancement of the performances throughout the lifecycle and it could provide useful feedbacks in the related research and development and in the planning of investments.

Starting from this general framework, the core of the present doctoral project has been the identification of a multiscale approach for assessing the integrity of energy infrastructures at different spatial levels, from macro to micro. This approach is in accordance with the two possible extreme pathways of the energy transition previously defined that will probably coexist in the future, with energy systems that will be a proper mix of the two options.

4.2 The adopted multi-dimensional approach

In order to build this multiscale approach, a **two-dimensional scheme** has been adopted, taking into account the following dimensions:

- **Spatial scale:**
    - **Energy corridors:**
      Include large infrastructures for the transnational transport of energy commodities. In this category are included captive routes like oil and gas pipelines, power lines, railways and roads for the transport of solid fuels and refined petroleum products, but also open-sea routes for delivering crude oil and refined products, solid fuels and LNG. These corridors run from the source country/area to the entry point of a country.
    - **Transmission / distribution infrastructures:**
      Include the infrastructures for widely distributing energy commodities inside a country, from production zones or national entry points (in the case of imports) to the various consumption areas of that country. They can be considered the internal energy backbone of the considered country.
    - **Local distribution networks:**
      Include the local grids, which carry energy commodities to the final users. They are systems that are most commonly implemented at urban scale, so they are characterised by a limited spatial extension. District heating networks represent one of the most relevant example.
- **Kind of threats:**
    - **Natural:**
      Related to extreme natural events (floods, tsunamis, earthquakes, wildfires, etc.) that can impact on the energy infrastructures, leading to possible disruptions or unavailability, requiring an evaluation of the criticality status and of the resilience of the infrastructures themselves.
    - **Accidental:**
      Related to unintentional technical failures that can determine the unavailability of the analysed infrastructure and, consequently, technical and/or economic instabilities in the considered energy system. Due to their technical nature, they are more common and frequent with respect to natural and intentional threats, which can be considered low-frequency and (in the case of intentional threats) unpredictable.
    - **Intentional:**
      Related to deliberate actions (sabotages, physical and cyber attacks by antagonistic or terroristic groups) against a certain infrastructure chosen as

relevant target or to international geopolitical tensions able to impact on the supply of energy commodities.

This scheme is graphically represented in Figure 25.

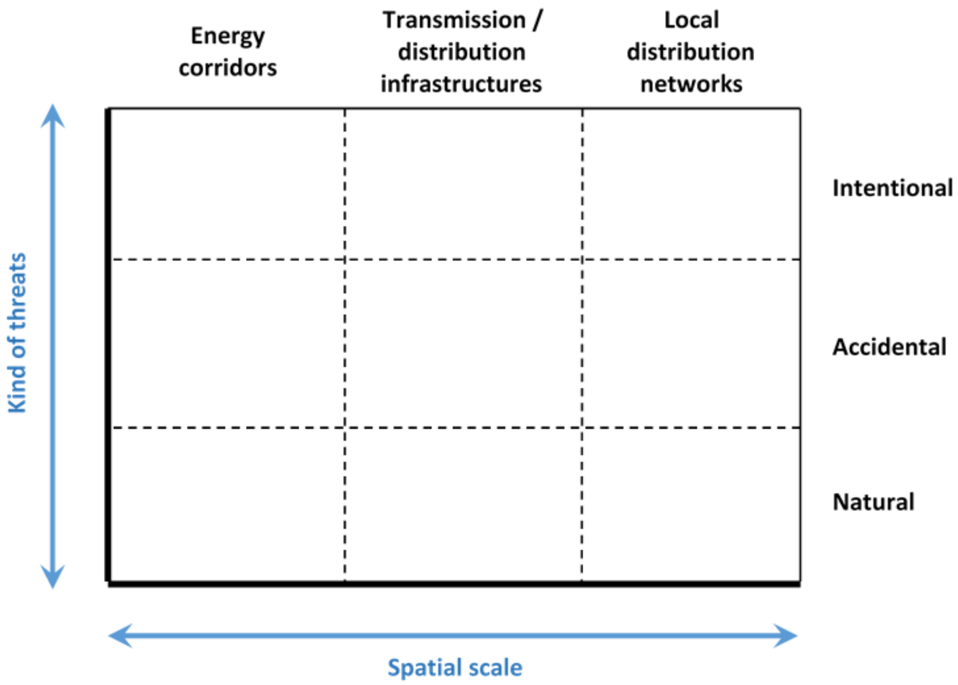


Figure 25: Scheme of the multi-dimensional approach adopted

The possible combinations of spatial scales and threats can differently impact on the infrastructure integrity dimensions, that can be categorised in the following four ones:

- **Integrity dimensions:**
  - **Technological:**
    Refers to the technical aspects that are involved in the operation of the considered infrastructure. It is thus related to capability for a given infrastructure to perform its function from the technical point of view, and on the evaluation of how technical failures can affect its functioning and service quality.
  - **Geopolitical:**
    Refers to the political status of the countries involved in the energy supply. Political tensions can, in fact, impact on the security, costs and availability of energy commodities, and on the strategical choices related to the planning of new large scale infrastructures. Furthermore, the geopolitical dimension has to be considered also with respect to the internal energy system of a country in the case of internal political instability and presence

of antagonistic groups that can consider energy infrastructures as possible target.

- **Environmental:**
  Refers to the environmental aspects that has to be considered with respect to energy infrastructures. In particular, it includes the impact that the environment can have on them and the environmental sustainability goals that have to be achieved and that require structural modifications of the energy systems, thus impacting on the infrastructures planning and development.

- **Economic:**
  Refers to the possible consequences of lack of integrity of energy infrastructures on the economic system of a country (like GDP losses). Furthermore, in also refers to possible cost-benefits of protective/mitigation countermeasures that can be implemented in the case of adverse events and threats and to the investments that has to be performed in the short-, mid- and long-term and that has to be prioritised according to the criticality status of the considered infrastructures.

The proposed approach allows to evaluate the effects of the considered hazards/threats at different scales on the integrity dimensions. Consequently, this **multidimensional approach** can be useful in defining **guidelines** for the integrity assessment and the development of energy infrastructure under a holistic perspective, in order to support the policy decision-making about strategical investments and their prioritization, planning, management, identification and ranking of criticalities of energy infrastructures.

A complete analysis should require that for each of the possible combinations of threats and spatial scales several case studies are developed and performed, thus exploring the whole spectrum of possible approaches to the integrity evaluation and identifying the common factors and the possible issues for each of them. Such an integrated analysis could allow to define, for each spatial scale, the main impacts of the different threats on the different integrity dimensions. In this way, the most fundamentally critical aspects can be highlighted, providing to the infrastructure designers the possibility of embedding integrity in the projects and to the decision-makers the opportunity of defining effective long-term strategies. These strategies can be thus tailored according to the different kind of needed infrastructures and to the most relevant threats (that can vary on the basis of the geographical position of the infrastructure, of the country in which it is located and of its path).

This kind of approach requires, of course, a wide range of analysis. For this reason, the aim of the present study was not to fully explore all the possible situations that can fill the above-described multidimensional scheme, but to identify and investigate a set of specific case studies covering all the considered spatial scales with respect to different threats, involving various integrity dimension.

This analysis can be useful, in particular, in

- identifying possible **interdependencies** among the considered dimensions
- assessing the **relevance** that each kind of threat can have on the various layers and on the different spatial scales.

This approach can be consequently represent an indication and a guideline for future studies aiming at analysing the energy infrastructures under and holistic perspective and a supporting tool for energy decision makers.

4.3 The analysed case studies

In particular, **five case studies** have been developed and analysed:

- Geopolitical supply security
- Resilience of distribution infrastructures
- Effects of renewables penetration
- Reliability of district heating networks
- Innovative vectors and security

These case studies can be graphically collocated (Figure 26) in the previous scheme according to the spatial scale of the considered infrastructures and to the main kind of involved threats.

Of course, as better clarified in the next sections, the collocation cannot be univocal, but the influences in terms of both dimensions and threats spread over different typologies. The proposed classification allows, however, to define the amplitude of the present work and to identify the areas that should be covered by future studies in order to effectively complete the multi-dimensional approach that has been previously described.

In general, the coverage of the developed case studies can be summarised as follows:

- Geopolitical supply security: macro-scale; related to intentional threats and impacting on the geopolitical dimension.
- Resilience of distribution infrastructures: transmission/distribution level; related to natural hazards and impacting on the technological, environmental and economic dimensions.
- Effects of renewables penetration: transmission/distribution level; mainly related to technical (i.e. accidental) failures and impacting on the technological and environmental dimensions.
- Reliability of district heating networks: micro-scale; related to technical failures and impacting on the technological dimension.

- Innovative vectors and security: micro-scale; mostly related to the supply security and impacting on the geopolitical and economic dimensions.

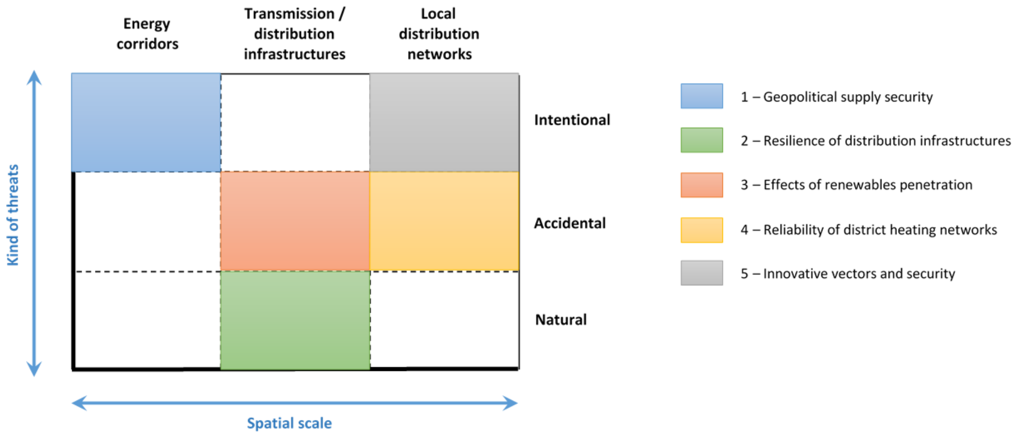


Figure 26: Collocation of the proposed case studies in the overall scheme

4.3.1 The macro-scale: a quantitative assessment of the geopolitical energy security

The first case study is related to the analysis of the large transnational energy **corridors** and to the development of a methodological approach for the assessment of the **energy supply security**. In this case, the security is considered not from a technological point of view, but from a geopolitical perspective, taking into account the possible political scenarios that could determine a disruption in the integrity of the supply corridors, thus leading to potentially negative relevant effects on the availability of the needed energy commodities.

Furthermore, the proposed quantitative evaluation of the **geopolitical supply risk** can be considered as a way for estimating the distance from a situation of loss of integrity of the involved infrastructures.

This analysis starts from the consideration that energy security represents a crucial issue for all countries. Among the possible **definitions of "energy security"**, the following one can be maybe considered at the same time the most general and the most comprehensive. Energy security is the capability of guaranteeing the availability of energy commodities (both primary and secondary) for the final uses, where they are needed, in the required quantities and over short-, mid- and long-term time periods. In order to ensure this availability, the access to the energy sources, the transportation of the commodities over long distances to the entry point of the considered country through ad hoc energy corridors, the eventual transformation from primary to secondary commodities and the distribution inside the country are requested key elements. Of course, it has to be highlighted that the energy security can be enhanced by acting not only on the local energy production or on the import of commodities from abroad, but also on the flexibility of the demand side, i.e. on the amount and type of energy requested by final users. However, all the above-mentioned aspects involve energy infrastructures: as a consequence, their integrity is a crucial factor for assuring the continuity of the supply chain from the sources to the end-users.

The security of energy supply becomes particularly relevant in countries characterized by a high level of **import dependency** (or, conversely, by a low self-sufficiency). This is a common situation for the majority of the European countries: at the EU28 level, the energy self-sufficiency in 2014 has been, in fact, equal to about 46.5%. Referring to Italy, in particular, the 2014 import dependency has been equal to 75.9%, thus putting into evidence how the security issues related to the import of energy commodities and to the possible international geopolitical events and scenarios can be considered critical.

For this reason, in the short term the assessment (through a quantitative science-based methodology) of the energy risk level related to the current composition of the energy mix and to configuration of the supply is relevant in identifying and rank criticalities, thus defining or increasing mitigation actions and countermeasures. Over mid/long-term time horizons, instead, the evaluation of the risk associated to different scenarios lead to the possibility of planning and prioritising strategic investments in alternative sources and new supply infrastructures.

In order to quantify the risk related to the energy supply, a methodology has been developed, by applying the classical approach used in the **risk analyses** performed in the industrial sector to the geopolitical dimension. This approach has been coupled to a spatial characterisation of the energy corridors, in order to embed this physical dimension in the analysis and in the relationships established to carry out it.

It has to be further highlighted that the proposed integrated perspective tries to link **geopolitical and economic aspects**. In fact, the geopolitical situation can determine a relevant influence on the costs of energy commodities, thus affecting the economy of the considered country. Moreover, it directly impacts on the security of supply level and on the availability of the external supply, which – in turn – impacts on the national economy.

This perspective can thus represent a **supporting tool for decision-making** processes, as it allows to better put into evidence and rank the criticalities of the analysed energy system and to compare scenarios that simulate different possible options on energy imports and infrastructure development.

The starting point of the study has been the analysis of the available literature for the quantification of the security of energy supply for a given country. Many of these approaches are based on the implementation of **quantitative risk parameters** (taking into consideration geopolitical aspects) and of **energy indicators** defined at country level.

Kruyt et al. [96] classified of some of the most relevant energy-related indexes, identifying t10 simple indicators (which include reserve-to-production ratio and import dependency) and 5 aggregated indictors, namely the IEA Energy

Security Index (ESI), the Shannon Index, the Supply-Demand Index, the Willingness to Pay Index and the Oil Vulnerability Index (OVI).

With respect to these 5 indicators, the IEA ESI [97] assesses the effects on energy prices of the supply market concentration, considering the supply countries risk rating from the geopolitical point of view. The Shannon-Wiennier Index (SWI) [98] quantifies instead the diversification level by taking into consideration the commodity shares in the composition of the fuel mix; for this reason, this index is also used for the assessment of the energy security. Scheeepers et al. [99], [100] focused on the Supply-Demand Index, which is defined according to the judgement of experts, through and hoc scoring rules. This index takes into account the entire energy chain over mid-/long-term time horizons. Bollen [101] defined a "Willingness to Pay" function starting from a cost-benefit analysis. The proposed function allows to quantify the percentage of GDP that the considered country is willing to pay in order to reduce its risk. Finally, Gupta [102] developed an overall oil vulnerability index (OVI), depending on the combination of 7 indexes (like the import dependency for oil and the GDP per capita), which are related to the economic level of the country and to the oil supply and consumption.

Martchamadol et al. [103] performed an analysis of several security indicators. Among these considered ones, the following can be cited:

- WEC Energy Sustainability Country Index (ESCI) [104], based on 22 indicators, like those related to stock, oil reserves and energy security;
- WEC Assessment Index (AI) [105], which assesses energy security through 5 indicators (which include diversification of the energy supply and net energy imports);
- UNDESA Energy Indicators for Sustainable Development [106];
- APERC study [107], which takes into account 5 indicators (like net import dependency, oil import dependency from the Middle East and net oil import dependency);
- Global Network on Energy for Sustainable Development (GNESD) indicator [108].

The authors also proposed a new composite index, called Aggregated Energy Security Performance Indicator (AESPI) [103], created by composing 25 indicators and ranging between 0 (low security) and 10 (high security). In turn, the source indicators are estimated on the basis of the historical data for macro-economic parameters like GDP and population, of the energy production, transformation, transmission losses, power generation capacity, net import and consumption, and emission factors of the main fossil fuels (coal, crude oil and natural gas).

It has to be noticed that the majority of the energy risk indexes are considered steady over time. Apart from the AESPI index, only few other indicaators, like the Composite Indicator developed by Badea et al. [14] and the Supply-Demand Index defined by Scheepers et al. take into account a possible time evolution. In particular, these two indicators have been both built on the basis of the energy projections taken from the PRIMES model, and have been adopted by the European Commission in order to estimate the EU Trends up to 2030 [109]. Among the other studies aiming at evaluating the long-term energy supply security and based on the PRIMES model, the one carried out by Checchi et al. [110] can be mentioned. It has to be noticed, however, that it does not define any index for numerically assess the energy security.

The International Index of Energy Security Risk (IIESR), defined by the U.S. Chamber of Commerce Institute for 21st Century Energy [111], is instead an indicator based on the analysis of time series, built in order to assess the security of 25 main consuming world on an annual base. In this methodology, eight categories of indexes have been introduced, including energy imports, reserves and production of crude oil, natural gas and coal) and 29 metrics has been defined for each category, over a time period ranging between 1980 and 2012. All the metrics has been normalised with respect to the 1980 OECD value and then weighted – for evaluating the overall IIESR value – through the International Weightings Index, which provides the contribution of each category.

Frondel et al. [112], [113], [114] developed instead an approach having as its goal the ranking of countries according to the risk related to the supply of the primary energy commodities over a mid/long-term time horizon. For each commodity, the authors defined a risk indicator function of the probability of

- The square value of the percentage contribution of the local production and of each exporting country to the fulfilment of the energy demand in the considered country;
- The interruption of the commodity flow the different export countries.

The authors correlated the shares for these countries to the Herfindahl index [115], which gives a measure of the import concentration for a certain commodity. Moreover, they estimated the unavailability of the supply for a given country according to considerations related to the economic stability and to the geopolitical situation.

Sovacool [116] introduced an indicator for the assessment of the energy security at country level, defining five key dimensions of security, i.e. availability, reliability, sustainability, regulations and technological development. He dividend these dimensions into 20 components, each of them related to a metric. The study focused, in particular, on the United States, Japan, India, China, South Korea, the European Union, Australia, New Zeeland plus 10 countries belonging to the Association of Southeast Asian Nations (ASEAN).

Guivarch et al. [117] investigated the evolution of energy security in Europe under a decarbonisation point of view, by considering the time evolution of several indicators (based on the concepts of robustness, resilience and sovereignty) in several scenarios.

Matsumoto et al. [118] focused instead on Japan, China and South Korea, analysing the effects of different climate mitigation policy scenarios through a computable general equilibrium model.

Valdés Lucas et al. [119] explored, over a long period, the correlation between energy security and the renewables exploitation, taking into account various indicators linked to three main energy policy dimensions, i.e. the environment, the security of supply and the competitiveness.

Kisel et al. [120] analysed various approaches and indicators used for the evaluation of the energy security and for the definition of energy policies. In particular, they introduced an Energy Security Matrix for structurally classifying the most relevant indicators in terms of technical vulnerability, technical and operational resilience, economic dependence and political affectability in different sectors.

Biresselioglu et al. [121] focused on the security of natural gas supply and on the evolution of several indexes (like the overall volume of gas imported, the number and the fragility of supply countries) over the 2001-2013 time horizon in order to build a Supply Security Index (SSI) by means of an application of the Principal Component Analysis (PCA) technique. Still referring to natural gas, Flouri et al. [122] investigated – through a Monte Carlo simulation approach – in which way a disruption in the natural gas supply from Algeria due to geopolitical reasons could impact on the security of the EU gas supply. In particular, they put into evidence the crucial role played by the diversification of suppliers in enhancing energy security.

Among the other studies aiming at assessing the importance of the geopolitical events in the estimation of the energy supply risk, the ones performed by Costantini et al. [123], Correlje and van der Linde [124], Umbach [125] and Hedenus [126] can be cited.

4.3.2 Transmission/distribution of energy: the resilience and criticality of distribution infrastructures

The aim of the second case study is to define a methodological approach able to assess the **resilience of critical infrastructures**. It has been generically developed for "energy corridors", i.e. independently on the spatial scale, but it can be considered, in particular, suitable for the resilience analysis of the transmission and distribution infrastructures.

In general, the reduction in the vulnerability to all the possible hazards (in many cases unpredictable) that could damage **Critical Infrastructures** (CIs) by improving the level of their protection and by increasing their resilience is one of the main goals of the European Union. The objective is to limit as much as possible the probability of widespread negative effects on EU's citizens and economy by ensuring services even in the case of significant disruptive events, coherently with the objectives of the Stockholm Programme [127] and of the EU Internal Security Strategy [128].

The United Nations International Strategy for Disaster Reduction (UNISDR) defined the **resilience** as "the ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions" [129].This general statement applies also to the CIs.

The definition firstly provided by the European Community in the 2004 Communication on "Critical Infrastructure Protection in the fight against terrorism" [130] states that Critical Infrastructures are crucial systems, facilities, networks or assets whose disruption would lead to relevant impacts on the socio-economic condition and development of a Member State (MS). In order to enhance their protection not only against terrorism, but also against all the other hazards (including natural disasters), the **European Programme for Critical Infrastructure Protections** (EPCIP) was set [131], [132]. The goal of this programme was to define a general framework based on several principles that include subsidiarity, confidentiality, complementarity, sector-by-sector approach, stakeholder cooperation and proportionality.

It focused on the **identification** of the European Critical Infrastructures (ECI), defined as those CIs located in EU's MS whose disruption would significantly affects at least two MS [131].

It also addressed

- their possible interdependencies,
- the assessment of their risk by means of common approaches, the measures that could be set to improve their protection,
- the impacts that hazards and accidents external to EU's borders could have on the EU,
- the contingency plans to reduce or mitigate the negative effects of CI disruptions [131].

One of the most relevant documents for the implementation of the EPCIP is the 2008 Directive on "the identification and designation of European critical infrastructures and the assessment of the need to improve their protection" [133]. It represents the first approach to identify ECI and to evaluate the need for increasing their protection level, and it refers to only two specific sectors (energy and transport), even pointing out the necessity of future reviews able to also include other sectors, like the information and communication technology (ICT) one. It also requires to owners/operators of the identified ECI to produce Operator Security Plans (OSP), which define the options existing or being implemented for the ECI protection.

In 2013, a revision of the EPCIP was introduced [134], aiming at organizing the implementation of the activities around three work streams (prevention, preparedness and response), at deepening the analysis of the **interdependencies** (both cross-sector and cross-border) and at taking into account also critical ICT infrastructures and their relationship with other CIs (especially electricity generation and transmission infrastructures).

Several studies have been performed in order to define methodologies for evaluating the **resilience of CIs** and the possible **economic effects** deriving from CI disruptions. Different reviews of the proposed approaches are available in literature, as those carried out by Ouyang [135], Griot [136] and Wang et al. [137].

Among these, the ones performed by the JRC can be firstly mentioned. In particular, Galbusera et al. [138] proposed a feasibility study for the application of stress tests (like those adopted in the nuclear and economic sectors) to the evaluation of CI resilience against several hazards. Giannopoulos et al. [139] carried out an analysis of the state of the art related to the risk assessment methodologies that could be useful for the protection of CIs. Theocharidou et al. [140] suggested a new methodology – called CRitical Infrastructures & Systems Risk and Resilience Assessment Methodology (CRISRRAM) – developed in an all-hazard perspective and based on a system-of-systems approach [141], which introduces three layers (society, asset and system) and evaluates the direct or indirect effects on economy, environment and citizens caused by the hazards considered in each scenario. A general approach to risk analysis and management of system-of systems can be found in the studies performed by Haimes et al. [142] and by Ariel Pinto et al. [143]. Eusgeld et al. [144] analysed instead the alternative modelling options (integrated and coupled models) for system-of-systems and proposed a specific High Level Architecture (HLA) for modelling Supervisory Control and Data Acquisition (SCADA) and "System under Control" (SuC, like gas supply system or power supply system). Another approach based on the system-of-systems concept, a Monte Carlo simulation and a Hierarchical Graph representation of the interdependent CI is the one described by Ferrario et al. [145], which was applied to two case studies – concerning respectively small electric and gas grids (plus a SCADA system) and a large electrical distribution network – for the evaluation of their robustness.

Furthermore, the JRC developed the Geospatial Risk and Resilience Assessment Platform (GRRASP), a graphical tool for analysing network systems that can be adopted to identify the critical elements of the network and to evaluate the cascading effects of CI disruptions [146].

The opportunity to model infrastructure **networks** as interconnected **system-of-systems** in order to properly describe the cascade effects due to their strong **interdependencies** has been underlined by Kröger et al. [147]. Zio [148], [149] furtherly suggested an approach – helpful in CI protection – based on the risk and vulnerability concepts and able to allow the identification of possible vulnerabilities (both evident and hidden), thus avoiding the failures that could originate when the CIs are subject to hazards of multiple nature. Johansson et al. also focused on the opportunity to use vulnerability analyses to complete reliability studies of CIs [150] and demonstrated it by applying a Monte Carlo approach for reliability analyses and a vulnerability analysis to an electric power system. Moreover, Johansson et al. [151] proposed a model that could be useful in the framework of vulnerability analyses of interdependent infrastructures that are described by both a network model (based on the graph theory) and a functional model.

Stergiopoulos et al. [152] explored the interdependencies among CIs that cause cascading effects in the case of failure. For this purpose, the authors started from the dependency risk methodology proposed by Kotzanikolaou et al. [153], [154] and introduced graph centrality metrics in order to identify the nodes that mainly affect the risk paths and that can thus be controlled in order to improve risk mitigation. Furthermore, Stergiopoulos et al. [155] extended the studies performed by Kotzanikolaou et al. [153], [154], [156] by considering the time evolution of each dependency (using fuzzy models) and the concurrent common-cause cascading failures, developing a supporting tool for decision making (named CIDA, i.e. Critical Infrastructure Dependency Analysis). This tool can be useful in assessing the CI's resilience under different scenarios and the effectiveness of possible mitigation actions.

Fu et al. [157] also focused on the opportunity of treating infrastructure networks as interdependent system-of-systems, while Utne et al. [158] proposed a methodological approach to model the interdependencies among CIs built starting from the use of relatively simple cascade diagrams.

Labaka et al. [159], [160] suggested instead a holistic framework (based on the identification of resilience policies, on their influence and on the methodology for their implementation) aiming at increasing the resilience of CIs by identifying their **resilience** level, their weaknesses and the possible improvements to be implemented.

Nan et al. [161] proposed a method for resilience estimation, which combines a hybrid multi-layer model (for capturing the interaction between different subsystems) and an integrated metric (for the quantification of the resilience, considering the different resilience capabilities).

Specific **models** and analyses have been developed in order to assess the physical security and the resilience of CIs against different kinds of hazards. In particular, Khalil et al. [162] focused on the modelling of physical security of CIs under attack scenarios by using a Monte Carlo-based probabilistic dynamic approach.

Urlainis et al. [163] implemented instead a **supporting tool** for decision making suitable to evaluate the risk related to oil & gas critical infrastructures after the occurrence of a seismic event. This tool adopts an approach, which provides for the use of fault-trees, decision trees and fragility curves and allows the identification of the most critical sections of the analysed system based on the damage state of its components.

In comparison with the mentioned studies available in the scientific literature, the proposed methodological approach mainly focuses on the geographical dimension of the infrastructures, allowing analyses characterised by a high spatial granularity definition. Moreover, this procedure is able to take into account the most relevant interdependencies among the parameters that could impact on the criticality of an infrastructure, even with a simple mathematical formulation. Therefore, it aims at being a supporting tool not only for public administrations, but also for infrastructures management companies and for the civil protection.

4.3.3 Transmission/distribution of energy: effects of renewables penetration

The enhancement in penetration of renewables in the energy mix of a country is more and more needed in order to comply with targets and constraints set by environmental policies aiming at counteracting global climate change phenomena. However, renewable energy sources (especially solar photovoltaic and wind) are characterised by a relevant variability throughout hours and seasons: for this reason, they can be considered non-programmable and can be identified by the acronym NPRS (Non-Programmable Renewable Sources). This fact lead to several issues related to their integration, that can be clearly understood by analysing the structure and management of the traditional power systems, which are mainly based on conventional (and almost uninterruptable) large plants for the base load and adjustable smaller plants for the peak coverage.

Analysing the available scientific literature, it can be observed that a large number of studies puts into evidence the need for quantitatively assessing the **impacts of an increase in NPRS** penetration on the power systems. This is due to the inflexibility of the traditional systems themselves and to the necessity of new solutions in order to allow high penetration rates avoiding, at the same time, relevant excess of electricity production from NPRS.

Among these studies, the one carried out by Denholm et al. [164] can be mentioned. It focuses on the assessment of the effects of solar photovoltaic (PV) on the ERCOT (Electric Reliability Council of Texas) power system. In particular, this analysis has been performed by simulating scenarios in which up to 50% of the system energy is produced by PV. Several options for avoiding the limitations related to the integration of high quantities of PV energy have been considered. The authors underlined that an increase in system flexibility is a key aspect for ensuring a relevant and feasible integration; however, further actions are required for managing the excess of PV electricity generation, especially during non-summer seasons. For this purpose, in this work the possible contribution provided by energy storage systems and by load shifting has been explored.

Denholm et al. [165] also proposed additional simulations on the ERCOT grid, in order to analyse the system variations corresponding to scenarios in which different mixes of wind, solar PV and concentrating solar power (CSP) are adopted for fulfilling up to 80% of the electricity demand, under the hypothesis that the ERCOT system cannot exchange power with other networks. The obtained results show that an increase in system flexibility allows NPRS penetration rates up to 50%, with curtailments lower than 10%. If a penetration rate of 80% is requested, the increase in flexibility is not sufficient by itself but a combination of load shifting and storage systems (both electrical and thermal) is needed.

Denholm et al. [166] in a technical report of the National Renewable Energy Laboratory (NREL) also analysed the economic issues related to the enhancement in NPRS penetration, including the integration costs of NPRS and the evaluation of the maximum NPRS penetration before storage systems become the most economic alternative for further increase. This work also highlighted the opportunity of developing optimisation analyses (by finding the system configuration corresponding to the minimum total cost) and cost/benefits analyses related to the storage systems.

Referring to the studies performed by other authors, Kirby et al. [167] still focused on the US power system, and in particular on the modification of the operating reserve policies caused by the increase in the NPRS penetration. This analysis put into evidence the need for these operating reserve requirements to become dynamic, taking into account the possible high penetration level that NPRS could reach in the future energy mix.

As the NPRS issue arises in selected **geographical areas** where the potential is high, it is interesting to mention the work of Solomon et al. [168], who studied and quantified the effects of the integration of very large-scale photovoltaic plants (VLS-PV) on the Israeli power system. The authors highlighted that this quantification is important in order to

- help energy planners in finding the optimal siting of VLS-PV plants and the best technological option to adopt
- defining future grid expansion strategies able to consider the need for increasing flexibility (thus anticipating a possible enhancement in NPRS penetration).

Focusing again on the Israeli power system, Fakhouri et al. [169] assessed the need for backup in the system on the basis of the Government’s target on NPRS penetration (supposed to reach 10% by 2020). In doing this, they also toke into account that Israel – from an electrical point of view – can be considered a closed market, i.e. an electricity island. Like the majority of the above-mentioned studies, this analysis shows that an increase in NPRS penetration has to be coupled with an increase in flexibility of the system and with the implementation of options (like storage systems) in order to guarantee reliability of the electricity supply and service quality, under a perspective of a smart management of the network.

Erdinc et al. [170] emphasised the additional critical issues that a high NPRS role in power generation could cause in insular electric systems, which typically suffer from a structural fragility with respect to the continental ones. This weakness is mainly determined by the low number of interconnections with the main grid and the small size of the local networks (with a low number of generators causing a low inertia of the systems and relevant sensibility to possible outages).

Ulbig et al. [171] proposed modelling approaches for assessing the operational flexibility of individual power system units and of clusters of several power system units.

Oree et al. [172] underlined the need for taking into account the variability and intermittency of the NPRS in planning techniques (commonly based on least-cost optimisation or, more recently, on multi-criteria methodologies), by critically revising the models and methodological approaches currently available in the scientific literature.

Franco et al. [173] considered possible scenarios able to assure an optimal NPRS penetration in the Italian energy system. The authors put into evidence that an increase in renewable penetration could be effective in reducing the consumption of fossil fuels (in particular natural gas for power generation). This reduction can also allow to enhance the energy security level, because it can contribute to reduce the import dependency, particularly high in countries like Italy. They also suggested that the increase in CHP plants and electric vehicles could promote the integration of wind and photovoltaic power. They further highlighted the possible issues deriving from the distance between large hydropower plants (mainly located in the North) and wind farm (mainly located in the South), which could impede the implementation of a wind and water model helpful in controlling the power intermittency.

Still referring to an Italian case study, the analysis carried out by Barelli et al. [174] can be mentioned. In this study, the authors focused on a peculiar issue of the Italian power system, i.e. the effect of the renewables penetration on the thermoelectric production. In fact,

- policy strategies aiming at promoting renewable sources penetration (especially photovoltaic) implemented in the period 2007-2013,
- the concurrent absence of additional actions for optimising their integration in the power system and
- the cost of natural gas, higher than the coal one,

led to the use of gas combined cycle (CC) plants as backup for renewable plants and no more as base-load plants, thus causing a decrease in the thermal generation efficiency, mechanical stresses on the CC plants and an increase in the related maintenance costs. In order to overcome this problem – as alternative solution to the retrofitting of the existing power plants – the authors suggested the integration between energy storage systems and large CC plants, allowing them to operate again close to the nominal conditions (with relevant benefits from the efficiency point of view), by storing the produced energy surplus.

Finally, Bigerna et al. [175] and Gullì et al. [176] analysed the economical and market aspects related to the enhancement of renewables penetration in Italy.

Bigerna et al. focused on the influence of renewables penetration on the possible contagion effect among the six regional electricity markets in which Italy is divided (North, Center-North, Center-South, South, Sicily and Sardinia) as a consequence of a shock in a certain market: they demonstrated that evidences of an increase in such effects caused by renewables penetration cannot be found.

Gullì et al. evaluated the impact of photovoltaic power generation on the wholesale electricity prices. The authors highlighted that an increase in electricity generation from PV could lead to non-univocal effects on the price.

Starting from these studies and findings, the aim of the proposed case study has been to analyse the **effects of NPRS on the Italian electrical transmission network** (that can be considered interesting due to its peculiarities) in the case of different penetration rates and flexibility levels. This analysis has been carried out by developing a tool based on the NREL approach methodology [166]. In particular, different penetration rates have been assumed in order to evaluate the sensitivity of the system.

4.3.4 The local scale: reliability of district heating networks

The main goal of this case study is the **integrated analysis** of the thermo-fluid dynamic behaviour and of the **reliability** aspects for District Heating Networks (DHNs), in order to quantitatively assess the **service quality**, also taking into account the possible contribution provide by a proper choice, sizing and location of Thermal Energy Storage systems (**TESs**).

DHNs are a common technological solution suitable for enhancing energy savings and ensuring **environmental benefits** at urban scale. In the scientific literature, several studies revising and analysing the current technological status, the role of these networks and their possible evolution in future energy systems are available. In particular, Rezaie et al. [177] highlighted the economic and environmental advantages related to district heating and cooling systems. They underlined that thermal energy networks able to integrate different typologies of heat producers (as industries, CHP plants and consumers that can sell overproduced heat) could support the penetration of district energy systems, and consequently the growth of contribution provided by renewables to the heat generation. Werner [178] considered instead several aspects (supply, technical, market, institutional) related to district heating and cooling systems at global level and underlined the possible relevant benefits deriving from these solutions in terms of carbon emissions and costs reduction and security of supply increase. However, they also put into evidence the need for additional efforts for effectively promoting the penetration of these systems. Furthermore, Lake et al. [179] in their review considered the importance that energy policies can have in enhancing the efficiency and quality of district heating networks and in supporting the transition towards renewables, thus positively impacting on sustainability. In fact, they highlighted that the district energy systems optimisation should take into account economic and environmental considerations, and not only thermal aspects.

It can be observed that these networks can be considered **complex structures**, made by several sub-systems, like heat production plants, pipelines, pumping stations, storages and final users. In turn, a high number of components reciprocally interfaced constitutes these sub-systems. Moreover, the complexity of these systems is enhanced by the distribution of plants and final users that leads to a difficult definition of optimal design, operating and maintenance.

Some DHNs are characterised by **storage** systems for increasing their efficiency by decreasing peak loads and consequently the plants size. Furthermore, this system configuration also allows to sell the electricity generated by CHP plants during the more suitable time frames. These configurations can also have positive impacts on the reliability and availability of the network. In fact, they can guarantee its function (the heat supply to the users) in case of failures causing outages and requiring repair actions and during the periods of planned maintenance, avoiding temporary interruptions of the service.

In general, the analysis of DHNs should not consider only technical, energy and economic aspects but it should also takes into account the **reliability** ones. In fact, these aspects can deeply impact on the maintenance costs and on the willingness to pay of the users. If the system is reliable, new users can be prone to be connected to the network. Apart from the environmental benefits and from the advantages for the public administrations, this could be positive also for the companies that manage the network, as they can improve both its reputation and revenues. However, the methodologies commonly adopted for the technical and topological planning of district heating networks do not consider, in a systematic way, reliability and maintainability aspects.

This is confirmed by the analysis of the available scientific literature, where few studies are devoted to the investigation of DHNs linking the energy aspects with the **reliability approaches**. Gang et al. [180] focused on Individual Cooling Systems (ICSs) and District Cooling Systems (DCSs) and introduced reliability concepts and uncertainties in the design phase (in turn deriving from building design, indoor conditions and outdoor weather) into an optimisation method (i.e. total system cost minimisation). In this way, they put into evidence the impacts on the optimal design arising from the presence of reliability considerations. Babiarz et al. [181] analysed instead the district heating networks under a probabilistic perspective, taking into account, in particular, the operational states and the modifications required for guaranteeing the coverage of the variable thermal loads. The authors described them by means of a semi-Markov method that could be also applied to reliability studies.

Rimkevicius et al. [182] and Valinčius et al. [183] proposed a **comprehensive methodological approach** that takes into considerations three main analyses: thermal–hydraulic deterministic analysis, probabilistic analysis and deterministic/probabilistic structural integrity analysis for the network pipelines. This approach has been applied to a case study related to a grid located in Kaunas (Lithuania). The authors, however, do not develop a single tool for evaluating the thermo-fluid dynamics, the availability and the reliability of the network taking into account all its most important components and their dynamics. The tool developed by Carpignano et al. [184] can be considered an alternative to this method. This tool considers hydraulic aspects and can also simulate failure and repair processes. Considering networks others than DHNs, Praks et al. [185] implemented a physical analysis of the natural gas grid in Europe through of the Maximum Flow Algorithm [186]. However, in their study, they modelled storage systems as infinite sources and do not consider the transport of heat and power.

Various analyses are instead devoted to the investigation of **innovative techniques** (mainly **optimisation** procedures) for DHNs design that typically include economic, technical and environmental considerations, but that do not include parameters able to numerically describe failure and repair processes or to evaluate the impacts of different network layouts on reliability. Among these analyses, some based on optimisation approaches and, in particular, on integer programming can be mentioned. Powell et al. [187] studied the potentiality of thermal energy storages in district energy systems through a dynamic optimisation approach able to find the more suitable time periods for storing the amount of energy produce in excess. They, in particular, divided the problem into a set of mixed integer non-linear problems (MINLP) having as objective functions the minimisation of the overall cost over a 24 hours period. Wu et al. [188] developed instead a multi-objective optimisation mixed linear programming (MILP) model for identifying the system configuration that corresponds to the minimum total cost and CO_2 emissions. This model is intended for studying distributed energy networks (DENs) in case of heat exchange between class of buildings; DENs include not only electricity and fuel networks, but also heating and cooling systems. Haikarainen et al. [189] developed a MILP optimisation model for DHNs in order to find the system configuration (both structural and operational) that minimise the total system cost; they used this procedure for a case study relted to a typical Finnish town. Mertz et al. [190] adopted instead a implemented an optimisation MINLP algorithm – by using the modelling environment GAMS [191] and DICOPT [192] as solver – for developing a tool for the layout design of district heating networks. The objective function of this model is the overall system cost and it takes into account both investments costs and operating costs.

Bordin et al. [193] implemented a linear programming model based on the graph theory. This model considers the technical and hydraulic characteristics and of the network and its goal is to optimise the connection of new users to the network itself under a minimum cost perspective.

Raine et al. [194] investigated the impact that a combination of Combined Heat and Power plants and storage systems can have on the fulfilment of variable heat demand at the level of individual buildings and multi-buildings. The authors demonstrated the positive effects in terms of costs savings (showing, in particular, the short payback period for storage system), in growing CHP running time and in decreasing CO_2 emissions. Bachmaier et al. [195] proposed instead a technical and economic optimisation methodology for identifying the location of thermal storage systems that is able to minimise investment cost, fuel cost and maintenance cost and maximise revenues obtained from the sale of electricity.

Wang et al. [196] considered the thermal characteristics of DHNs optimisation by defining a matrix model for simulating the thermal steady-state behaviour of the network, helpful in increasing the efficiency in the grid design and operation. This model described the system as a set of branches and nodes and it is based on a non-linear objective function, corresponding to the difference between the temperatures observed and those predicted by the model, which has to be minimised.

Vesterlund et al. [197] developed a new approach for describing thermal energy distribution in DHNs. They considered, in particular, the network loops, that typically are not appropriately taken into account in other more classical methods (as the German [198] and the Danish [199] ones) that combine small branches into larger branches. Vesterlund et al. [200], in another analysis, implemented a tool embedding this approach and tested it through an application to a case study represented by the DHN located in Kiruna (Sweden). In this way, they highlight its advantages and usefulness in redesigning the grid when a reorganisation of urban districts is scheduled, avoiding modification on its physical structure.

Wang et al. [201] – starting from the expected relevance of renewables penetration in next decades – analysed instead the impacts of coupling renewables, storages and CHP plants by means of an optimisation approach for planning procedures. The goal of this approach is the minimisation of the overall net acquisition cost, in the deregulated market, for power and heat. Considering that CHP plants are not a proper option for the coverage of the peak loads, Wang et al. [202] investigated also the economic and energy impact on the network caused by alternative siting solutions for boilers adopted for covering peaks. In this way, it is possible to define the positions that determine the lowest overall system costs. Moreover, Wang et al. [203] developed a multicriteria decision making methodology useful in for studying and comparing different combinations of CHP plants for covering the base load and gas-fired boilers used for the peak shaving. By means of ad hoc sub-models, the authors modelled the various energy, environmental, economic and technical characteristics. Among the technical characteristics, they considered the reliability by introducing a coefficient able to describe the back-up heat capacity in the case of the worst hydraulic failure that could happen in the system. They demonstrated that gas-fired boilers can positively impact on the reliability, as they can be independently operated in case of failures, thus being beneficial from the point of view of the system functionality. Eventually, Wang et al. [204], proposed a fuzzy grey multicriteria model for solving issues associated to the uncertainties that can affect measures and weights of criteria. In order to do this, they linked the grey relational analysis and the fuzzy set theory and, for testing purposes, applied this approach to a case study related to a Chinese city.

Bach et al. [205] studied – by means of the bottom-up energy optimisation model Balmorel [206] (which focuses on heat and electricity and whose objective function is the minimisation of the overall system cost) – the effects of an integration of heat pumps in the district network of Greater Copenhagen under different scenarios.

Ascione et al. [207] proposed a georeferred energy model for the optimisation of production and use at urban scale. In addition to the assessment of the energy demand of the building stock and of the benefits determined by the application of measures aiming at enhancing the energy efficiency, they investigated the positive effects of distributed power generation and of district heating and cooling systems.

Other studies have been devoted to the analysis of alternative strategies for design and planning of DHNs, exploring the impacts on the grid given by the adoption of new options. Comodi et al. [208] focused on the ways for facing the most relevant criticalities associated to networks based on CHP plants, as low market revenues and the plants oversizing, able to cause low energy efficiency. They considered, in particular, alternative options to be introduced into the system, like high temperature heat pumps, thermal heat storages and internal combustion engines. They highlighted that heat pumps can increase the revenues but not the efficiency, while storages can enhance the energy efficiency but not the revenues. Cogeneration gas internal combustion engines can instead beneficially affect both these aspects. Brand et al. [209] estimated the effect of the introduction of heat pumps and small solar collectors for giving the opportunity to consumers to become producers (i.e. prosumers). The authors underlined that this option could be feasible from a technical point of view, but it needs to carefully consider the whole grid management for avoid various criticalities that could impact on the DHNs. Laajaletho et al. [210] assessed the advantages of adopting network configurations that include a ring network design and a mass flow control system with respect to the classical design techniques. The results of a case study related to the city of Helsinki (Finland) showed that this approach is more effective in comparison with the traditional ones. Lundström et al. [211] analysed, under the environmental and efficiency perspective, the impact of heat demand curves that represent eight energy conservation measures (ECMs) in buildings, showing that only the improvement in building envelops and the reduction in electricity consumption are beneficial regardless other conditions and factors. Lizana et al. [212] investigated the benefits of district heating networks in a decarbonisation framework, underlining that this could be a key option for reducing emissions in the residential sector. In particular, the authors considered biomass and solar networks (because of the high availability of these resources) that integrate underground storage systems in Mediterranean areas characterised by a low or moderate population density and developed a case study related to the South of Spain. Kyriakis et al. [213] focused on a district heating system based on geothermal energy and on the use of a hot water storage tank for the covering a part of the peak load. For assessing the economic, energy, and environmental benefits of this solution, the authors analysed it through two models: one for the analysis of the operational phase of the system and one for the design and sizing of the system itself. Schweiger et al. [214] studied the 4th generation of DHNs, which takes into account storage systems, low-temperature heat, enhancement in renewables penetration, and integration in smart energy systems, with electricity and natural gas. They developed a thermo-hydraulic optimisation and simulation approach based on the language Modelica [215]. Furthermore, they highlighted that this methodology can be applied to real cases by proposing two applications:

- a dynamic optimisation of a network for a district of a virtual city;
- an existing network, by simulating the characteristics of the 4th generation DHNs, considering decentralised producers, meshed grid, thermal transients and prosumers).

Pavičcević et al. [216] developed a MILP model for optimising, besides the size and operation of heat production plants and of heat storage systems, the buildings retrofit, which in turn impacts on the heat demand. They put into evidence the importance of investing in thermal insulation of buildings, which can significantly affect the evolution of the network in the long term, particularly if low-temperature systems with relevant amount of heat produced from renewables are taken into account.

Finally, other studies like the one carried out by Shabanpour-Haghighi et al. [217] proposed the implementation of methodologies for simultaneously optimising district heating networks, electric grids and natural gas grids under an integrated perspective, thus considering their interdependencies.

4.3.5 Alternative energy vectors: the role of hydrogen

Hydrogen has been often considered, during last decades, a possible relevant option for future applications in different fields. However, it should be emphasised that up to now its role is relatively limited, even if numerous studies on this topic have been carried out.

The goal of this case study is to evaluate the role that hydrogen could play in the EU energy mix and supply security, under different scenarios and over a mid-/long-term period, by means of an optimisation energy modelling methodology, focusing in particular on the effects of hydrogen penetration in the mobility sector and, in general, at urban scale.

Referring to the findings related to hydrogen penetration that can arise from the analysis on the studies available in the scientific literature, it can be noticed that relevant outlooks, like the ETP 2014 [218], underlined that the unavailability of efficient storage technologies may have been slowed down the hydrogen penetration as transport fuel.

Several technologies using hydrogen are instead already commercially feasible and are characterised by a good development stage, as highlighted in the IEA roadmap in hydrogen and fuel cells [219]. In this document, an overview related to the status of the current hydrogen-fuelled vehicles and of the entire transport sector, distribution and retail chain is proposed. Even if the costs are still relevantly higher than the ones of the corresponding technologies based on fossil fuels, a modification during next years can b expected, in particular if policies for decreasing the relevance of fossil fuels in the energy transition framework will be implemented. In particular, Cantuarias-Villessuzanne et al. [220] estimated the possibility of reducing the period for profitability of hydrogen-fuelled buses if carbon externalities related to other powertrains are considered.

Focusing on the EU, the Roadmap 2050 [16] defines as key goal a decarbonisation by 95% of the power sector and a decrease by 80% with respect to the 1990 level for the GHG emissions by 2050. In order to make these objectives achievable, a shift to electrification of the end-uses, biomass, and hydrogen is requested in the most relevant sectors, i.e. buildings, industry and transport. The hydrogen penetration in the building sector is expected to take place mainly thanks to CHP systems [219], fuelled by natural gas converted into hydrogen by means of internal reforming. Even if this solution can be considered technically feasible, there are various issues related to standards, regulations and grid connections that have to be solved while field tests are ongoing (*ene.field* in Europe [221] and *ene-farm* in Japan [222]).

Over long term, a relevant contribution from passenger vehicles electrification cars and from the diffusion of vehicles based on hydrogen fuel cells is expected in the mobility sector. Consequently, this will require the implementation of ad hoc infrastructures for electricity and hydrogen distribution, new emission standards and regulations for the road transport and a decrease in costs (that could be obtained through technological improvements) [223].

As mentioned, the proposed case study is developed by means of an optimisation forecasting energy model. This model is based on the TIMES (The Integrated MARKAL-EFOM System) model generator.

In the available literature, some researches adopted TIMES-based models and (more generally) optimisation approaches for analysing scenarios including the hydrogen option. For instance, the one performed by Yang et al. [224] applied the H2TIMES model for assessing hydrogen penetration in California by 2050, modelling the needed infrastructures for hydrogen supply to 8 Californian areas. A baseline scenario and different sensitivity analyses were considered for evaluating the hydrogen role in the case of

- policy constraints like those setting reduction goals for carbon intensity and the implementation of carbon capture and storage (CCS) systems;
- resources availability;
- technological improvement.

The obtained results underlined the relevance of the CCS systems and of the availability of biomass in assuring low-emission and low-cost hydrogen.

Still focusing on the Californian sitution, but considering the urban scale, Stephens-Romero et al. [225] adopted the STREET (Spatially and Temporally Resolved Energy and Environment Tool) tool for energy planning for finding the optimal configuration of the hydrogen infrastructures in the Irvine city. On the basis of the obtained results, this configuration could enhance the penetration of fuel cell vehicles, that could replace internal combustion engine (ICE) vehicles in a context of long-term strategies devoted to reach environmental (increase in the air quality and emissions reduction at urban scale) and security goals. The authors highlighted that only 8 hydrogen fueling stations are requested for obtaining services that comparable to the ones provided by the current gasoline infrastructures. Moreover, GHG emissions, air pollution and energy and water use can be lower than those of the vehicles stock fueled by gasoline. This result is independent from the way by means of which hydrogen is produced (conventional resources, like natural gas, or renewable sources locally available).

Strachan et al. [226] investigated instead the link between the UK MARKAL model and a GIS representation of hydrogen demand, resources and infrastructures. Through this integrated approach, they evaluated the hydrogen competitiveness in the case of CO_2 decrease scenarios related to the UK, particularly with respect to the mobility sector.

Starting from an improved version of the same UK MARKAL model, Dodds et al. [227], [228] studied possible options for the UK natural gas grids by considering several alternative under a decarbonisation point of view. Among these options, the authors included the use of the grids for delivering hydrogen. They showed that this alternative could decrease the total buildings heating cost in the UK.

Furthermore, Dodds et al. [229] investigated the possible role played by hydrogen for heat generation in the industrial and residential sectors, focusing on the benefits provided by fuel cells (that in several countries are a technological option close to the market). The analysis also compared several regional and multi-regional models (like the Canada, Norway and Belgium TIMES, the UK MARKAL, the JRC-EU-TIMES and the ETSAP-TIAM,), for checking if the hydrogen chain is taken into account. Among these models, only

- the JRC-EU-TIMES, which takes into account the injection of hydrogen into the gas grid and hydrogen burners,
- the UK MARKAL, which takes into account fuel cells technologies,
- the Canada TIMES and
- the UKTM, which takes into account fuel cells and hydrogen boilers

consider the heat production from hydrogen.

According to the authors' analysis, the JRC-EU-TIMES adopts high investment costs, which make uneconomic these technologies. This study emphasizes the relevance of considering hydrogen-based technologies for heat production in the industrial and residential sectors in every energy model, for considering all the possible alternative solutions in the long-term decarbonisation scenarios.

Agnolucci et al. [230] used instead the mixed-integer linear programming model SHIPMod, for finding the optimal system configuration for the hydrogen supply in the UK, considering also storage systems and CCS. The authors showed that the decisions of the model in terms of production and distribution of hydrogen and the resulting costs highly depend on the demand and on its spatial distribution.

It can be observed that the above-described analyses mainly focused on the relevance of hydrogen in decarbonisation scenarios at urban level or at regional/country scale. With respect to these analyses, the aim of the present case study is to highlight the effects that hydrogen penetration in "decarbonised" local systems, as the urban and intercity mobility sector, can have at a broader level, in particular on the energy system of the European Union. This approach can be useful for understanding in which way general goals (like the energy security and environmental) can be reached through local policies and actions (for instance in urban areas) and through the integration of smart local networks with the main distribution grids.

Chapter 5

Different perspectives and case studies with respect to the spatial scale of energy infrastructures

Part of the activities described in this Chapter have been also already published in [85], [86], [87], [88]

5.1 The macro-scale: first case study

The new methodological approach for the quantitative assessment of the security of energy supply at country scale has been developed considering that the energy security of a given country is related to 2 "**fronts**" (Figure 27).

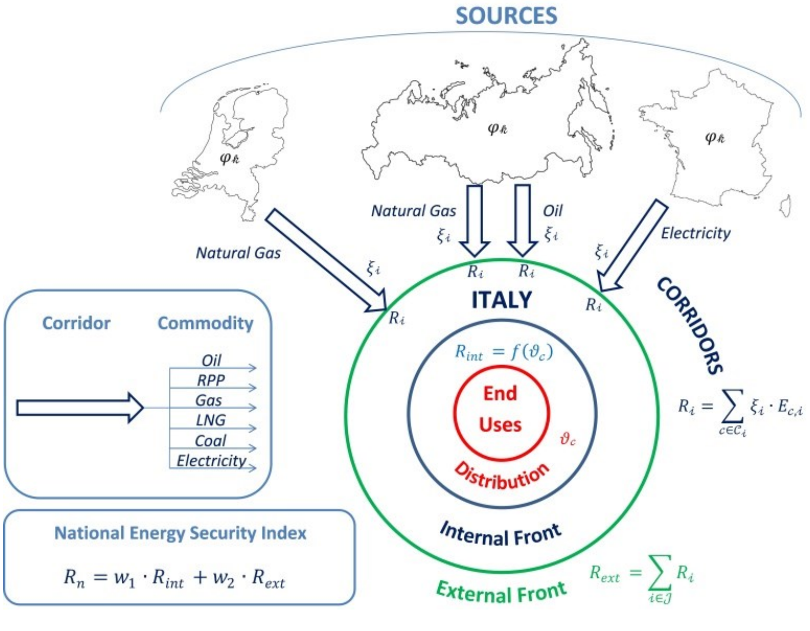


Figure 27: The different fronts and indexes for the energy security evaluation under a geopolitical perspective

The first front is the **“internal”** one and it is related to the following security aspects:

- the national (i.e. “internal”) resources for all the primary commodities (coal, oil, natural gas);
- the resilience with respect to potential attacks against the internal infrastructures and transformation plants (like terminals for LNG regasification and refineries).

The second front is the **“external”** one and involves:

- the level of geopolitical security of the source countries for the different commodities;
- the security of the energy corridors along their routes (that could be captive or open sea), from the source countries to the national entry points, considering the risk of the various crossed countries;
- the impacts on the energy imports due to the unavailability of the above-cited corridors.

In general terms, a security index able to quantify the energy risk can be related to each of the fronts, and their combination can give a measure of the security of the considered country.

The different **parameters** and indexes defined and introduced for developing the methodology are listed in Table 7.

Table 7: Main parameters and indexes

Parameter / Set	**Description**
$\mathcal{C} = \{\ldots, c_{c,} \ldots\}, dim(\mathcal{C}) = C$	**Set of energy commodities**
$\mathcal{J} = \{\ldots, i_{i,} \ldots\}, dim(\mathcal{J}) = I$	**Set of energy corridors**
$\mathcal{C}_i \subseteq \mathcal{C} \mid c_i \in \mathcal{C}_i$	**Commodity delivered by corridor i_i**
$\mathcal{K} = \{\ldots, k_{k,} \ldots\}, dim(\mathcal{K}) = K$	**Set of countries (both source and corridor)**
$\mathcal{K}^i \subseteq \mathcal{K} \mid k^i_h \in \mathcal{K}^i$	**Country crossed by corridor i_i**
$\mathcal{L} = \{\ldots, l_{l,} \ldots\}, dim(\mathcal{L}) = L = I$	**Set of corridor lengths (km)**
$\mathrm{B}^i = \{\ldots, b_{b,,} \ldots\}, dim(\mathrm{B}) = B^i,$	**Set of the lengths of branches of corridor i_i**
$\mathcal{D} = \{\ldots, d_{d,} \ldots\}, dim(\mathcal{D}) = D$	**Set of distribution / transmission infrastructures**
γ_k	**Geopolitical country index weight for Country k, depending on the length of each corridor branch**
$\vartheta_{c,d}$	**Resilience index for the internal distribution network d carrying commodity c**
ξ_i	**Risk index of corridor i**
φ_k	**Geopolitical country index for country k**
X	**Import dependency (%)**
ω_i	**Probability of success of corridor i**
Q	**Energy Intensity of the Economy**
w_1	**Weight coefficient for the internal risk**
w_2	**Weight coefficient for the external risk**
R_i	**Risk of corridor i**
$R_{int\ (ext)}$	**Overall internal (external) risk value**
$R_{int\ (ext),m}$	**Overall internal (external) risk, monetary units**
S_i	**Expected supply of corridor i**
$S_{int\ (ext)}$	**Overall internal (external) expected supply**
E	**Total energy supply**
$E_{c,i}$	**Energy flow of commodity c carried by corridor i**
R_n	**National Energy Security Index**

The risk related to the internal front has not considered in the framework of this study, however it has been mentioned in order to identify the possibility of expressing the overall country risk as a suitable weighted combination of the two risks. The **internal risk** can be considered, in general, a function of the resilience of the transmission/distribution network.

$$R_{int} = f\left(\vartheta_{c,d}\right) \tag{8}$$

Where $\vartheta_{c,d}$ is an index that quantifies the resilience of the internal infrastructure d_d distributing the commodity c_c.

The **external risk** is instead evaluated starting from the risk associated to each corridor. In turn it is assumed as a weighted function of the contribution provided by single risk indexes related to the source country and to the countries crossed by the corridor, and of the energy content of the commodity carried by it.

A corridor i is defined as:
$\forall i_i \in \mathcal{J} : i_i = \{c_c, l_l, \mathcal{K}_i\} \mid c=l=i$
Corridor $i_i \in \mathcal{J}$ is characterised by:

- a commodity $c_i \in \mathcal{C}_i$
- a length $l_i \in \mathcal{L}$
- a set of countries crossed by the corridor $\mathcal{K}^i$ with $k^i_i \in \mathcal{K}^i$, the country of origin, $dim(\mathcal{K}^i) = K_i$ the number of countries crossed.

For assessing the criticality level of a country from the **geopolitical** point of view, an index $\varphi_k \in [0,100]$ has been introduced.

For each **corridor** i_i a risk index ξ'_i is introduced, according to the concept of **"probability of failure"** [231]:

$$\xi'_i = 100 \cdot \left[1 - \prod\nolimits_{k_i \in \mathcal{K}_i} \left(1 - \frac{\varphi_k}{100}\right)\right] \tag{9}$$

Where:

- $\left(1 - \frac{\varphi_k}{100}\right)$ is the probability of success in crossing country k
- $\prod_{k_i \in \mathcal{K}_i} \left(1 - \frac{\varphi_k}{100}\right)$ is the probability of success (for independent events) in crossing the whole set of countries present along the path of the corridor
- $1 - \prod_{k_i \in \mathcal{K}_i} \left(1 - \frac{\varphi_k}{100}\right)$ is the probability of failure for the whole corridor, evaluated as the complement to 1 of the probability of success.

Each corridor is made by several branches crossing several countries, and each branch is characterised by a different length. The total length l_i of corridor i_i is expressed by the sum of the single lengths of all the branches:

$$l_i = \left\|\mathrm{B}^i\right\|_1 \tag{10}$$

According to this, a **"spatial dimension"** in the assessment of the risk is considered: the contribution of a certain country (characterized by a risk index φ_k) to the total corridor risk is assumed proportional to the length of the corridor branch crossing that country.

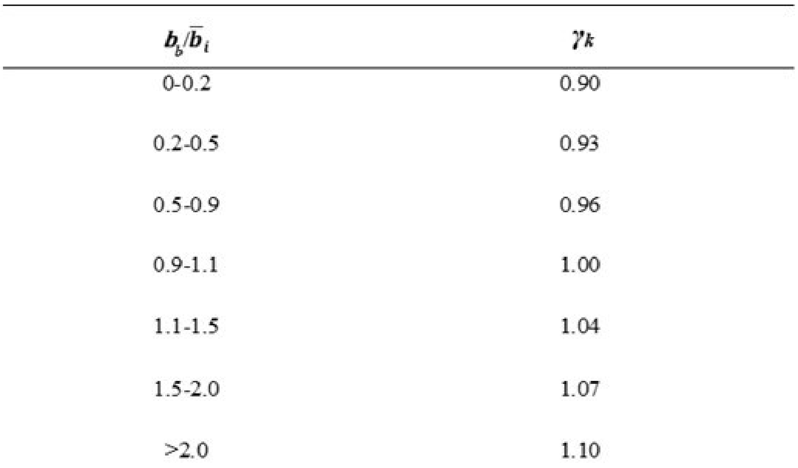
For this purpose, an empirical **weighting function** γ_k is introduced into (9):

$$\xi_i = 100 \cdot \left[1 - \prod\nolimits_{\mathscr{k}_i \in \mathcal{K}_i} \left(1 - \frac{\gamma_k \cdot \varphi_k}{100}\right)\right] \tag{11}$$

The values of γ_k assumed in the analysis are a function of the ratio among the actual corridor branch length, b_b, and the average corridor branches length, $\bar{b}_i$, and are reported in Table 8.

$$\bar{b}_i = \frac{l_i}{K_i} \tag{12}$$

Table 8: Weighting function γ_k



$b_b/\bar{b}_i$	γ_k
0-0.2	0.90
0.2-0.5	0.93
0.5-0.9	0.96
0.9-1.1	1.00
1.1-1.5	1.04
1.5-2.0	1.07
>2.0	1.10

Regarding maritime routes and submarine pipelines, it has to be highlighted that territorial waters and international waters has to be considered in the evaluation of the corridor risk. For avoiding an underestimation of the risk of the open sea corridors with respect to the one of the land corridors, an area of influence (covering a portion of the international waters) could be defined for each country. To this zone, the same index φ_k of the country can be adopted.

According to the classical definition provided by the common approach of the risk analysis, the **risk** R_i, associated to corridor i_i, can be estimated as the product between probability and damage. The probability is represented by the probability of failure ξ_i and the damage by the energy flow (associated to a commodity c_c) $E_{c,i}$, carried by the corridor and potentially lost:

$$R_i = \sum_{c_i \in \mathcal{C}_i} \frac{\xi_i}{100} \cdot E_{c,i} \tag{13}$$

The **total external risk** can be thus calculated by summing the risk values for all the corridors that supply the considered country:

$$R_{ext} = \sum_{i_i \in \mathcal{J}} R_i \tag{14}$$

This physical risk can be converted into an **economic risk** (i.e. in equivalent monetary units) by means of the country “energy intensity of the economy” Q (measured, for instance, in TJ/G€). This indicator is in turn expressed as the ratio among the gross internal energy consumption (measured in energy units, like TJ) and the Gross Domestic Product (GDP, measured in monetary units, like G€).

$$R_{ext,m} = \frac{R_{ext}}{Q} \tag{15}$$

This conversion can allow quantify the economic effects of the geopolitical energy risk, due to the fact that a possible loss of imported energy flows related to the unavailability of a given energy supply can determine a corresponding GDP loss [232].

Referring to the **time scales**, the analyses can be performed with reference to different time granularities, for instance on a yearly, quarterly or monthly base. While the annual time scale is the one commonly used with respect to the country energy balances, a finer time discretization (like the monthly one), could allow the study of specific criticalities, as the seasonal ones related to the supply of natural gas during winter.

Furthermore, with respect to the external front, it is possible to introduce and estimate the **“expected supply”**. Taking into account that the above-mentioned probability of success of each corridor (i.e. its availability) can be expressed as:

$$\omega_i = 100 \cdot \left[\prod\nolimits_{\mathscr{k}_i \in \mathcal{K}_i} \left(1 - \frac{\gamma_k \cdot \varphi_k}{100} \right) \right] \tag{16}$$

The expected supply value S_i for corridor i_i can be calculated as the product between the probability ω_i and the energy flow $E_{c,i}$ of the commodity c_c carried by the corridor:

$$S_i = \sum_{c_i \in \mathcal{C}_i} \frac{\omega_i}{100} \cdot E_{c,i} \tag{17}$$

As a consequence, the overall expected supply S_{ext} (measured in energy units, like TJ) is the sum of the expected supply values for all the corridors:

$$S_{ext} = \sum_{i_i \in \mathcal{J}} S_i \tag{18}$$

Moreover, the expected supply can be also expressed as the difference between the total energy supply E and the total external physical risk R_{ext}:

$$S_{ext} = E - R_{ext} \tag{19}$$

It has to be further underlined that proposed methodological approach considers the events as independent, thus leading to a risk overestimation, which is conservative.

The internal (as previously said, not developed in this doctoral project) and the external risk values can be combined in order to define a National Energy Security Index R_n. In particular, the two risk values can be weighted by means of two coefficients (w_1 and w_2) and summed together:

$$R_n = w_1 \cdot R_{int} + w_2 \cdot R_{ext} \tag{20}$$

The coefficients w_1 and w_2 can be calculated as a function of the percentage import dependency χ of the analysed country:

$$w_1 = 1 - \chi \tag{21}$$
$$w_2 = \chi \tag{22}$$

Figure 27 graphically summarises the two considered fronts and the developed risk indexes for the assessment of the energy security in a geopolitical perspective, with respect to a single country (namely, in the figure, Italy).

It has to be underlined that aim of the described approach is to assign a probability to each country, in order to describe the likelihood that a given corridor crossing the country fails because of geopolitical reasons, and it is not to carry out forecasting studies regarding unpredictable events. For this reason, the error analysis on the main parameters (like energy flows and corridor branch lengths) in the proposed methodology is not particularly relevant with respect to the need of understanding if an event could happen or not. Obviously, disruptive geopolitical events can unexpectedly occur, and they could relevantly impact on the probability values associated to the single countries. Consequently, sensitivity analyses on the risk parameters can allow to assess the effects of such events on the overall energy risk. Moreover, in outlining sensitivity scenarios, it could be suitable to take into account that an event occurred in a given country can impact on other countries belonging to the same geographical area. As a consequence, in some situations the level of geopolitical risk should be jointly quantified, homogeneously modifying the risk values of all the countries in the area. This consideration could be especially significant for areas like North Africa and the Middle East (the presence of terroristic groups in these zones and the so-called “Arab Spring” can be assumed as examples).

This methodology has been applied to the **Italian national energy supply**, focusing on the assessment of the external risk component (i.e. the R_{ext} parameter), neglecting instead the internal one.

In particular, six imported commodities (crude oil, refined petroleum products, coal, LNG, natural gas and electricity), carried by 263 corridors (including oil and gas pipelines, maritime routes, power lines, roads and railways) have been considered. They account for 97.5% of the Italian energy import in 2014 [233], [234].

Referring instead to the country risk indexes, the adopted **country risk indexes** are shown in Figure 28 and in Table 9.

They have built on the basis of those proposed in the FP-7 European project REACCESS (Risk of Energy Availability: Common Corridors for Europe Supply Security) [235]. As said in the previous Chapter, the goal of the project was the development of a tool able to allow the implementation of scenario analyses for the European energy system, by linking three forecasting optimisation TIMES-based [46] energy models and by including a numerical evaluation of the geopolitical supply risk. For this purpose, a risk index (steady over time and ranging between 0 and 100) was introduced for all the countries (both source and crossed) involved by the energy corridors paths. The country indexes are a function of the political-institutional, socio-political, economic and energetic security level of the countries, and have been estimated through factor analysis methodologies by Marín-Quemada et al. ([236], [237], [238]). In the follow-up of the project, these indexes have been combined by Gerboni et al. [231], by means an application of the reliability theory, for building a unique risk index for each corridor, assuming the risk index associated to each crossed country as the probability that a corridor crossing that country would fail. Assuming the same risk indexes, Doukas et al. [239] implemented a web tool for analysing oil and gas corridors, applying it to a case study related to the Greek supply. Starting from the same methodological approach based on factor analysis techniques, Muñoz et al. [240] defined the country composite indicator GESRI (Geopolitical Energy Supply Risk Index). This index combines the political and social dimensions in a unique risk vector and it introduces a new vector, representing the relations of exporting countries and transit countries with the European Union. Furthermore, in the framework of the REACCESS project, Carpignano et al. [241] developed a methodology for evaluating the technological risk and the production losses due to failures of energy corridors, including these elements in the analysis of the scenarios for the European energy supply.

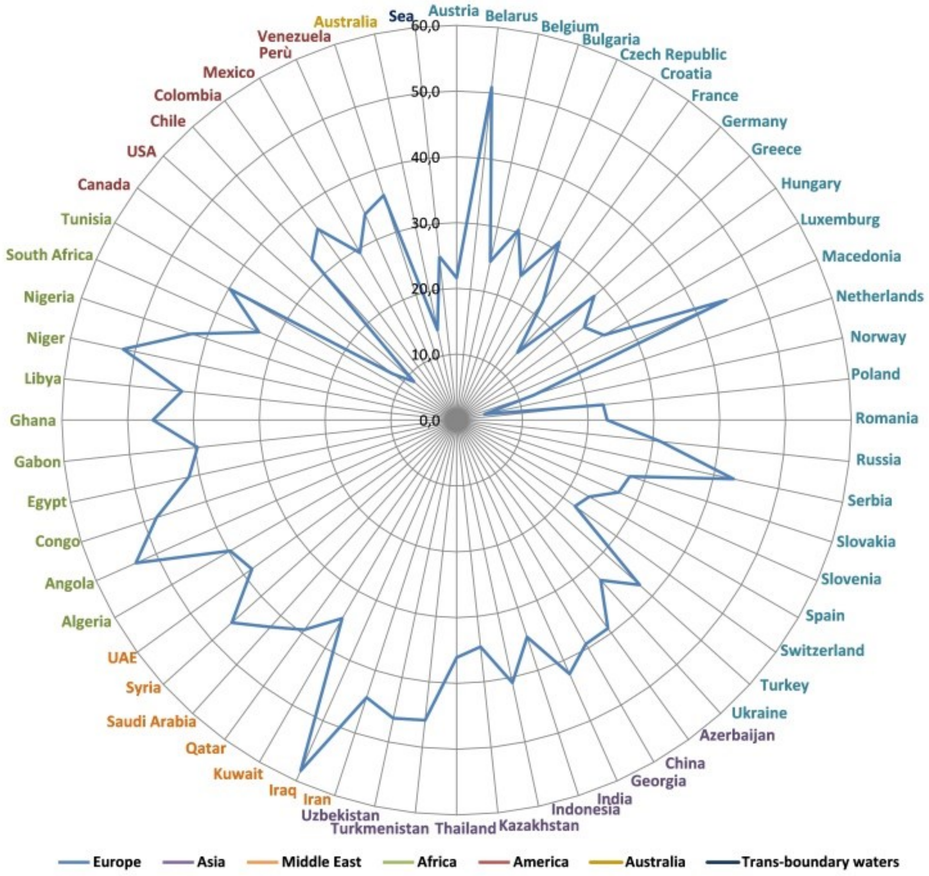


Figure 28: Polar diagram of the geopolitical country index φ_k

Table 9: Geopolitical country index φ_k

Source Country	φ	Source Country	φ
Algeria	44.7	Mexico	31.7
Angola	61.7	the Netherlands	10.5
Australia	12.5	Nigeria	48.0
Austria	22.0	Norway	0.4
Azerbaijan	43.9	Qatar	44.2
Belgium	25.8	Russia	34.0
Canada	9.9	Saudi Arabia	47.9
China	44.1	Slovenia	28.7
Colombia	39.9	South Africa	36.1
Congo	55.0	Spain	24.1
Egypt	47.0	Switzerland	22.8
France	23.0	Syria	52.5
Gabon	44.5	Thailand	40.1
Germany	12.3	Tunisia	44.7
Ghana	52.7	Turkey	41.8
Greece	30.2	Turkmenistan	52.3
India	38.3	the Ukraine	35.9
Indonesia	46.0	the UAE	43.1
Iran	50.4	the USA	5.9
Iraq	67.9	Venezuela	39.9
Kazakhstan	38.3		
Kuwait	38.5		
Libya	47.5		

Italian energy security has been evaluated with respect to 5 **scenarios**. These scenarios are related to two possible configurations:

- the criticality of the country increases because of a deterioration of the geopolitical conditions. This situation is simulated by increasing the values of the geopolitical country index
- the country is involved in actions that lead to a corridor failure.

In detail, the five scenarios (*S1*-*S5*) that have been modelled are (Table 10):

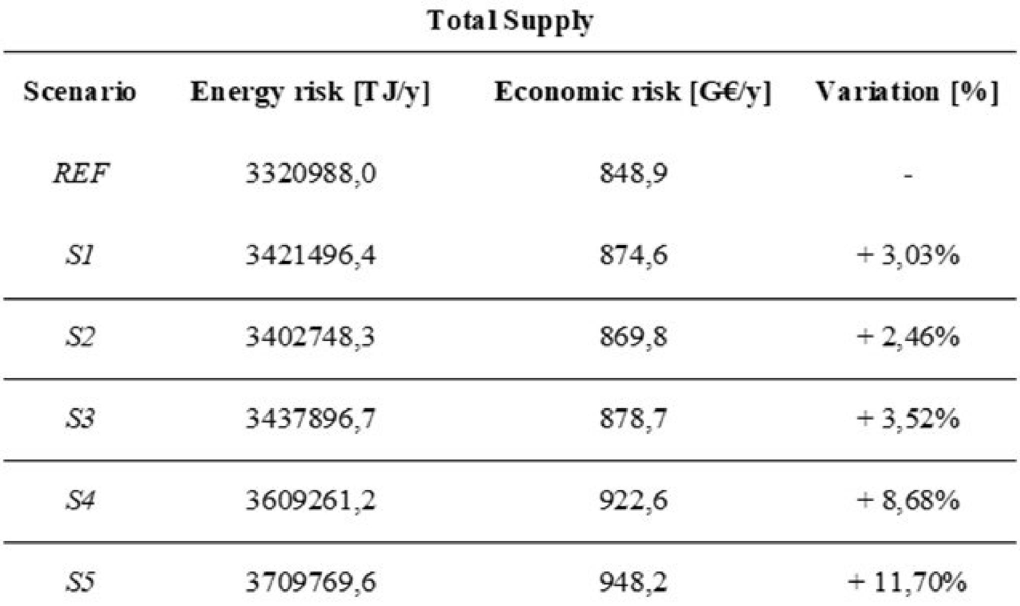
- *S1*: Increase in terroristic groups activity in North Africa countries (Egypt, Algeria, Tunisia, Libya);
- *S2*: Deterioration of the diplomatic relations among Italy and Qatar, causing a cut in LNG exports from Qatar to Italy;
- *S3*: Actions of antagonistic groups in Libya, leading to a disruption of the Greenstream natural gas pipeline;
- *S4*: Increase in the political tensions among the Ukraine and Russia, with a growth in the country risk and the disruption of natural gas and oil corridors starting from Russia crossing the Ukraine;
- *S5*: Simultaneous occurrence of scenarios S1 and S4.

Table 10: Considered scenarios

Scenario	Description	Country risk φ_k	Corridor disruption
S1	Increased activity of terroristic groups in NA	+15% Algeria, Egypt, Libya, Tunisia	-
S2	Deterioration of the Italian/Qatari relations	-	Unavailability of all the Qatari LNG corridors (4)
S3	Antagonistic actions in Libya	-	Disruption of the NG Greenstream corridor (1)
S4	Increase in contrast between Russia and the Ukraine	+10% Russia, Ukraine	Closure of the NG/Oil pipelines in the Ukraine (3 +1)
S5	Simultaneous Scenarios 1 + 4	+15% Algeria, Egypt, Libya, Tunisia; +10% Russia, Ukraine	Closure of NG/Oil pipelines in the Ukraine (3 +1)

The impacts of these scenarios have been calculated, taking into account the energy risk R_{ee} and economic risk R_{em} (Table 11). These values have been compared to the ones for 2014 (Reference configuration, *REF*: defines to the actual situation of energy flows, suppliers and corridors), in turn calculated by means of the country indexes indicated in Table 9.

Table 11: Impacts for the analysed scenarios, all the commodities (*REF* 2014)

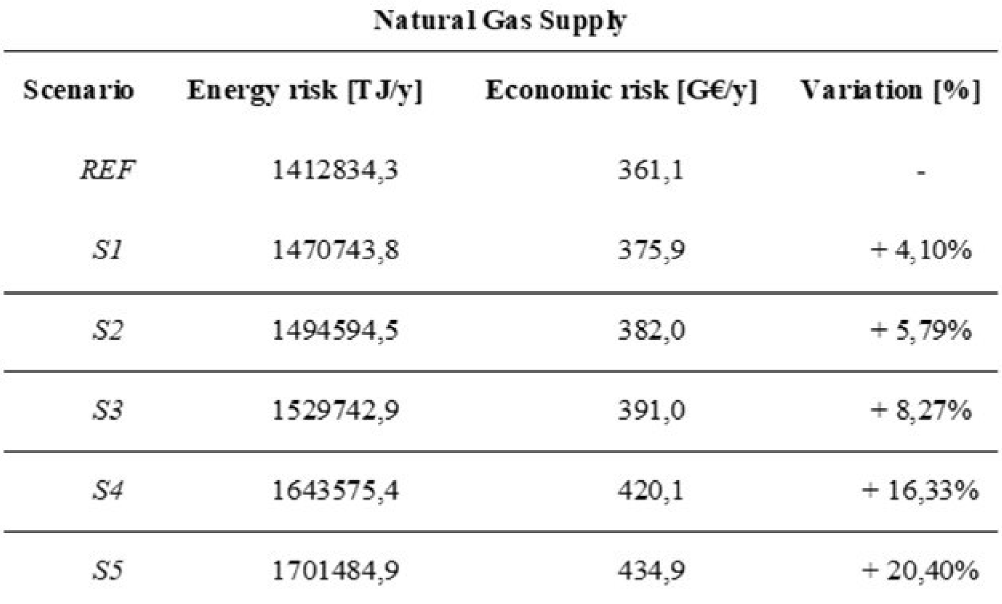


Total Supply

Scenario	Energy risk [TJ/y]	Economic risk [G€/y]	Variation [%]
REF	3320988,0	848,9	-
S1	3421496,4	874,6	+ 3,03%
S2	3402748,3	869,8	+ 2,46%
S3	3437896,7	878,7	+ 3,52%
S4	3609261,2	922,6	+ 8,68%
S5	3709769,6	948,2	+ 11,70%

In Table 12, the indexes have been calculated taking into account only the supply of natural gas, which accounted for 33% of the Italian imports in 2014.

Table 12: Impacts for the analysed scenarios, only natural gas (*REF* 2014)



Natural Gas Supply

Scenario	Energy risk [TJ/y]	Economic risk [G€/y]	Variation [%]
REF	1412834,3	361,1	-
S1	1470743,8	375,9	+ 4,10%
S2	1494594,5	382,0	+ 5,79%
S3	1529742,9	391,0	+ 8,27%
S4	1643575,4	420,1	+ 16,33%
S5	1701484,9	434,9	+ 20,40%

S1 shows a growth (about 3%) for R_{ee} and R_{em} , mainly related to the high number of corridors (i.e. 79, corresponding to 30% of the total) involved in the growth of the geopolitical risk of the considered countries; their average risk index ξ grows by 17.6%, with respect to the *REF*, and the total ξ value growss by 5.4%.

Table 13: Energy risk and Economic risk change on monthly base for *S1*

Month	Energy risk [TJ/month]		Economic risk [G€/month]		Variation [%]
	REF	*S1*	*REF*	*S1*	
January	326301,9	335475,6	83,4	85,7	+ 2,8%
February	266461,9	275681,2	68,1	70,5	+ 3,5%
March	285720,8	292396,6	73,0	74,7	+ 2,3%
April	271453,4	280431,3	69,4	71,7	+ 3,3%
May	303996,6	313961,8	77,7	80,3	+ 3,3%
June	260970,7	267085,1	66,7	68,3	+ 2,3%
July	290410,6	297436,9	74,2	76,0	+ 2,4%
August	259432,6	268039,6	66,3	68,5	+ 3,3%
September	246424,2	255304,8	63,0	65,3	+ 3,6%
October	264644,3	271567,0	67,6	69,4	+ 2,6%
November	266992,5	276374,6	68,2	70,6	+ 3,5%
December	278178,6	287741,8	71,1	73,5	+ 3,4%

In Table 13 the analysis is carried out at a monthly scale. In this case, the two risk indexes show a peak in September, because of a growth in the energy flow from the countries involved in the scenario *S1*. A risk growth can be noticed for *S1* but, because of the absence of corridors disruptions, the inflows are ensured.

S2 shows a critical situation regarding the LNG supply (whose flow from Qatar was 172.8 PJ/y in 2014). By simulating the complete unavailability and expected supply = 0 for the whole set of the Qatari corridors (obtained by imposing the corridor risk index equal to 100%), the total risk grows by 2.46%. This change is caused by the gas corridors, whose contribution to the overall risk grows by 5.79% with respect to the *REF* scenario.

S3 shows a growth in the total risk by 3.52%. This variation is due to the disruption of the Greenstream natural gas corridor (ξ = 100%). This unavailability has a significant impact on the risk related to the natural gas supply, which grows by 8.27%. Moreover, the energy lost as a consequence of the Greenstream gas pipeline disruption cannot be replaced by a same amount imported from the same supplier (i.e. Libya) as LNG. In fact, the only Libyan LNG terminal (located in Marsa al-Brega) was damaged during the civil war and it has been out of service since 2011.

S4 impacts on the entire national gas import from Russia (which corresponds to 48.82% of the total) and on 3% of the imports of crude oil. This configuration has a relevant effect on the total risk, leading to a growth equal to 8.68% (+16.33% for the risk associated only the gas supply). This is mainly caused by the high Italian import dependency on Russia. Consequently, this scenario puts into evidence the relevance of supply diversification (in terms of sources, corridors and suppliers), for avoiding similar criticalities and increase the level of security.

S5 combines the effects of *S1* and *S4*. This scenario is particularly risky, due to the fact that it involves 46.1% of the overall National energy supply. This situation is particularly critical for the gas supply, because it affects more than 70% of the import. The percentage of coal, oil and refined petroleum products imports involved is lower, but still relevant, ranging between 20% and 50%. The increase in the total risk is equal to 11.7%, mostly caused by the natural gas contribution (+20.4%). This significant growth can be explained by taking into consideration that 7 suppliers (namely Russia, the Ukraine, Libya, Algeria, Tunisia, Egypt and Nigeria) and 98 corridors are subject to a change. In particular, the average ξ value grows by 17.5% with respect to the *REF* scenario.

If a scenario causes a loss of energy flow (*S2-S5*), ad hoc countermeasures have to be defined, in order to guarantee the requested supply. For this reason some possible **mitigation options** for the different scenarios have been hypothesised (also analysis their feasibility) and tested through the proposed methodology, by performing a comparison in terms of risk reduction with respect to the related scenario.

For the scenario ***S2***, the following alternative actions have considered:

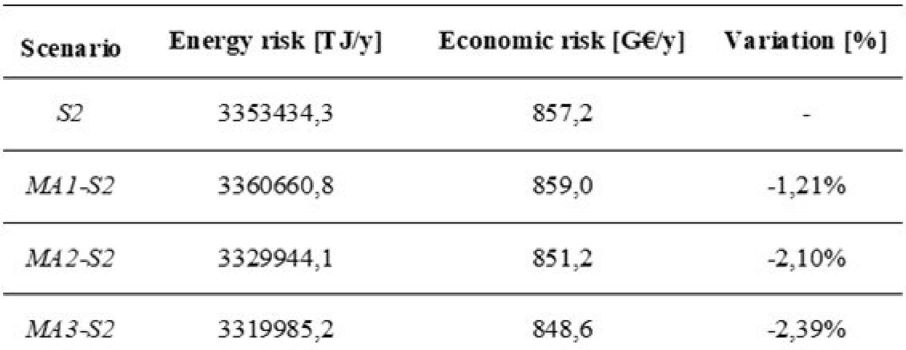
- *MA1-S2*) *Replacement of the LNG flow from Qatar with a natural gas flow from Russia (50%, via the TAG pipeline) and Algeria (50%, via the Transmed pipeline).*
  This option is compliant with the maximum capacities at the Italian entry points and it allows to assure the requested yearly natural gas supply, with a risk decrease by 1.21% with respect to *S2*.

- *MA2-S2*) *Replacement of the LNG flow from Qatar with a natural gas flow from Russia (50%, via the TAG pipeline), the Netherlands (25%, via the Transitgas pipeline) and Norway (25%, via the Transitgas pipeline).*
  This option leads to a risk reduction equal to 2.10%, higher than the one obtainable from the option *MA1-S2*, due to the low risk related to Norway and the Netherlands.

- *MA3-S2*) *Replacement of the LNG flow from Qatar with a natural gas flow from the UAE (100%, via LNG maritime routes arriving in the regasification terminals near Porto Levante and Panigaglia).*
  The obtained risk reduction (-2.39%) is close to the one determined by the option *MA2-S2* (-2.10%). From the risk point of view, this configuration is comparable to the reference one, because the country indexes for the UAE (39.4) and Qatar (38.5) and the open-sea routes can be similar.

The effects of these mitigation actions are shown in Table 14.

Table 14: Energy risk and economic risk changes for mitigation actions to *S2*



Scenario	Energy risk [TJ/y]	Economic risk [G€/y]	Variation [%]
S2	3353434,3	857,2	-
MA1-S2	3360660,8	859,0	-1,21%
MA2-S2	3329944,1	851,2	-2,10%
MA3-S2	3319985,2	848,6	-2,39%

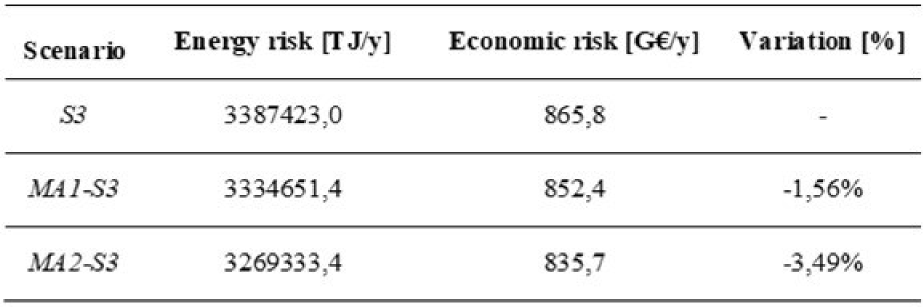
For the scenario ***S3***, two options have been identified:

- *MA1-S3) Replacement of the natural gas flow from Libya with a flow from Algeria (50%, via the Transmed pipeline) and Nigeria (50%: 25% via the Transmed pipeline; 25% as LNG).*
  In this case, the overall risk decreases by 1.56% with respect to the *S3* scenario. It has to be observed that the ξ value related to these corridors is higher than the Greenstream one. This is not caused by the source country risk indexes (because the ones for Algeria and Nigeria are close to the Libyan one), but to the high number of crossed countries, especially for Nigeria.

- *MA2-S3) Replacement of the natural gas flow from Libya with a flow from Qatar (50%, as LNG) and the UAE (50%, as LNG).*
  In this case, the overall risk index decreases by 3.49%. This can be explained by the fact that in this option only open-sea corridors, which can be considered more flexible and consequently more effective from the security perspective, are used.
  It has to be noticed that the missing flow cannot be fully replaced by Norway and the Netherlands (safer European countries), because the needed capacity is higher than the maximum one of the Transitgas pipeline.

The impacts of the analysed mitigation actions are shown in Table 15.

Table 15: Energy risk and economic risk changes for mitigation actions to *S3*



Scenario	Energy risk [TJ/y]	Economic risk [G€/y]	Variation [%]
S3	3387423,0	865,8	-
MA1-S3	3334651,4	852,4	-1,56%
MA2-S3	3269333,4	835,7	-3,49%

For the scenario ***S4***, two possible mitigation options have been hypothesised:

- *MA1-S4) Replacement of the natural gas flow from Russia with a flow from all the other countries supplying Italy, coherently with the maximum capacity of the involved pipelines, i.e.:*
    - *Algeria (30%),*
    - *Nigeria (30%),*
    - *the Netherlands (10%),*
    - *Norway (10%),*
    - *Libya (7%),*
    - *Qatar (7%)*
    - *the UAE (6%).*

  Replacement of the crude oil flow from Russia with a flow from Azerbaijan (50%) and Kazakhstan (50%);
  On the basis of these hypotheses, the total risk reduces by 9.88%: this is mainly caused by the reduction in the risk contribution of natural gas (-21%).

- *MA2-S4) Replacement of the natural gas flow from Russia as in MA1-S4. Replacement of the crude oil flow from Russia with a flow from Russian corridors not crossing the Ukraine.*
  This option leads to a reduction by 10.08% in the total risk. This reduction is comparable with the one obtained in *MA2-S3* and it is mainly due to the diversification in the natural gas supply.

It has to be underlined that the possible future configuration of the energy corridors can determine additional alternatives in terms of mitigation effects. The supply from Russia by means of different corridors not crossing the Ukraine mostly depends on strategical choices regarding possible new pipelines.

One of these new corridors could be the South Stream gas pipeline (characterised by a capacity of 63 bcm/y and an overall length of about 2380 km, of which 931 offshore through the Black Sea, to Bulgaria), even though this option currently seems no more feasible. At the end of 2013, this project was in fact declared not compliant with the EU Third Energy Package regulations [45]. This regulation, in particular, introduced the incompatibility between producers and TSOs, thus impacting on the role played by Gazprom, the main Russian company operating in the sector of production and distribution of natural gas. This decision has to be also analysed in the more general context of political tensions between Russia and the EU, related to the economic sanctions imposed after the 2014 Crimea crisis.

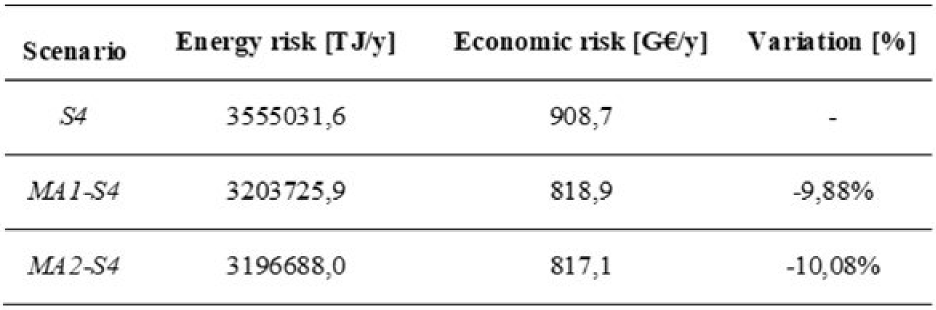
After that Russia declared the abandon of this project, the alternative Turkish Stream (also called TurkStream) pipeline has been proposed. This pipeline – expected to be characterised by the same capacity of the South Stream corridor – should run from Russia to Turkey crossing the Black Sea (with a subsea branch of about 900 km) and it should deliver 31.5 bcm/y. Its construction is expected to be completed by 2019. On the basis of the most recently available information, Russia could build an additional line for connecting Turkey to Greece, allowing the supply to Europe, in particular by delivering 15.75 bcm/y to Turkey and 15.75 bcm/y to Europe.

Among the other alternatives, an interconnection between the Turkish Stream and the Trans Adriatic Pipeline (TAP) can be cited. The TAP pipeline will be connected to the Trans Anatolian Pipeline (TANAP) – as a part of the Southern Gas Corridor (SGC) – and it will run from Greece to Italy for delivering to Europe natural gas from the Azeri field of Shah Deniz. This pipeline (currently under construction) is characterised by an initial capacity of 10 bcm/y, a planned maximum capacity of 20 bcm/y and a length of 878 km. The construction of the TAP, and the possible link with the Turkish Stream, could be significant for Italy, which could become a hub for natural gas coming from Russia and Azerbaijan. Considering the security perpective, in 2014 the total natural gas import of Italy has been equal to 55.78 bcm, 46.9% of which (corresponding to 26.15 bcm) from Russia. Assuming that the TAP corridor could reach its maximum capacity, if the gas import remains constant, in the long term this pipeline could affect for about 36% the Italian supply. By considering the latest available from the Italian Ministry of Economic Development and related to the year 2015 [242], a growth in the total imports can be noticed of up to 61.20 bcm. Moreover, by analysing the historical trends, it can be observed that the 2014 natural gas import is relevantly lower than the average gas import during the last 12 years (equal to 69.27 bcm, with a peak of 77.40 bcm in 2006). These facts, coupled with the progressively reducing National gas production (corresponding to 11.5% of the Gross Inland Consumption in 2014), allow to hypothesise that the natural gas imports in 2020 (the scheduled starting year of the TAP pipeline) could be higher than the current ones. It can be reasonably expected that, however, these imports will be lower than 80 bcm/y. In this case, the contribution provided by the TAP corridor will range from 12.5% (starting capacity = 10 bcm/y) to 25% (maximum capacity = 20 bcm/y). Finally, considering the country risk indexes (Table 9), it can be noticed that the value for Azerbaijan is higher than the one of Russia (43.9 vs. 34.0), and that the route of the TAP corridor (crossing Azerbaijan, Armenia, Turkey, Greece and Albania) cannot be considered “safer” than the one of the TAG pipeline (crossing Russia, the Ukraine, Slovak and Austria). Due to these reasons, it can be concluded that the TAP pipeline would not probably lead to a reduction in the absolute supply risk value, but it could contribute in enhancing the supply diversification, and it could also represent an important alternative that helpful in case of political tensions or crises between the Ukraine and Russia.

Other alternative, like the Yamal pipeline, cannot be taken into consideration because of the constraint on the maximum capacity at the National entry point (Passo Gries).

The impacts of the analysed mitigation actions are shown in Table 16.

Table 16: Energy risk and economic risk changes for the S4 mitigation actions



Scenario	Energy risk [TJ/y]	Economic risk [G€/y]	Variation [%]
S4	3555031,6	908,7	-
MA1-S4	3203725,9	818,9	-9,88%
MA2-S4	3196688,0	817,1	-10,08%

For scenario ***S5***, energy flows coming from Russia and crossing the Ukraine (i.e. one oil and three gas corridors) have to be ensured through other options (like in scenario *S4*). On the opposite, this option is not required for energy flows from North Africa, but it could be suggested due to the high risk (in turn caused by the supposed escalation in the activity of terroristic groups) with respect to the *REF* scenario. Referring to the oil import, several options are available for avoiding the use of North African corridors. In particular, ship transportation from Russia could be adopted, or Caucasian, North and South America countries can be used as suppliers. Referring instead to natural gas, if the North African supply is avoided, only 60% of the flow to be replaced can be ensured without overcoming the maximum capacity of the Italian entry points. Consequently, under the present configuration of supply countries and corridors, the issue cannot be faced. For overcoming this problem, relevant system modifications have to be considered, including a higher diversification of suppliers and improvements in the infrastructures, like new pipelined or regasification plants.

The proposed methodology and the case study have been developed under a single country perspective. However, they can be applied at different spatial scales (like macro-areas, countries or regions). In particular, it could be relevant to analyse the security issues for developing countries as India and China, which are characterised by a relevant growth in the energy consumption, and for countries that show a relevant import dependency. For instance, the studies performed by Geng et al. [243] – focused on the evolution of Chinese energy supply security, by taking into account 7 indexes and 4 dimensions– and the one carried out by Bambawale et al. [244], based on the study of several perspectives related to the energy security of India, can be cited.

This approach could be useful also for other Asian countries, as South Korea and Japan. The energy import dependency of Japan in 2014 was equal to 93.5%, and particularly relevant for crude oil (99.7%) and natural gas (97.6%). The import dependency of South Korea in 2014 was instead equal to 82.8% (9999.5% for crude oil and 3% for natural gas) [5].

Some European Countries are also strongly affected by this issue [245]. Among the most populated ones, the Italian import dependency is considerably high, but the situation of smaller countries, like the Baltic ones, should also be considered, because they have completely depended on Russia (i.e. a unique supplier) since their independence and up to recent years [246].

The developed methodological approach can be effective in policy decision making support over short-, mid- and long-term time horizons. It allows a complete description of the energy inflow of a country, the evaluation of its **geopolitical risk** and a cost-benefit analysis, suitable for comparing different **strategic options** for

- in the short-/mid-term, allocating efforts for protecting a given corridor
- in the mid-/long-term, planning and implementing new supply options and energy corridors.

Furthermore, it allows to defining **mitigation countermeasures** in case of adverse events or of a growth in the geopolitical risk, which could cause the unavailability of a certain percentage of the requested supply. The efficacy of these countermeasures can be compared, and the related economic effects can be measured in terms of reduction in GDP lost.

Considering the case study related to the **Italian external supply**, the scenario analysis has put into evidence the crucial role of **diversification** in decreasing the total external risk. In a high import-dependent country, the spatial dimension of energy corridors (i.e. their lengths, routes and the geopolitical security level of the crossed countries) considerably affects the risk. Furthermore, under a strategic point of view, because natural gas is the most "risky" commodity, investments in new LNG routes and terminals or for increasing the capacity of those already existing could be helpful in the security perspective.

Preventive actions for terroristic attacks against high-risk targets, like natural gas pipelines, could also lead to important economic benefits, as they could prevent relevant GDP losses related to the sudden and unexpected unavailability of a given supply infrastructure.

The analysed scenarios are focused on the current configuration of the Italian energy system. Under a more general perspective, the need for taking into consideration climate changes and for introducing ad hoc policies could have an impact on energy security [247]. In general, it could lead to a new configuration, based on a high decarbonisation of the system and on the key role that renewables could play, like in the case of global interconnections [3]. This configuration could determine a modification in energy security at global scale, and could radically vary the whole situation.

5.2 Transmission/distribution of energy

The set of case studies is related to the spatial mesoscale of energy infrastructures, i.e. the transmission and distribution of energy inside a country. It is thus intermediate with respect to the large transnational corridors, which deliver energy commodities up to the national entry points, and the local distribution systems, like the district heating and cooling networks.

5.2.1 Second case study

The main goal is to define a methodology for the evaluation of a **criticality index**, related to the failure of an energy infrastructure due to **extreme natural hazards** like earthquakes, floods, storms, landslides and wildfires.

This criticality index should be useful for assessing the **criticality level** of each section of the infrastructure itself (taking into account its spatial dimension) with respect to the socio-economic damage (measured in economic unit) caused by the failure.

Furthermore, the possibility to estimate the **distance from the criticality status** even in case of non-critical scenarios and to compare the criticality condition with a risk acceptability criterion (identifying – for the most critical sections – the need for undergoing structural tests) could give a valuable support in prioritising investments and in defining suitable countermeasures and protective actions.

The first step has been represented by the definition of a set of **parameters** that could affect the criticality level of an energy infrastructure, by their clustering into different groups and by the analysis of their interdependencies.

Moreover, in order to take into account the spatial dimension of the energy infrastructures, the possible dependency of each parameter on the **geographical position** z_c (ranging between 0 and the corridor length l_c and measured in km) along the infrastructure itself has been explored. In fact, an infrastructure (like a pipeline) can typically run over long lengths and the natural environment surrounding it could significantly change along the route: as a consequence, certain natural hazards could be considered only for a limited set of branches and not for the overall length.

Eventually, the **effects** of a variation in the value of each parameter on the damage have been estimated. In particular, in this study 15 parameters and 4 groups (“Event related”, “Corridor related”, “Backup sources related” and “Users related”) have been considered: the parameters taken into account are listed in Table 17 and the dependency matrix is shown in Table 18.

The **interdependencies** are identified assuming as increasing the value of each independent parameter and reporting the effect on the dependent parameter (decreasing or increasing when the independent parameter increases). The table reports also the effect of each parameter on damage.

Table 17: Considered parameters by group

Group	Parameter	Description	Unit
1. Event related			
	p	Probability to involve more than a single facility	-
	λ	Relaxation parameter (measure of the potential damage area of the event)	km
	τ	Time scale of the event (measure of its duration)	s
	s	Seasonal factor (influence of the season on the event)	-
2. Corridor related			
	l_c	Length of the corridor	km
	$c_{p,c}$	Peak capacity of the corridor	GJ/s
	RT	Repair time	s
3. Backup sources related			
	d_b	Distance between a single source and the corridor	km
	$c_{p,b}$	Peak capacity of the source	GJ/s
	$r_{m,b}$	Minimum available reserves for the single source	GJ
	α_b	Availability of the source	-
	α_{tec}	Technical availability of the source	-
4. Users related			
	i	Interruptible capacity	GJ/s
	α_i	Availability of interruptible capacity	-
	e	Energy intensity for the considered commodity	GJ/€

Table 18: Interdependencies and effects on damage

Parameter	**Description**	**Dependency on the position z_c**	**Effects on damage**		**Interdependencies**	
			↑	↓	**↑ with**	**↓ with**
p	Probability to involve more facilities	X	X		λ	d_b
λ	Relaxation		X			
τ	Event time scale		X		s	s
s	Season					
l_c	Corridor length	X	X			
$c_{p,c}$	Corridor peak capacity		X		s	s
RT	Repair time	X	X		τ, s	s
d_b	Distance source-corridor	X		X		
$c_{p,b}$	Source peak capacity			X	s	s
$r_{m,b}$	Minimum reserve of the source			X	s	s
α_b	Availability of the source	X		X	s, d_b	λ, s
α_{tec}	Technical availability			X	s	s
i	Interruptible capacity			X	s	s
α_i	Availability of i			X	s	s
e	Energy intensity		X			

Referring to **Group 1**, the seasonality s – that represents the variability of the considered natural event across the year – is the parameter that mainly affects the other ones. The probability p that the natural event could have an impact not only on the analysed corridor but also on other infrastructures supplying the same commodity (backup sources) is strictly related to the magnitude of the event itself and on the geographical context and it depends on the distance between the corridor (or corridor branch) and the considered backup source.

In general, an increase in all the parameters related to the corridor (**Group 2**) causes an increase in the potential damage. It has to be highlighted that RT – which includes not only the time needed to repair the infrastructure but also the time for reaching the damaged section of the corridor and the time to get the requested spare parts – depends not only on the season but also on the temporal and spatial scale of the event. The greater is the geographical extension of the natural event and its duration, the longer is the time needed to reach the damaged section.

As it can be reasonably expected, an increase in the parameters related to the availability of backup sources (**Group 3**) causes a decrease in the damage. It can be underlined that the average distance between the backup sources provides information about the probability that a backup source could be involved in the considered extreme event: in fact, the higher the value of this parameter, the lower the probability. The availability of these sources depends not only on the seasonality, but also indirectly on the distance between the corridor and the source: in particular, it increases if the source is far from the epicentre of the event.

Considering **Group 4**, the parameters are related with the reference market: in case of a possible corridor failure, the market operator could decide a supply interruption for some selected users, in order to reduce the load of the considered infrastructure; the interruptible capacity could depend on season. The energy intensity e (i.e. the amount of energy needed to produce a unit of GDP), instead, gives a measure of the importance of the commodity delivered by the considered corridor, allowing to quantify the economic damage deriving from the supply lost as a consequence of an extreme event.

It can be highlighted that the event related parameters can be evaluated on the basis of geological surveys and studies on natural hazards with respect to the specific site analysed. Among them, the probability of involving more facilities needs *ad hoc* formulations and cannot be generically expressed by means of a single mathematical relationship. The majority of the corridor related and the backup sources related parameters are instead technical data that are usually available for the specific infrastructures considered. Only the repair time should be estimated by means of suitable databases. Eventually, referring to the users related parameters, the interruptible capacity is an information that should be known as depending on already signed contracts and agreements, while the energy intensity for the commodity carried by the infrastructure can be obtained from statistical sources.

Furthermore, for the proposed method, the corridor can be assumed as one-dimensional, i.e. only characterised by the running coordinate z_c. This is because only the position along the corridor, the distance between the backup sources with respect to the corridor and the distance between the epicentre of the considered natural hazard and the corridor itself are relevant for the analysis.

Starting from the parameters and interdependencies identified in Section 2.1, in order to define a criticality index able to quantify the criticality of a single branch/corridor, a relationship expressing the **socio-economic damage** *D* due to a certain extreme natural hazard has been defined. It expresses the damage D in the section of the branch/corridor identified by the coordinate z_c (running over the corridor length, from 0 to l_c).

$$D(s,p,z_c,\tau) = \left\{ RT(s,z_c,\tau) \cdot \left[c_{p,c}(s) - \alpha_i(s) \cdot i(s) - \sum_b \alpha_b(s,p) \cdot c_{p,b}(s) \cdot \left(\frac{T_b}{RT(s,z_c,\tau)} \right) \right] \cdot \frac{1}{e} \right\} \tag{23}$$

Where:

$$\begin{cases} T_b = T_b(s,z_c,\tau) = RT(s,z_c,\tau) & RT(s,z_c,\tau) \le \dfrac{r_{m,b}}{c_{p,b}} \\ T_b = T_b(s) = \dfrac{r_{m,b}(s)}{c_{p,b}(s)} & RT(s,z_c,\tau) > \dfrac{r_{m,b}}{c_{p,b}} \end{cases} \tag{24}$$

$$\alpha_b(s,p) = \alpha_{tec}(s) \cdot [1 - p(z_c)] \tag{25}$$

The first equation defines the economic value of the share of the commodity carried by corridor *c* over the emergency time period (identified by *RT*) that cannot be directly delivered notwithstanding the contribution of interruptible users and the availability of backup sources. In fact, focusing on the square bracket in the equation:

- the term $c_{p,c}$ identifies the maximum amount of commodity that can be delivered per second in season *s* and that is lost due to the failure; as a consequence, the product between $c_{p,c}$ and *RT* defines the amount of energy unavailable during the repair time after the adverse event that caused the corridor failure
- the product between α_i, *i* and *RT* defines the part of this supply that can be avoided during the emergency due to the fact that some users are interruptible

- the product between α_b, $c_{p,b}$ and T_b corresponds to the amount of energy commodity that can be certainly supplied by the backup sources during the repair time.

Referring to the probability that the event could involve other facilities (in particular, the backup sources) than the considered corridor, this can be expressed by several relationships or by more complex considerations that do not allow a simple mathematical formulation according to the different classes of natural events. For example, in the case of a river flood, p is a function not only of the distance between the corridor and the facility but also of the distance between the river and the facility. Furthermore, p is equal to 0 if the considered facility is outside the boundaries of the natural hazard, regardless of the distance between the source and the corridor. A possible relationship that can be adopted for some classes of events, like earthquakes, is the following one (where the possible involved facilities are supposed to be the backup sources *b*).

$$p(z_c) = \begin{cases} \dfrac{\lambda}{d_b(z_c)} & d_b(z_c) \geq \lambda \\ 1 & d_b(z_c) < \lambda \end{cases} \tag{26}$$

Moreover, it has to be highlighted that Eq. 26 is defined if

$$c_{p,c}(s) - \alpha_i(s) \cdot i(s) - \sum_b \alpha_b(s,p) \cdot c_{p,b}(s) \cdot \left(\frac{T_b(s)}{RT(s, z_c, \tau)} \right) > 0$$

as, from the risk analysis point of view, the damage *D* has to be positively defined. A negative value of *D* means that the corresponding corridor section is not critical: negative values of this term could be obtained, for instance, in the case that no other facilities are involved by the natural event and the loss of corridor capacity is completely supplied by backup sources).

For this reason, the proposed relationship for defining the **criticality index** *CI* as a function of the socio-economic damage is the following one:

$$CI = \begin{cases} [1 + D(s,p,z_c,\tau)] \cdot \left[1 + e^{-D(s,p,z_c,\tau)}\right] - 1 & D(s,p,z_c,\tau) \geq 0 \\ \dfrac{1}{1 - D(s,p,z_c,\tau)} & D(s,p,z_c,\tau) < 0 \end{cases} \tag{27}$$

In this case, *CI* does not correspond to an economic value of the damage caused by the considered event (like *D*), but it allows to associate a numerical value also to the corridors sections that are not strictly critical (i.e. those for which *D* is negative) thus measuring their "proximity" to a real potential damage and ranking them according to a criticality perspective, as the safety margins progressively reduce when a negative value of *D* approximates to 0.

As it can be noticed, the *CI* relationship is built in order to have $\lim_{D\to\infty} CI = D$ and $CI = 1$ for $D = 0$ (i.e., when the infrastructure status changes from "non-critical" to "critical").

A graphical representation of *CI* as a function of *D* can be observed in Figure 29.

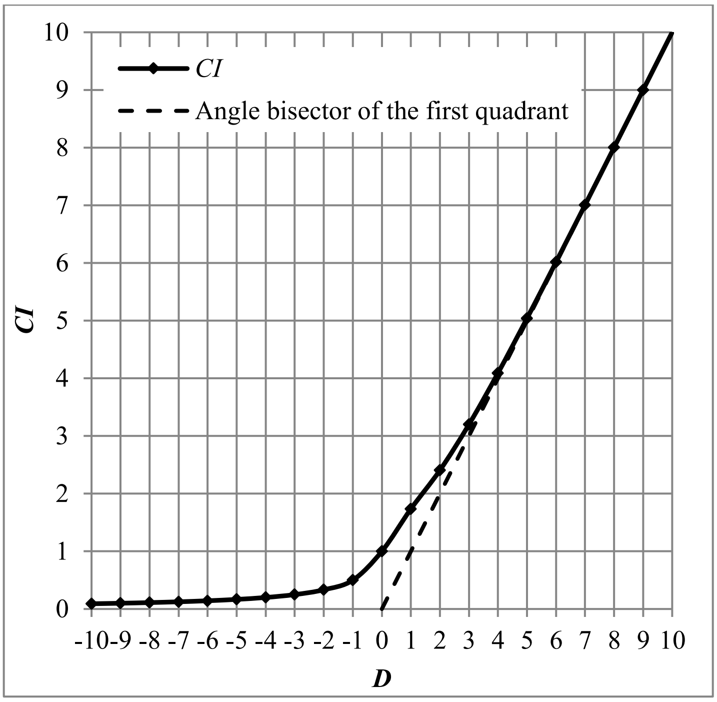


Figure 29: Graphical representation of *CI* as a function of *D*

In the scientific literature, few studies are available to identify **risk acceptability criteria** for the socio-economic risk, and the differences among the economic systems do not allow to define easy procedures suitable to be applied to different contexts (like developed, developing and less developed countries).

For this reason, in the present analysis a specific criterion has been proposed, based on the overall economic estimation of damages due to natural events, which takes into account both direct (i.e. to houses, infrastructures, industrial facilities, etc.) and indirect (i.e. productive losses, lack of basic services to population) damages.

According to the Munich Re insurance company statistical data, related to the global natural loss events worldwide (including geographical, meteorological, hydrological and climatological events) over the period 1980-2015 [248], the 2015 overall losses accounted for about 0.14% of the global GDP (GDP data from World Bank statistics [83]). However, during previous years significantly higher percentage values have been reached, in particular in 2011 (mostly due to the Tōhoku earthquake and tsunami in Japan), when the losses peaked at about 380 billion US dollars, and in 2005, mainly related to the hurricane Katrina in the U.S.. These two events, in particular, highlight that extreme events involving developed countries generally lead to more relevant economic effects even at a global scale.

The proposed expression for the acceptable annual economic damage related to a certain corridor is evaluated as a fraction of the annual GDP, by taking into account

- the contribution of the energy sector to the GDP composition,
- the contribution of the analysed corridor to the overall energy supply of the country/area,
- the weight of the economic losses due to an extreme natural event.

In particular:

- The contribution of the energy sector to the GDP is expressed by the f_{en} factor, defined as:

$$f_{en} = \frac{VA_{en}}{GDP} \tag{28}$$

where:

VA_{en}: value added of the energy sector; it has to be noticed that the GDP at market prices is the sum of the gross value added at market prices for all the productive sectors [249], [250]

- The contribution of the analysed corridor to the regional energy supply is given by the economic value of the commodity carried by the corridor *c* per year; the factor f_c, is defined as:

$$f_c = \frac{EV_c}{VA_{en}} \tag{29}$$

where:

EV_c: economic value of energy commodity delivered by corridor *c*

- The annual value of economic losses and expenditures related to the failure of the corridor *c* due to the event *ne* is assumed as the maximum acceptable risk, and the factor f_{ne} is defined as:

$$f_{ne} = \frac{L_{ne}}{GDP} \tag{30}$$

where:

L_{ne}: total economic losses and expenditures due to the natural event *ne*

As no statistical data is available to evaluate the specific expenditures and economic losses for a natural event causing the failure of corridor *c*, the average value f_{ne}, defined at regional/country scale, is used as equivalent of the "local" ratio between the annual economic losses and expenditures associated to the failure of corridor *c* and the economic value EV_c of the commodity carried by *c* per year.

The previously described steps can be summarised into a single relationship, which allows to quantify the acceptable economic risk in terms of monetary losses as a consequence of an adverse natural event:

$$R_a = f_{ne} \cdot f_{en} \cdot f_c \cdot GDP \tag{31}$$

Once the acceptable risk is defined, the **maximum tolerable frequency** (number of events per year) for a given damage in the corridor section identified by the coordinate z_c is assessed by adopting a graphical approach. This approach starts from the previously defined Criticality Index (i.e. the economic value of the damage caused by the service disruption due to the analysed event) (Figure 30).

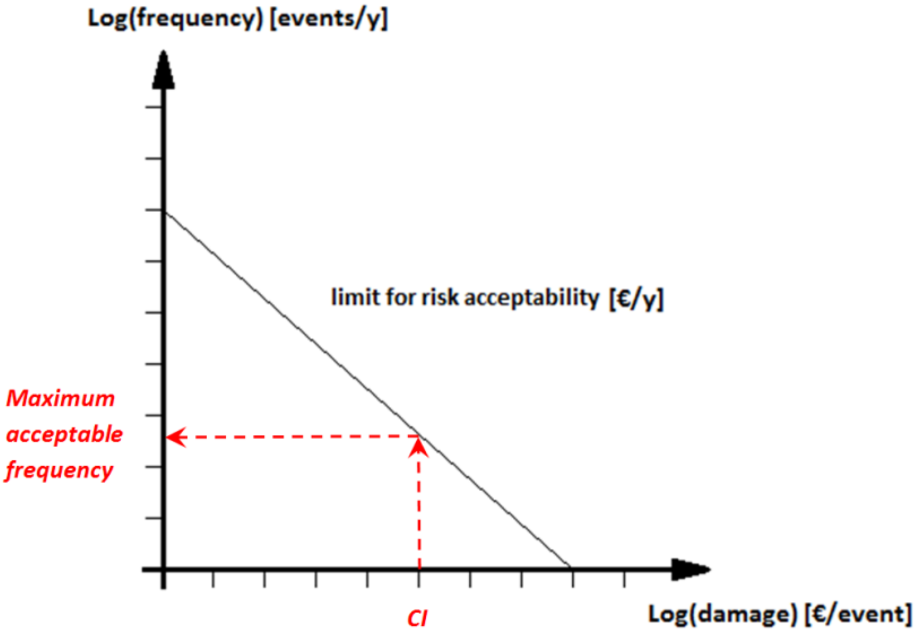


Figure 30: Identification of the maximum tolerable frequency according to the *CI* value

From the obtained maximum acceptable frequency, the corresponding **event intensity** can be evaluated using the frequency-intensity curve, which is characteristic for each class of events (Figure 31).

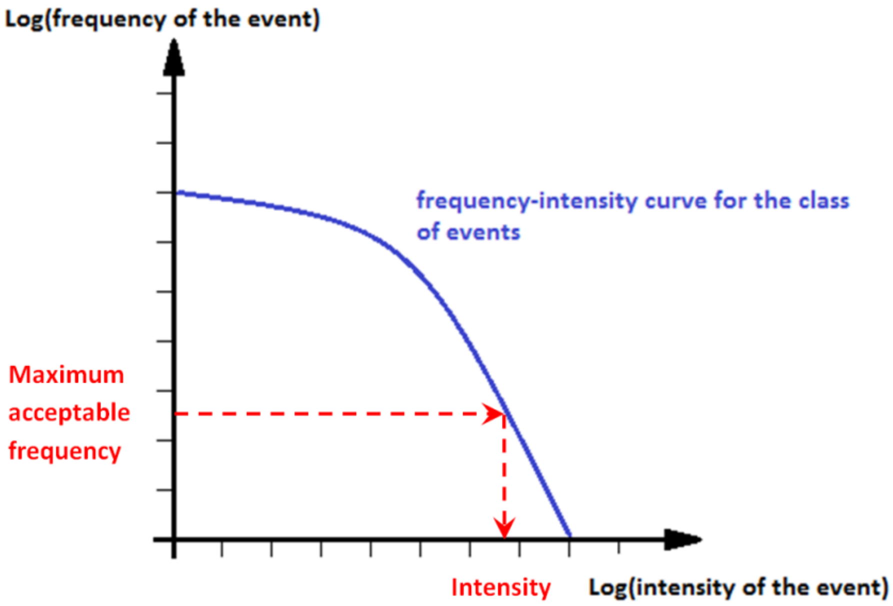


Figure 31: Evaluation of the event intensity related to the maximum tolerable frequency according to frequency-intensity curve

Several studies are available in literature regarding the relationship between the frequency and the intensity (or magnitude) of natural events. For example purpose, the ones performed by Hungr et al. [251], Jakob et al. [252], [253], Riley et al. [254] (related to the debris flow landslides), Hooke [255], Zhang et al. [256] (focusing on floods), and Papadakis [257] (considering earthquakes in Greece) can be mentioned.

In general terms, the intensity is associated to specific characteristics of the considered event (like the peak ground acceleration for the earthquakes, the maximum water level for floods, the maximum wind speed for storms and the heat flux for fires) and the link between intensity and frequency is evaluated on the basis of historical data analyses.

The obtained intensity has to be compared with the **design limit** value for the analysed infrastructure.

It has to be further underlined that in the case of a **reassessment** (i.e. a reduction) of the limit for risk acceptability, the same *CI* value corresponds to a lower maximum acceptable frequency, which – in turn – corresponds to a higher intensity that could exceed the design conditions of the infrastructure. In such a situation, **new structural analyses** have to be performed in order to verify its resilience and the possible need for mitigation actions, such as structural reinforcement, redundancy or relocation.

The proposed methodological approach has been then tested by applying it to a **simplified case study**.

The main **assumptions** adopted can be summarised as follows:

- an ideal infrastructure and related surrounding environment have been taken into account;

- only two classes of extreme natural events (river floods and earthquakes) have been considered;
- three backup sources are available, able to cover the load for the entire period of unavailability of the corridor; these alternative sources are independent from the corridor itself;
- there is no interruptible capacity;
- the considered parameters are seasonally independent;
- a reassessment of the limit for risk acceptability has been assumed, with a risk reduction of one order of magnitude.

The spatial layout of the corridor and of the backup sources is shown in Figure 32, while their characterisation and the values of the main parameters are reported in Table 19.

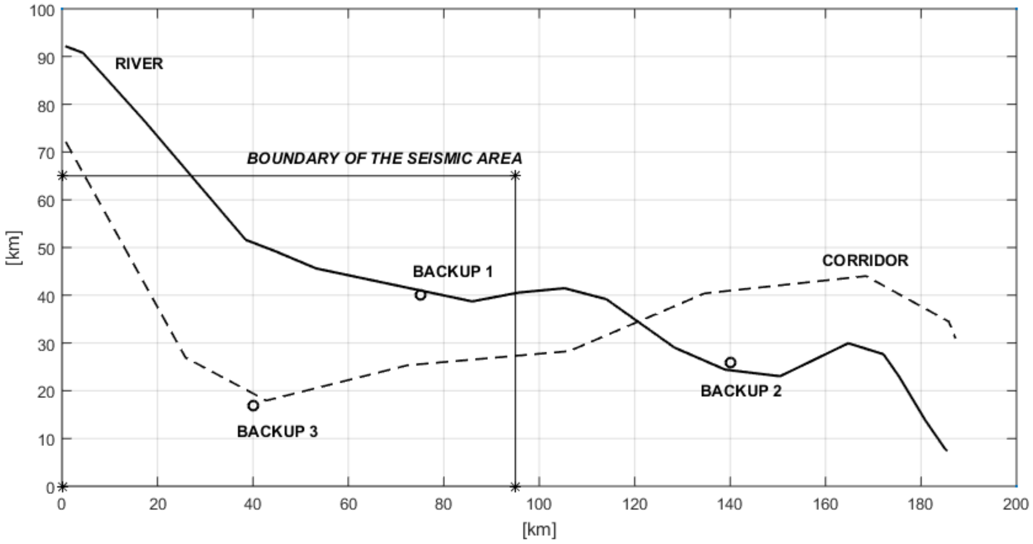


Figure 32: Spatial layout of the corridor and of the backup sources

Table 19: Values of the main considered parameters

Parameter	Description	Value	Unit
$p_{1,f}$	Probability to involve backup source 1 – flooding	0.5	-
$p_{2,f}$	Probability to involve backup source 2 – flooding	0.5	-
$p_{3,f}$	Probability to involve backup source 3 – flooding	0	-
λ_e	Earthquake relaxation parameter	5	km
λ_f	Flooding relaxation parameter	5	km
s	Seasonal factor (influence of the season on the event)	0	-
$c_{p,c}$	Peak capacity of the corridor	100	J/h
RT	Repair time	1	h
$c_{m,b1}$	Minimum operative margin in capacity – backup source 1	50	J/h
$c_{m,b2}$	Minimum operative margin in capacity – backup source 2	35	J/h
$c_{m,b3}$	Minimum operative margin in capacity – backup source 3	45	J/h
$\alpha_{t,b1}$	Technical availability of the backup source 1	0.95	-
$\alpha_{t,b2}$	Technical availability of the backup source 2	0.95	-
$\alpha_{t,b3}$	Technical availability of the backup source 3	0.95	-
i	Interruptible capacity	0	J/h
e	Energy intensity for the considered commodity	1	€/J
DBE	Magnitude of the design base earthquake	4.8	
DBF	Maximum discharge of the design base flood	2000	m^3/s
	Limit for risk acceptability	1	€/y
	Reassessed limit for risk acceptability	0.1	€/y

It has to be underlined that, in this simplified case study, the values of the parameters have been chosen in order to be realistic but they are not corresponding to a real case. In general, if the proposed procedure is applied to a real system, the evaluation of the parameters should be performed according to the considerations previously expressed.

The obtained *CI* (z_c) is shown in Figure 33 for both earthquake (E) and flooding (F) events. In particular, it can be observed that the corridor sections characterised by the highest *CI* values are those close to the backup sources in the seismic area (in the case of earthquake event) and to the river (in the case of flooding event). The sections where $CI < 1$ are those corresponding to a damage $D < 0$, i.e. the capacity of the backup sources is more than the one requested to ensure the coverage of the load in the case of unavailability of the corridor. However, it has to be remarked that all the sections characterised by *CI* value slightly lower than 1 have to be considered as they are close to a critical condition.

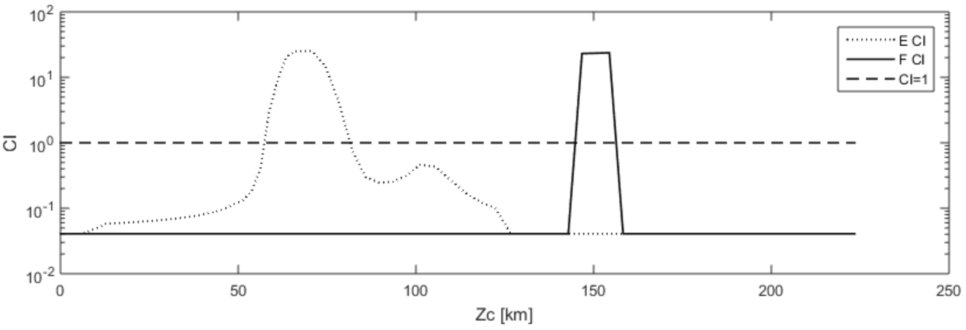


Figure 33: *CI* evolution with respect to the position z_c; $CI < 1$ corresponds to $D < 0$

Referring to the evolution availability parameter α_b (s,p) for the three backup sources, it can be noticed (Figure 34) that the lower the distance between the corridor and the source, the lower the availability: this is because if the natural event involves an area in which the corridor and the backup are close to each other, the probability for the backup source to be damaged is higher, and so its availability is lower.

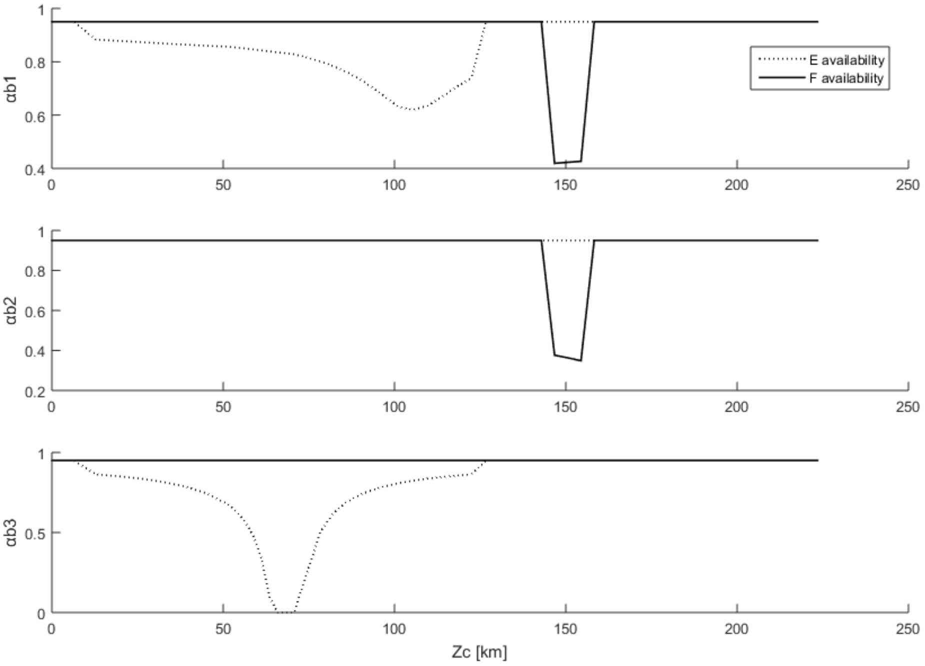


Figure 34: Evolution of the availability of the backup sources with respect to the position z_c

Figure 35(a) shows the frequency-*CI* curves corresponding to the original limit for risk acceptability and to the reassessed one. Figure 35(b) and Figure 35(c) represent the frequency-magnitude curves, which have been built by using two different approaches for the two considered classes of natural events:

- the Gutenberg-Richter law [258] in the case of earthquakes;
- a logarithmic relationship based on the one proposed by Wald et al. [259] in the case of flooding.

The vertical lines correspond to the design base earthquake magnitude (DBE) and flood (DBF) for the corridor.

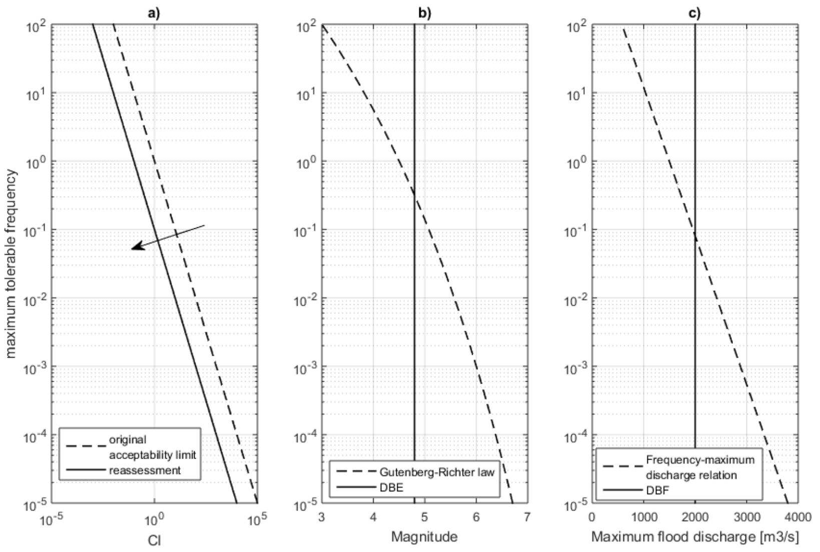
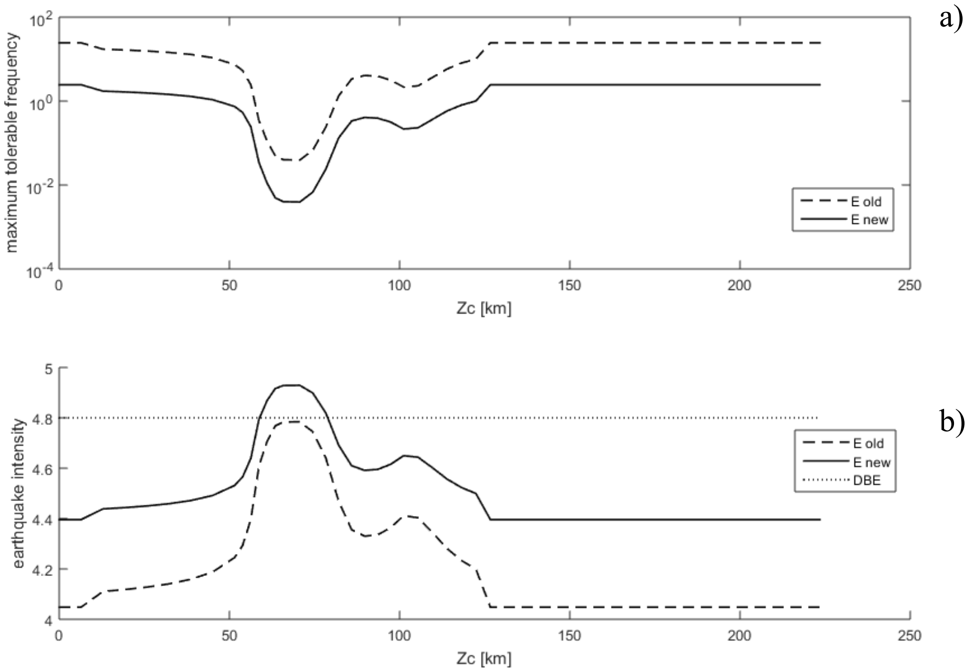


Figure 35: Frequency-*CI* (a) and frequency-magnitude curves (b, c) for the analysed case study

Starting from these curves and from the previously defined *CI* evolution, the maximum acceptable frequencies and the related intensities for both earthquake and flood events and for both the original (E/F old) and reassessed (E/F new) limit for risk acceptability have been estimated, as reported in Figure 36.



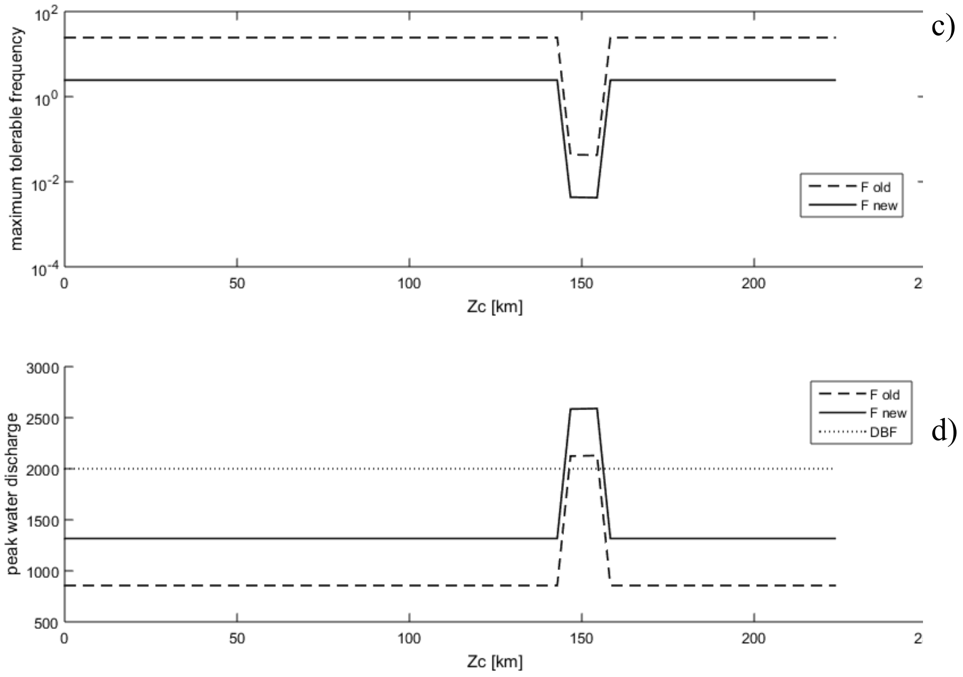


Figure 36: Maximum acceptable frequencies and intensities for the analysed case study

As it can be observed in Figure 36(a), the maximum acceptable frequency for earthquakes reaches its minimum value (corresponding to the maximum intensity, visible in Figure 36(b)) in the section where the corridor and the backup source 3 are closest each other and are both affected by the natural event (*p*=1 in Eq. 29).

Furthermore, it can be observed that in the case of reassessed risk limit the intensity is beyond the design condition (DBE, Figure 36(b)), thus leading to the need for performing tests in order to assess the robustness of the involved corridor section and to define suitable mitigation actions. The same considerations are valid for the flood (Figure 36(c,d)): the main difference is that – in this case – in the most critical corridor section the intensity overcomes the design value also for the original risk limit (DBF, Figure 36(d)), requiring further resilience tests also without hypothesising a reassessment of the limit for risk acceptability.

As mentioned before, the values of the considered parameters have been assumed without a specific reference to a real case, as the goal of the analysed case study is to show the functioning and the applicability of the proposed methodology through a theoretical example. For this reason, an analysis of the uncertainties has not been performed. Future works aiming at deeply exploring the criticality of existing infrastructures will include this aspect, especially regarding the event related parameters, with a particular attention devoted to the probability that different facilities are involved. As previously discussed, in fact, this probability needs detailed and complex considerations to be properly quantified with respect to the specific natural hazard and site studied.

This simplified case study, however, shows the potentiality of this approach in evaluating the possible critical sections of the infrastructures, prioritising the investments and the interventions in reinforcing them and in making them resilient to adverse extreme natural events.

On the other hand, it also allows to identify some aspects that could be more deeply investigated in future studies in order to enhance the applicability to real cases and the effectiveness of the obtained results. In particular, among them, the unambiguous definition of the system boundaries can be mentioned. In fact, the identification of boundaries can be not easy in the case of meshed networks like natural gas distribution systems or power lines, for which it is difficult to define a single entry point and a single end point.

Another relevant aspect is represented by the availability of complete and uniform databases for both the technical characteristics of the analysed infrastructures /backup sources and the classes of natural events affecting the environment surrounding the infrastructure.

In brief, the developed methodology can be an effective **supporting tool** for decision makers and public administrations, for companies that have to manage crucial infrastructures for energy commodities transport and for the civil protection. This because it allows – through a simple mathematical formulation – to identify the sections of an energy corridor that are critical with respect to a specific natural hazard or that are close to a criticality status, thus defining priority areas of intervention, preventive investments, mitigation actions and *ad hoc* countermeasures.

The introduced criticality index assesses in a numerical way the **socio-economic damage** (measured in monetary units) due to the effects of an extreme natural event on the selected infrastructure and can be used to evaluate the maximum acceptable frequency and the corresponding intensity of the event itself, allowing a comparison with the design condition of the infrastructure.

Furthermore, the possibility to evaluate the criticality index also for negative damage values (i.e. for not critical configurations) permits to measure the **distance from the criticality**, allowing to pay preventive attention to those sections that are closer to critical situations.

In general, the described approach gives the opportunity of **ranking** the single branches of an infrastructure according to their criticality and for all the different natural hazards, and, consequently, it gives the authorities in charge of protecting critical infrastructures the opportunity of prioritising the interventions.

The application of this methodology to a simplified case study (considering one corridor and two extreme events) has underlined the advantages of the procedure, especially if a reassessment of risk acceptability limit is introduced, because it puts into evidence the **safety margin** with respect to the design conditions or the need for performing structural tests, quantifying the infrastructure resilience.

However, additional aspects have to be deeply analysed in the case of an extensive application of the proposed methodology, including – in particular – the availability of complete and homogenous technological and environmental

databases and the proper definition of the **system boundaries** that could be not trivial in the case of meshed networks like the natural gas distribution ones.

Further studies could also be devoted to the analysis of multi-risk scenarios, i.e. to the concurrent occurrence of two or more extreme natural events. In particular, suitable strategies to allocate the acceptable risk (for instance by taking into account the safety margins of the infrastructure, if they are present) should be defined, in order to test the infrastructure resilience in the worst (and low-frequency) conceivable conditions.

5.2.2 Third case study

On the basis of the analysis of the literature state of the art, reported in Chapter 4.3.3, a new methodological approach for assessing the impact of different **non-programmable renewable sources** has been proposed.

It aims to evaluate the percentage of energy produced by NPRS that cannot be immediately consumed because it exceeds the **instantaneous flexibility** of the system, i.e. the difference between the instantaneous load and the minimum output power of the other plants belonging to the analysed system.

This minimum power is defined **inflexibility** (Figure 37) and identifies the threshold below which the production of the base load plants has to be modified, often causing the shutdown of certain units in order to avoid damages.

Starting from the load profile and the NPRS production profile, the **net load** is calculated as the difference between the hourly load of the considered system and the hourly production from NPRS. Therefore, the obtained profile corresponds to the load that has to be covered by means of base-load units, load-following units and peak shaving units. If the net load is lower than the inflexibility value, the surplus of energy produced by NPRS plants cannot be instantaneously consumed: if storage systems are not available, some NPRS plants have to be disconnected from the grid.

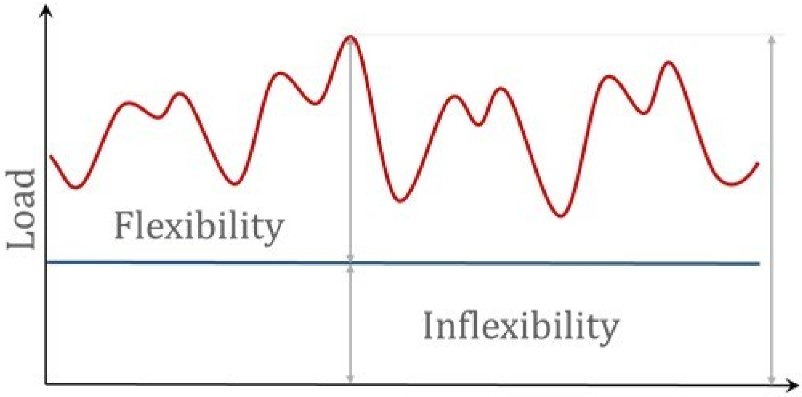


Figure 37: Definition of Flexibility / Inflexibility in an electric system

Input data has been collected from Terna, the Italian transmission system operator (TSO), which provides access to load, generation and transmission profiles in an ad hoc section of its website [260]. Figure 38 shows hourly load and

NPRS generation valued obtained from Terna database for a representative day in 2013 (January 3rd). To build this figure, data have been summed up for the different Italian areas and the NPRS production has been assumed equal to the sum of wind and photovoltaic electricity production. Later in the study, the different Italian geographical areas have been kept separated in order to allow a more detailed analysis.

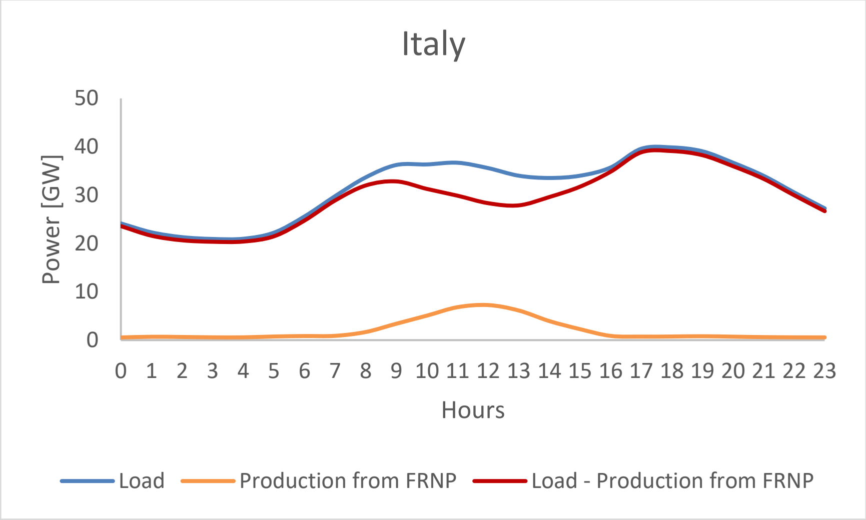


Figure 38: Typical load and NPRS generation profile for a sample day (January 3rd 2013) **[260]**

For implementing the procedure, a MATLAB-based **simulation tool** has been developed. The general approach adopted for the implementation can be summarised as follows:

- **Input Data:**

  Starting from an Excel template including data on the hourly load, the hourly wind and photovoltaic production (expressed in GW) in 2013 for several Italian areas (corresponding to the regional market zones mentioned in Section 1), the algorithm firstly calculates the following parameters:

  - Electricity production from NPRS for each hour in all the considered areas:

$$\begin{aligned} &NPRS\ production\ (h,z) \\ &\qquad = PV\ production(h,z) \\ &\qquad + Wind\ production\ (h,z)\quad [GW] \end{aligned} \tag{32}$$

Where:
h = hour (ranging over the year)
z = ID of the geographical area
$h\ \in\ \mathbb{N}\,[0\,;8760]\quad ;\quad z\ \in \mathbb{N}\,[1\,;7]$
$z = 1 \rightarrow NORTH$

$z = 2 \rightarrow CENTER - NORTH$
$z = 3 \rightarrow CENTER - SOUTH$
$z = 4 \rightarrow SOUTH$
$z = 5 \rightarrow SICILY$
$z = 6 \rightarrow SARDINIA$
$z = 7 \rightarrow Italy$

- Net load for each hour in each geographical area:

$$Net\ load\ (h, z) = Load\ (h, z) - NPRS\ production\ (h, z) \quad [GW] \tag{33}$$

- Annual load and NPRS production in each area:

$$Total\ load\ (z) = \frac{1}{1000} * \sum_{h=1}^{8760} Load\ (h, z) \qquad [TWh] \tag{34}$$

$$Total\ NPRS\ production\ (z) = \frac{1}{1000} * \sum_{h=1}^{8760} NPRS\ production\ (h, z) \quad [TWh] \tag{35}$$

- Percentage contribution given by NPRS to the total load in each area:

$$NPRS\ contribution\ (z) = \frac{Total\ NPRS\ production\ (z)}{Total\ load\ (z)} * 100 \qquad [\%] \tag{36}$$

- Peak load and minimum load:

$$Peak\ load\ (z) = \max\big(Load(h, z)\big) \qquad [GW] \tag{37}$$

$$Minimum\ load(z) = \min\big(Load(h, z)\big) \qquad [GW] \tag{38}$$

- Minimum flexibility factor of the system:

$$FF_{minimum}(z) = \frac{Peak\ load(z) - Minimum\ load(z)}{Peak\ load\ (z)} * 100 \quad [\%] \tag{39}$$

- **NPRS penetration and Flexibility Factor:**

For each geographical area, the annual quantity of energy produced by NPRS that cannot be instantaneously consumed is evaluated as a function of the imposed NPRS penetration and of the Flexibility Factor of the system.
First of all, the factor K is defined as the ratio between the imposed NPRS penetration and the corresponding annual production:

$$K(z) = \frac{NPRS\ penetration}{NPRS\ contribution\ (z)} \quad ; \quad NPRS\ penetration \in \mathbb{R}\,[0\,;100] \tag{40}$$

$$Total\ NPRS\ (z) = K(z) * Total\ NPRS\ production\ (z) \qquad [TWh] \tag{41}$$

For each area the inflexibility corresponding to a certain imposed Flexibility Factor FF is then evaluated:

$$Inflexibility(z) = Peak\ load(z) * \left(1 - \frac{FF}{100}\right) \qquad [GW] \tag{42}$$

Where:
$FF \in \mathbb{R}\,[FF_{minimum}(z)\,;100]$

The net load profile corresponding to the imposed NPRS penetration is:

$$Net\ load\ (h,z) = Load\ (h,z) - K(z) * NPRS\ production\ (h,z) \qquad [GW] \tag{43}$$

The amount of energy given by NPRS that cannot be instantaneously consumed is then:

$$Excess\ (h,z) = \begin{cases} Inflexibility\ (z) - Net\ load\ (h,z) & if \quad Net\ load\ (h,z) < Inflexibility\ (z) \\ 0 & if \quad Net\ load\ (h,z) \geq Inflexibility\ (z) \end{cases} \tag{44}$$

Summing over the total number of hours, the annual quantity of NPRS energy that cannot be immediately consumed is:

$$Excess_{annual}(K, FF, z) = \sum_{h=1}^{8760} Excess(h,z) \qquad [GWh] \tag{45}$$

As a consequence, the percentage rate of unconsumed energy from NPRS referred to the total energy yearly produced by NPRS can be expressed as:

$$Excess\,rate\;(K, FF, z) = \frac{Excess_{annual}(K, FF, z)}{Total\;NPRS\;(K, z)} * 100 \qquad [\%] \qquad (46)$$

By applying the above described procedure to different NPRS penetration and *FF* values, the evolution of the **Excess rate** for each geographical area can be obtained.

The Excess rate as a function of the NPRS penetration is shown in Figure 39 and Figure 40 a-f (respectively at National and area scale) for different *FF* values (i.e. 70%, 80%, 90% and 100% for all the areas and 60% for the major islands, where *FF* = 100% means that the amount of energy produced by NPRS is sufficient to cover the entire annual load).

In all the simulations, the obtained curves are monotonically increasing: the annual amount of energy produced by NPRS that cannot be instantaneously consumed increases when the NPRS penetration increases or *FF* increases.

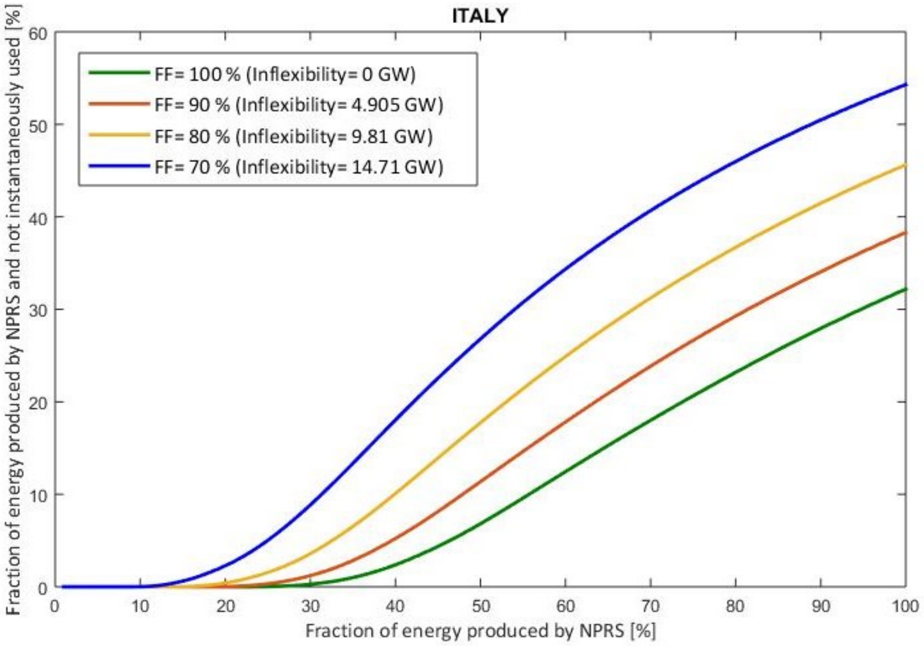


Figure 39: Energy yearly produced by NPRS that cannot be instantaneously consumed (Excess rate), expressed as a function of the fraction of energy produced by NPRS (NPRS penetration) for different *FF* values at National scale

Referring to the single areas, in the case of NPRS penetration = 100%, it can be noticed that in the most favorable case about 30% of the NPRS production cannot be instantaneously consumed (SOUTH with *FF*=100%), while in the worst case the amount of inconsumable NPRS energy is higher than 70% (NORTH with *FF*=70%).

In particular, NORTH and SOUTH areas show a behavior slightly different in comparison with the one of the remaining areas, as – for the same *FF* value – the amount of NPRS production that cannot be instantaneously consumed is higher, as it can be noticed comparing the curves represented in Figure 40 for a certain *FF* (for instance, *FF*=70%).

The results obtained in this study highlight the relevant role that the amount of energy from NPRS that cannot be instantaneously consumed plays when the issue related to the integration of the NPRS in the power generation system is taken into account. As previously shown, in fact, this parameter can reach high values (in particular, it can be equal to 70% of the production).

As a consequence, if alternative solutions (like storage systems or ad hoc interconnections) are not available, this limitation can have a significant **impact on the increase in NPRS penetration**, especially for power systems characterised by an already high amount of NPRS installed capacity. This is due to the fact that further new wind or photovoltaic plants could be affected by longer payback time and the whole management of the system could be more complex.

In order to reduce the amount of energy that is not instantaneously consumed, different **alternative options** can be explored.

The first one is the **increase in the flexibility** of the power system. This goal could be reached by substituting the base load plants with more flexible ones (like load-following units). These interventions, however, are characterized by relevant investment costs and the obtainable benefits could be not so relevant, because – as previously seen – even in the case of a Flexibility Factor equal to 100% a significant amount of NPRS energy still cannot be consumed, especially in some areas. It can be noticed that this solution could be more effective if applied to Southern Italy and to the islands (Sicily and Sardinia).

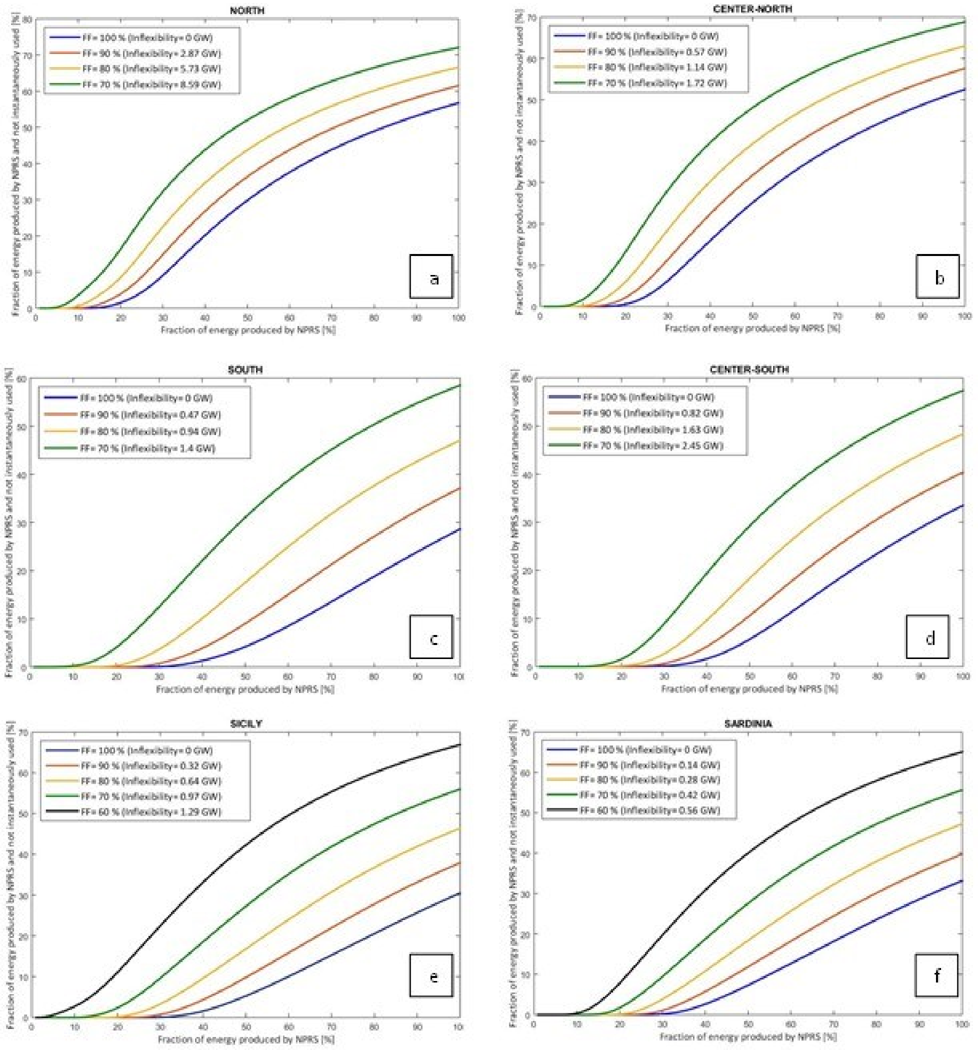


Figure 40: Energy yearly produced by NPRS that cannot be instantaneously consumed (Excess rate), expressed as a function of the fraction of energy produced by NPRS (NPRS penetration) for different *FF* values at area scale

The second alternative is to **increase the transmission capacity** among the different areas. This solution gives only limited benefits in terms of reduction of the Excess rate and requires relevant investments; however it can be useful not only for the purpose of allowing a better management of the NPRS but mainly to obtain a more reliable service and an easier dispatching.

The last option is the introduction of **storage systems** that can be particularly valuable for electrical systems characterised by an NPRS penetration of about 60% and an NPRS production mostly based on photovoltaic.

Each of these possible actions has to be considered and explored for each area independently, in order to find an equilibrium among reduction of the NPRS Excess rate, economical aspects, technical feasibility, possible future developments, climatic conditions, etc.

However, generally speaking, , it has to be underlined that the best solution for each area could be represented by a **mix of the three actions** above described, according to more detailed studies and analyses.

It can be further demonstrated that the kind of NPRS installed plant (photovoltaic or wind plants) matters. The power generation mix has to be suitably defined: by well-balancing the contribution given by wind and photovoltaic, a relevant reduction in the Excess rate, up to 25%,can be obtained. The main advantage of this solution is represented by the fact that no further investments in new plants are required.

Moreover, the analysed case study has put into evidence that the obtained results are similar even if the load profiles are quite different among the considered areas. This means that the NPRS Excess rate seems to be independent from the load profile. However, this outcome should be confirmed by taking into account other typologies of load profiles and by applying the methodology to different countries.

Referring to other possible future improvements, it has to be underlined that the available data used for the analysis are hourly based and so they do not allow to extend the study to the sudden load variations (usually characterised by an order of magnitude of minutes, seconds or fractions of a second) that can happen in a power system. Some of the available storage technologies (like flywheels and supercapacitors) are used in order to face these rapid load changes, and thus a finer timescale should be adopted when these systems are implemented into the algorithm.

5.3 The local scale

The two proposed case studies are devoted to the analysis of local distribution systems (in particular, district heating networks) and to the role that the penetration of alternative energy vectors (like hydrogen) in the energy mix composition at local scale can play, especially with reference to the impact on the energy security.

5.3.1 **Fourth case study**

The analysis of the scientific literature allowed to see that the commonly adopted approaches for **design and planning** of DHNs are generally focused on functional and energy aspects, but they does not include **reliability considerations**, carrying out the related evaluation as ex-post analyses.

The goal of this study is to put into evidence the importance of comprising these aspects in the design of the network. In particular, the objective is to develop a supporting tool for DHNs design and optimisation, able to couple a **Thermo-fluid dynamic Module** for simulating the physical behaviour of the grid, and a **Monte Carlo Module** for managing the network failure and repair processes.

This tool could be useful in optimising the layout and the maintainability of the grid, and in defining the most suitable size and location of **thermal heat storage systems** (TESs) through a comparison among different network configurations. In fact, TESs could play a key role decoupling heat production and demand, in managing the network and the installed power capacities and also in guaranteeing benefits from the grid reliability perspective, enhancing the service quality.

This procedure for developing a MATLAB-based tool linking technical DHNs aspects and reliability aspects started from the preliminary results obtained by Carpignano et al. [184]. The goal of this approach is to represent a first step towards an integrated methodology for the support of planners and designers during the definition of optimal architectures of the grid.

Usually, the key systems of any DHN are

- production plants,
- delivery and return pipelines,
- pumping stations and
- final users.

A part of an **Italian city DHN** (that supplies heat for space heating and water heating), graphically shown in Figure 41, has been assumed as case study. In particular, all the system elements previously mentioned plus thermal energy storages have been taken into account.

In the figure are represented:

- 2 production plants, PP1 (2 gas turbines + 3 boilers) and PP2 (3 boilers);
- the main distribution grid, where each line represents both the delivery and return pipelines, characterised by operational temperatures respectively equal to 120°C and 60°C.

The pumping stations PS1, PS2 and PS3 outlets have a reference pressure of 16 bars. The BCT boxes represent instead the thermal barycentres connected to the related network trunk.

Each BCT represent a distribution tree network connected to the single buildings (Figure 42).

The BCTs have been defined with reference to the actual behaviour of the grid, and the analyses have been limited to the main distribution grid. The laws of mass and energy conservation are always respected along the network, in each BCT branch.

Production plants have an installed pumping capacity (Table 20) equal to 3770 kg/s, which is higher than the actual hot water mass flow rate of the real plant (2644 kg/s).

Two main network nodes (GN1, GN2) have also been considered and modelled from the thermodynamic point of view for closing the grid loop.

It can be observed that in this first architecture there are not storage systems along the considered section of the grid.

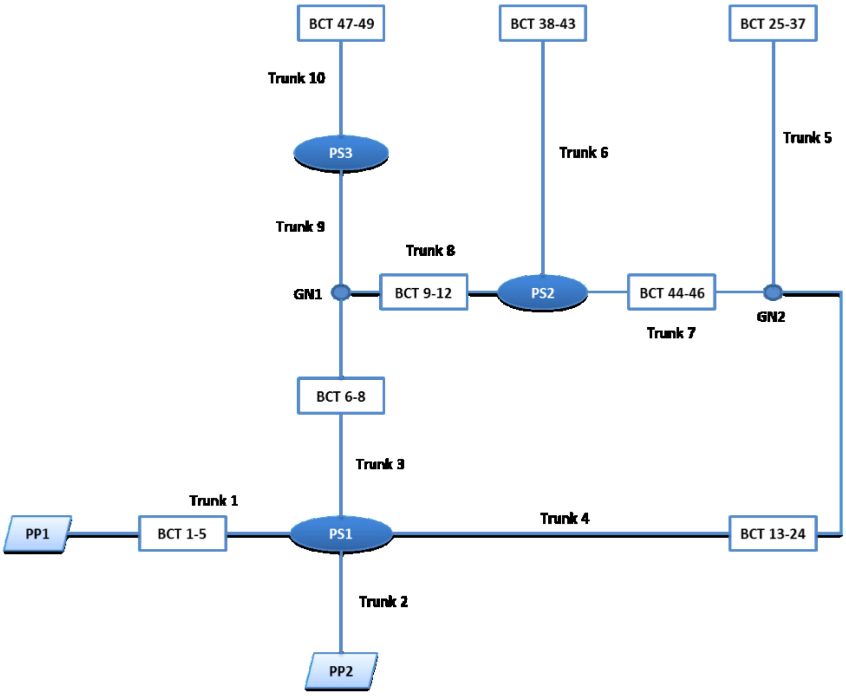


Figure 41: DHN Scheme

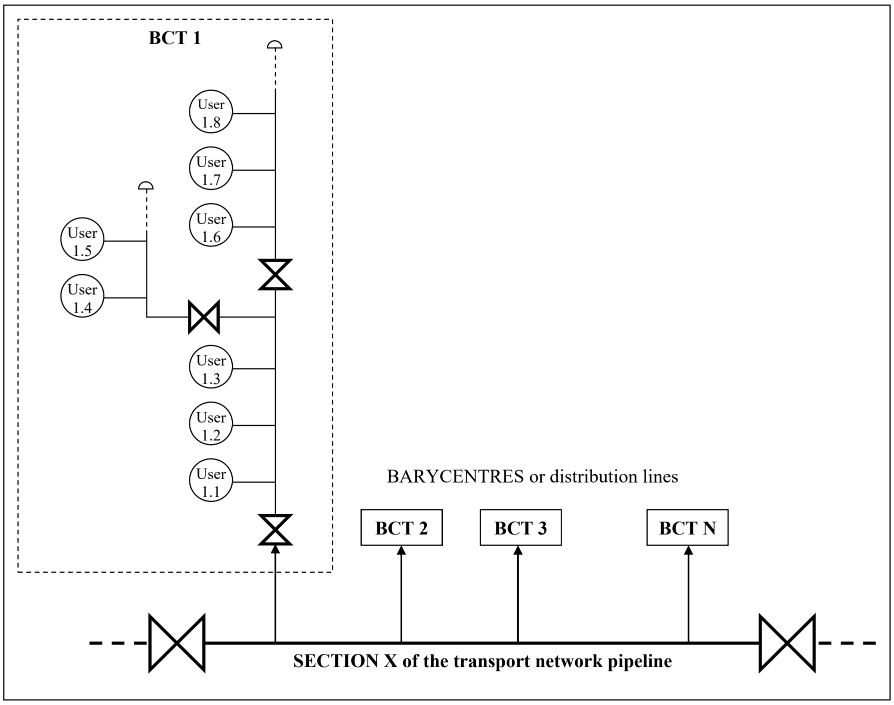
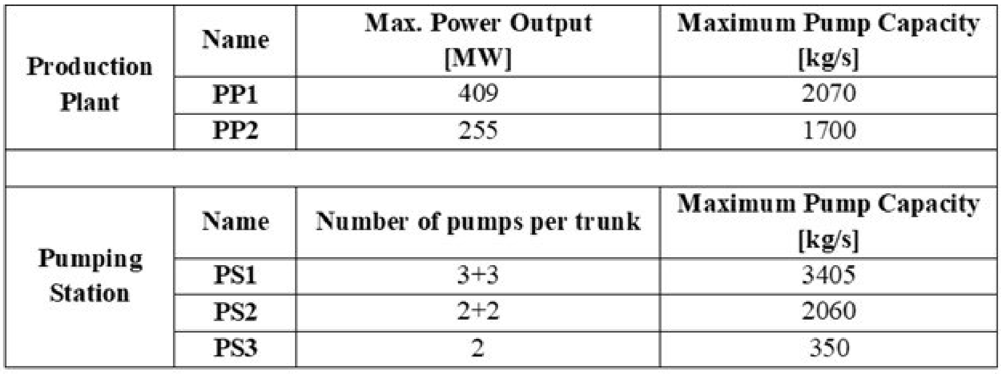


Figure 42: Thermal Barycentres

The main characteristics of the different system elements are reported in Table 20 and Table 21.

The total average BCTs demand iso 558 MW (Table 21), to which corresponds a total average water mass flow rate equal to 2222 kg/s.

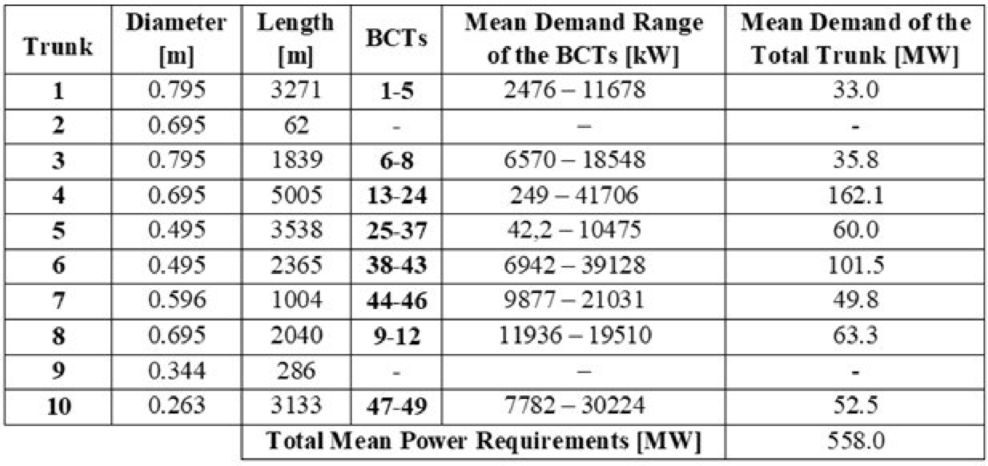
Table 20: Characteristics of power plants and pumping stations



Production Plant	Name	Max. Power Output [MW]	Maximum Pump Capacity [kg/s]
	PP1	409	2070
	PP2	255	1700

Pumping Station	Name	Number of pumps per trunk	Maximum Pump Capacity [kg/s]
	PS1	3+3	3405
	PS2	2+2	2060
	PS3	2	350

Table 21: Trunk characteristics and related Thermal Barycentres



Trunk	Diameter [m]	Length [m]	BCTs	Mean Demand Range of the BCTs [kW]	Mean Demand of the Total Trunk [MW]
1	0.795	3271	**1-5**	2476 – 11678	33.0
2	0.695	62	-	–	-
3	0.795	1839	**6-8**	6570 – 18548	35.8
4	0.695	5005	**13-24**	249 – 41706	162.1
5	0.495	3538	**25-37**	42,2 – 10475	60.0
6	0.495	2365	**38-43**	6942 – 39128	101.5
7	0.596	1004	**44-46**	9877 – 21031	49.8
8	0.695	2040	**9-12**	11936 – 19510	63.3
9	0.344	286	-	–	-
10	0.263	3133	**47-49**	7782 – 30224	52.5
		Total Mean Power Requirements [MW]			558.0

For understanding how storages can impact on the grid management and on the installed power capacity, an hourly **Load Profile** has been introduced. In Figure 43, the blue line represents the installed capacity of the considered power plants, or the maximum available heat in output (664 MW, Table 20). The orange line corresponds to the average heat demand of the connected BCTs (558 MW). The red line represents a realistic hourly variable load.

This configuration is related to an external temperature of -8 °C, which is the reference condition for the design of heating systems in the considered city, and it can be assumed as the most conservative case.

As the total production plants capacity is lower than the peak demand, TESs are required: it can be demonstrated that, in this case, a storage capacity corresponding to at least 8500 m^3 is requested.

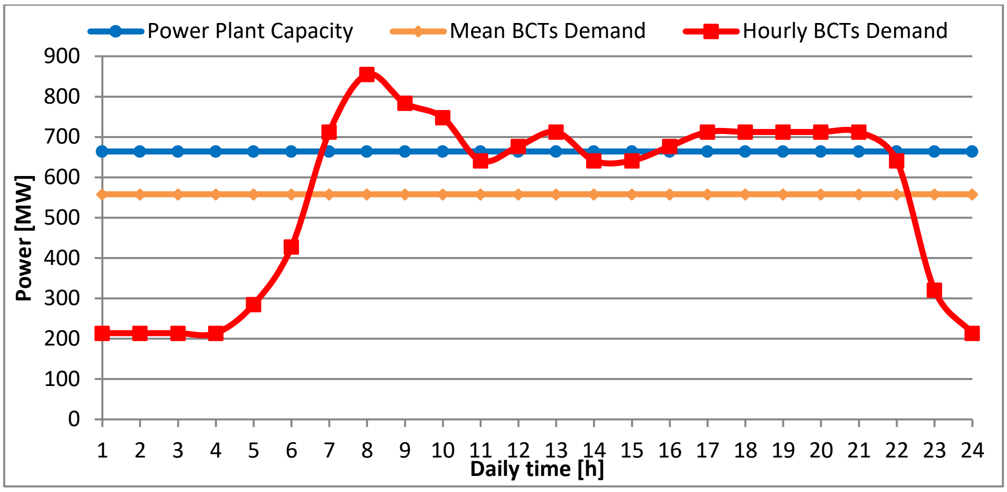


Figure 43: Users Load Curve and Production Output Curve

Thermal Energy Storages (TESs) are a significant element for planning and management of DHNs, because they can have a central relevance not only in the design phase and for the system behaviour, but also for its reliability, availability, maintainability and safety (RAMS).

Among the possible types of TES (a complete description of the available typologies and applications is proposed in [261]), in this study sensible heat storages [262] have been considered, because:

- DHNs commonly operate with pressurised water at high temperatures
- Hot water tanks are already available in the grids
- Phase change materials (PCM) and chemical storages still require significant improvements and costs reduction.

The TES has been hypothesised to be located parallel with respect to the network, for supplying the BCTs or to be charged by the network. The tank is hypothesised Thermal Stratified (see Figure 44), for obtaining a high efficiency. Heat losses are assumed to be minimised, and they are estimated as a water tank temperature reduction rate equal to 0.5÷1 °C per hour.

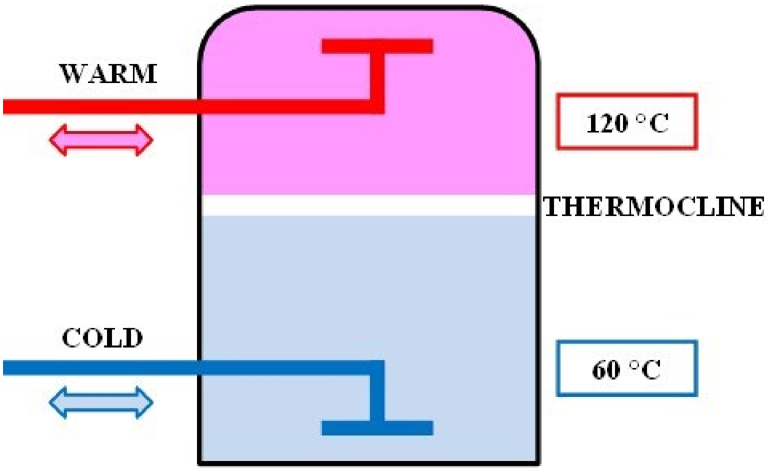


Figure 44: Simplified Heat Storage Model

The following rationale for the heat storages management for each hour is assumed:

- if all the BCTs downstream with respect to the TES are properly served, the TES can be charged with the appropriate flow rate
- if some BCTs downstream with respect to the TES are not served, the TES begins the discharging phase, with the minimum flow rate required for serving the highest number of BCTs.

The proposed tool aims at evaluating the effects of components failure on the service quality (in terms of number of failures and hours of service disruption) and at assessing the role that proper design, sizing and location of TESs can have in the minimisation of the service outages. The methodological approach couples a thermo-fluid dynamic simulation of the grid (TFD Module) and an assessment of the failure and repair of its components (MC Module). The functioning of the tool, and the link among the two modules is described in the diagram shown in Figure 45.

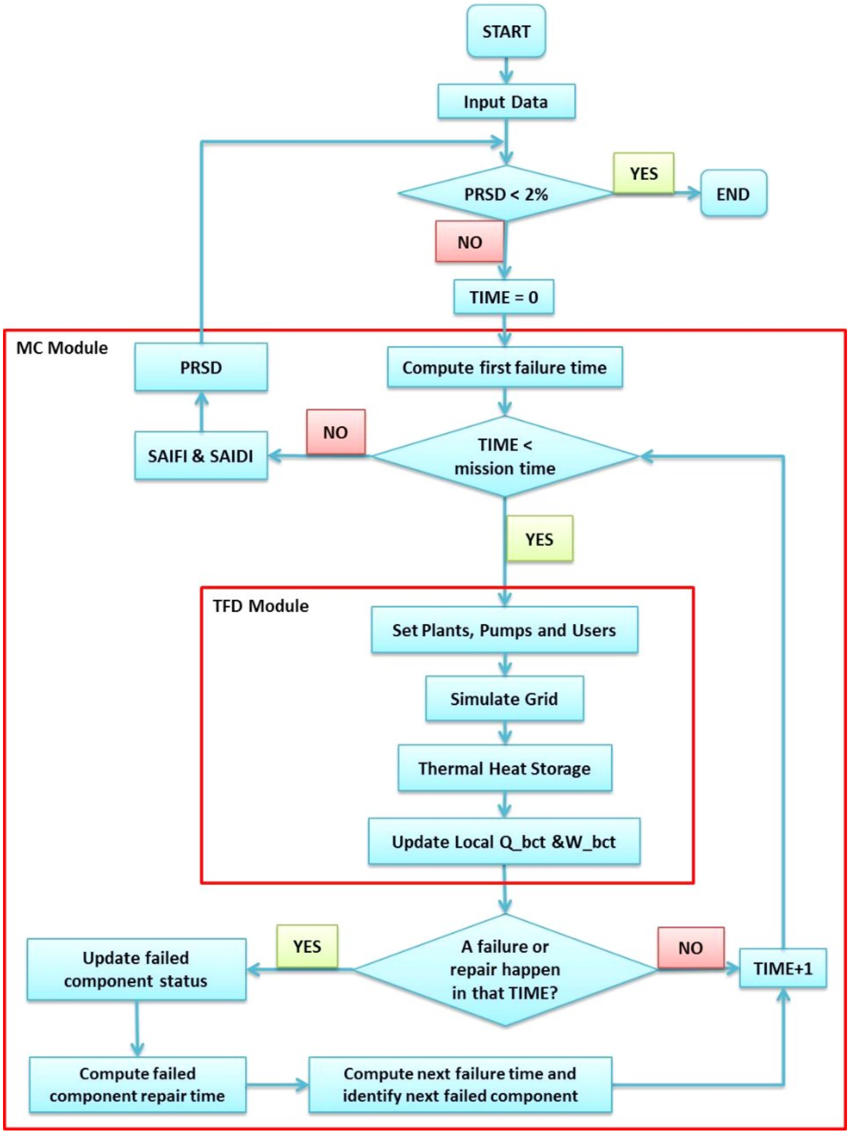


Figure 45: Diagram of the Simulation Program

- **Thermo-Fluid Dynamic (TFD) Module:**

The Thermo-Fluid Dynamic Module sets the hydraulic parameters of the plants and users, allowing the simulation of the dynamic thermo-fluid behaviour of the whole network.

For each time step, according to the status, number and characteristics of the components, this module evaluates the heat and water produced by the power plants requested for fulfilling the users' needs, comparing them with the maximum capacity of the pumping stations.

For users and pumping stations, water mass flow rate ($\dot{V}_i$) and heating power ($\dot{Q}_i$) are linked by the following relationship:

$$\dot{Q}_i = \dot{V}_i \cdot c_p \cdot \Delta T = \dot{V}_i \left[\frac{kg}{s}\right] \cdot 4{,}186 \left[\frac{kJ}{kgK}\right] \cdot 60[K] \tag{47}$$

The physical properties are assumed constant in each time step. Hourly load profiles for the production plants have not been introduced because, if sudden failures can occur and specific necessities can consequently arise, it would be meaningless to fix their power output. The only performed control is the one related to the fact that the production plants are able to satisfy the total requirements of the users or not.

Starting from the updated structural and thermo-hydraulic data, the module simulates the water and heat distribution along the network to the users. The entire approach is based on a pipeline *drag parameter* defined for the *b-th* branch of the network according to the following relationship:

$$R_b = \sqrt{\sum\nolimits_{k=1}^{n} \frac{L_{eq,k}}{d_k}} \tag{48}$$

The module starts from each production plant, and it takes into consideration the next branches that have to be fed. Their drag parameters are compared, and the lower one is assumed as representative of the lower hydraulic losses. The tool is thus able to identify and choose the preferential path through which it can deliver water and heat to the next barycentre.

All the pipeline branches are systematically taken into account, until the entire network has been completely analysed or the available quantities of water and heat have been exhausted. Consequently, at each time step the served and unserved barycentres can be identified.

- **Monte Carlo (MC) Module:**

The Monte Carlo Module allows to manage the whole time evolution of the grid during the prescribed "mission time".

> The Monte Carlo method is effective in assessing the reliability and service quality of flow networks, as shown by several authors. Todinov [263] developed a mixed approach (Breadth-first and Monte Carlo method) for network design and topological analyses. Furthermore, in [264], he analysed in a detailed way optimisation algorithms for repairable flow networks. Among other studies, the ones performed by Praks et al. [265], [266] and Carpignano et al. [267] can be mentioned. Carpignano et al., in particular, confirmed that Monte Carlo simulation can be a suitable option for the reliability analysis of meshed evolving fluid networks, even the ones characterised by time-dependent components (like storage systems).
>
> Referring to the evaluation of the reliability of other network types (as electrical and telecommunication networks), several approaches are available in the scientific literature. Among them, the Artificial Neural Network (ANN) [268], [269], the Bayesian model [270] and the multi-state modelling [271] can be cited, as well as mixed techniques, like Monte Carlo simulation and Cellular Automata [272], [273] or Monte Carlo and Breadth First [274]. These methodologies, however, suffer from some drawbacks (for instance, the Bayesian model requires previously defined graphs, no closed loops and oriented lines) or need for the adoption of Monte Carlo Methods (like the ANN method, which is suitable only for defining different topological designs).

The key phenomena involved in the simulation of the time evolution of the network behaviour are failure and repair processes. The thermo-hydraulic parameters are modified on the basis of these processes and then, through the TFD Module, a check is made for verifying which barycentres have been properly served.

The system is supposed to be Markovian, i.e. the system evolution is assumed influenced only by the present state and by the age of the components or by previous failures.

According to the risk analysis principles [275] and starting from the Probability Density Functions (PDF), for an exponential time distribution

$$f_{\rho}(t)dt = \lambda e^{-\lambda t}dt \tag{49}$$

implemented by means of the inverse transform method, the failure time (i.e. the time at which a given component *c* changes its state from "working" to "failing") and the corresponding repair time, can be calculated as follows:

$$failure\ time: \quad t_s = t_0 - \frac{1}{\sum \lambda_c} \cdot \log(\rho) \tag{50}$$

$$repair\ time: \quad t_r = t_s - \frac{1}{\mu_c} \cdot \log(\rho) \tag{51}$$

The adopted values for the different components are listed in Table 22.

Table 22: The adopted Component Failure and Repair Rates [276]

Component	Failure Rate [1/h]	Repair Rate [1/h]
Pumps (PS, PP1, PP2)	1,00E-5	0,083
Boilers (PP1, PP2)	5,00E-3	1
Gas Turbine 1 (PP1)	1,65E-3	0,106
Gas Turbine 2 (PP1)	5,16E-4	0,123

At the beginning of each simulation, the first failing component is identified. Then, the repair time and the next failure time are computed each time a new failure happens: as a consequence, the Monte Carlo module varies the grid structure analysed by the TFD module.

Due to the characteristics of DHNs (i.e. multiple and different users spatially spread), it is not easy to identify availability and reliability parameters able to clearly measure the service quality for a given configuration and for specific system characteristics.

Several **indexes** aiming at expressing the **RAMS features** for a network have been proposed. **Two** of them have been assumed in this analysis and have been adapted, for making them suitable for the study of DHNs. These indexes are:

$$\begin{aligned} SAIFI &= \sum_{i=1}^{N_{bct}} SAIFI_i \\ &= \sum_{i=1}^{N_{bct}} \frac{\dfrac{\sum_{j=1}^{N_{sim}} \dfrac{W_{bct\,i,j}}{t_m}}{N_{sim}} \cdot V_i}{\sum V_i} \qquad \left[\frac{service\ failures}{h}\right] \end{aligned} \tag{52}$$

$$\begin{aligned} SAIDI &= \sum_{i=1}^{N_{bct}} SAIDI_i \\ &= \sum_{i=1}^{N_{bct}} \frac{\dfrac{\sum_{j=1}^{N_{sim}} \dfrac{U_{bct\,i,j}}{t_m}}{N_{sim}} \cdot V_i}{\sum V_i} \qquad \left[\frac{hours\ of\ service\ disruption}{h}\right] \end{aligned} \tag{53}$$

They respectively represent the average number per hour (**SAIFI**) and the average time per hour (**SAIDI**) of service disruption for the entire network. They have been originally proposed for the reliability analysis of power systems [277] and have been adopted in various applications. Among these applications, the study carried out by Abbasi et al. [278], which include these parameters in the objective function of an optimisation model for thermal and electricity distribution grids, can be cited.

These indexes are obtained from the number of service failures ($W_{bct_{i,j}}$) and the hours of service disruption ($U_{bct_{i,j}}$) during each simulation j.

For all the users associated to the *i-th* barycentre, the tool counts, over the mission time, how many times there is a transition from the served to the unserved status (corresponding to a lack of water or power) and how many hours the users has to remain unserved (i.e. the time period between the transition from served to unserved and the transition between unserved and served). These numbers are respectively stored into the $W_{bct_{i,j}}$ and the $U_{bct_{i,j}}$ variables.

These values are firstly divided by the mission time t_m in order to calculate the hourly value. They are then summed over the entire set of simulations and divided by the number of simulations, N_{sim} , for evaluating the average value.

Finally, they are weighted using the BCT water flow rates for considering that a service disruption for important and large users (like hospitals) is more crucial than a disruption for a residential building. The SAIFI and SAIDI indexes are finally obtained by summing these values over the number of BCTs.

SAIFI and SAIDI allow a synthetic but complete information about the overall system situation and consequently they can be adopted for analysing and comparing scenario results.

The **loop functioning** of the model can be summarised as follows (Figure 45):

- For each simulation, the time at which the first failure occurs is identified and it is considered as starting time
- The network behaviour is simulated hour by hour, until the mission time is reached or until a new status transition (a failure or a repair) of the system occurs
- If a new transition occurs over the mission time, the status of the involved component is updated. In case of a repair, the component status is restored, while in case of a failure the component status is modified and the related repair time is calculated before moving on to the next time step
- For calculating SAIFI and SAIDI, the $U_{bct_{i,j}}$ and $W_{bct_{i,j}}$ counters (storing the local information on the service quality) are updated after each completed TFD simulation
- The TFD simulation of the grid behaviour consists in:
    - defining needs and capacities of the system, according to the status of the components
    - analysing the heat and water transport along the network and the possibility of charging the storages or of using their heat
    - identifying all the served and unserved users and updating the parameters $U_{bct_{i,j}}$ and $W_{bct_{i,j}}$ that are needed at the end of the simulation for calculating SAIFI and SAIDI

- In order to get meaningful results, the Percentage Relative Standard Deviations (PRSD) of the SAIFI and SAIDI indexes is evaluated and the iterative procedure runs until the errors of SAIFI and SAIDI are equal to or lower than 2%.

For testing the proposed approach, 3 **scenarios** have been defined and analysed:

- Base case (without users load profiles and storages)
- Scenario 1 (with users load profiles and centralised storages)
- Scenario 2 (with users load profiles and both centralised and local storages)

These scenarios have been built for showing the criticalities of the network and the impacts of different components failures.

- **Base Case:**

  The key assumptions are:

  - Duration of each simulation: mission time $t_m = 2160$ hours (i.e. 3 months)
  - Constant overall production plants output = 664 MW
  - Constant users demand = 558 MW.

  This configuration is different from the actual one but allows to test the procedure and gives information on possible reliability issues at a single-user level.
  The obtained results are:

  - SAIFI = 0.00117
  - SAIDI = 0.00656.

  Starting from these values, the number of failures and the hours of service disruption in a given time period can be calculated by multiplying the SAIFI and SAIDI values by the period time length.
  For instance, during 6 months or 4320 hours (i.e. the typical heating period in Northern Italy), the average values of service failures and hours of disruption over all the barycentres and weighted on the requested service are:

  - $0.00117 \cdot 4320 = 5$ service failures
  - $0.00656 \cdot 4320 = 28$ hours of service disruption.

  These values are, of course, related to the scenario hypotheses, especially to the fact that the demand of users is lower than the power production.
  Considering the local unreliability and unavailability shown in Figure 46, it can be noticed that Thermal Barycentres 37, 42 and 43 need attention and

have the highest effect on the global performance of the network. This is because these barycentres are the extreme nodes of the network or because the network meshing density for the trunks they belong to is low.

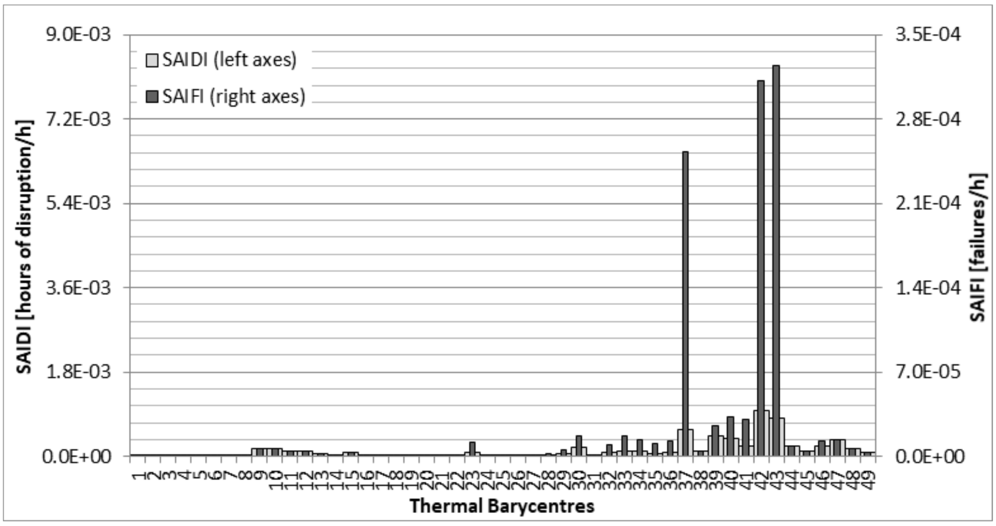


Figure 46: Local Reliability Parameters for the Base Case

Moreover, it can be seen that the local SAIDI and SAIFI values do not automatically grow as the distance between barycentres and production plants increases, due to the fact that these indexes are weighted by the single BCT water mass flow rates.

- **Scenario 1:**

  The key assumptions of this scenario are:

  - Duration of each simulation: mission time $t_m = 2160$ hours (i.e. 3 months)
  - Constant overall production plant output = 664 MW
  - Users demand represented by the Load Profile
  - 2 centralised storages located as in Figure 47 (TES GN1, TES BCT 13), with a total volume ≥ 8500 m^3.

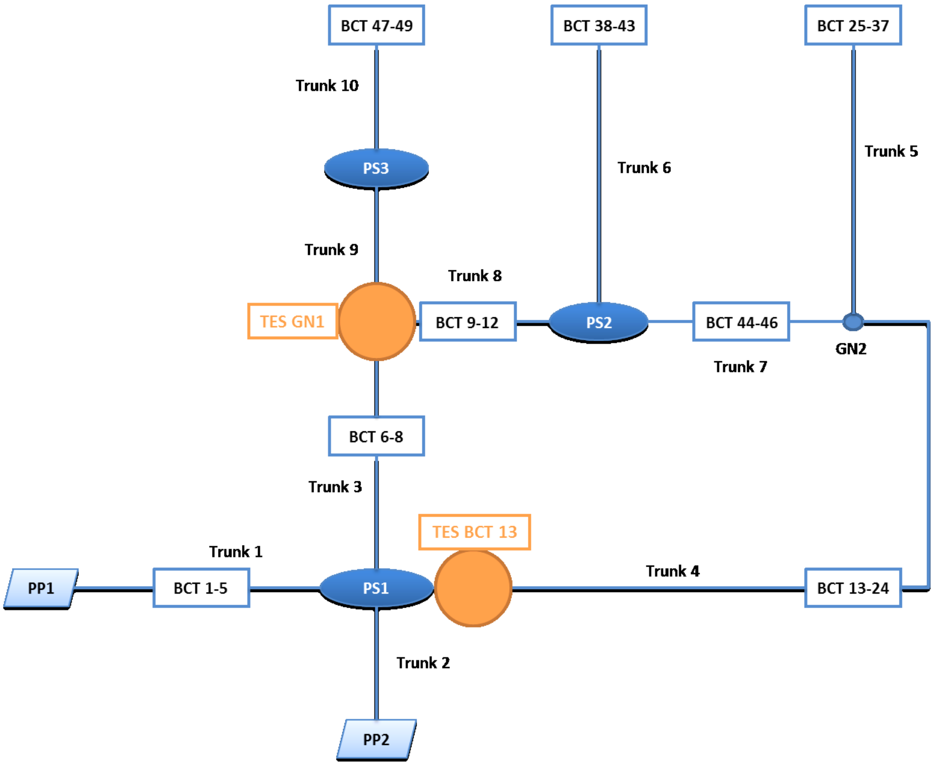


Figure 47: Scenario 1 – Centralised TES localization

Different configurations for Scenario 1 have been analysed, by varying the size, the position along the network and the water flow rate of the two TESs. Table 23 shows the best obtained configuration in terms of reliability.

Table 23: Best configuration and related results for the centralised storages

Storage	**Volume [m³]**	**Flow Rate [kg/s]**
GN1	4900	1805
BCT 13	3600	1325
Parameter	**Result**	**Variation in comparison with the Base Case**
SAIFI	0,00211 (4.6 failures over t_m)	+80%
SAIDI	0,03648 (78.8 h of disruption over t_m)	+456%

The growth in the values of SAIFI and SAIDI underlines that the grid (which operates according to an actual load profile) cannot guarantee the service ensuring the Base Case performances.

The unavailability and unreliability conditions of the local barycentres are shown in Figure 48.

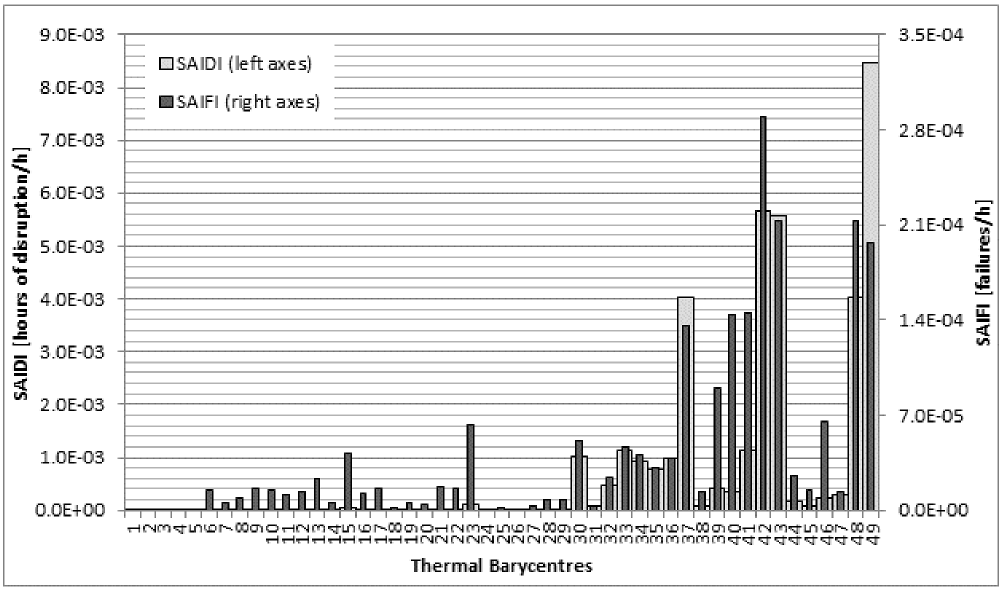


Figure 48: Local SAIFI and SAIDI for Scenario 1 (with centralised storages)

The comparison among Figure 48 and Figure 46 allows to notice that SAIFI and SAIDI are higher than the corresponding ones obtained in the Base Case. This is because the introduction of the load profile has largely modified the grid dynamics and the response to failures.
Additionally, it can be seen that, in this configuration, the network is affected by 9 failures in a time period of 6 months, leading to about 157 hours of service disruption for the final users.
The main considerations that arise from the analysis are the followings:

- The simulation of the dynamic behaviour of the final users by means of load profiles is mandatory for obtaining relevant results
- Centralised storages are required, and their proper siting and sizing allow to manage the entire system in an efficient way
- Centralised storages are probably not sufficient for ensuring a good service quality
- Considering the actual load profile, BCT 49 shows a criticality, as for the BCTs 37, 42 and 43 previously identified.

The fact that the grid is not able to effectively fulfil the required service, even in presence of TESs, underlines the need for improving the storage planning. According to this purpose, Scenario 2 aim at evaluating the effects of small distributed storages for the single barycentres on the grid reliability and availability.

- **Scenario 2**

In comparison with Scenario 1, the main hypothesis of this scenario is the introduction of local TESs for the final users recognised as critical during the previous analysis (Figure 49). Their volumes are assumed smaller than those of the centralised storages, and for the various considered configurations, they have been set for ensuring more than one hour of heat to the related BCTs.

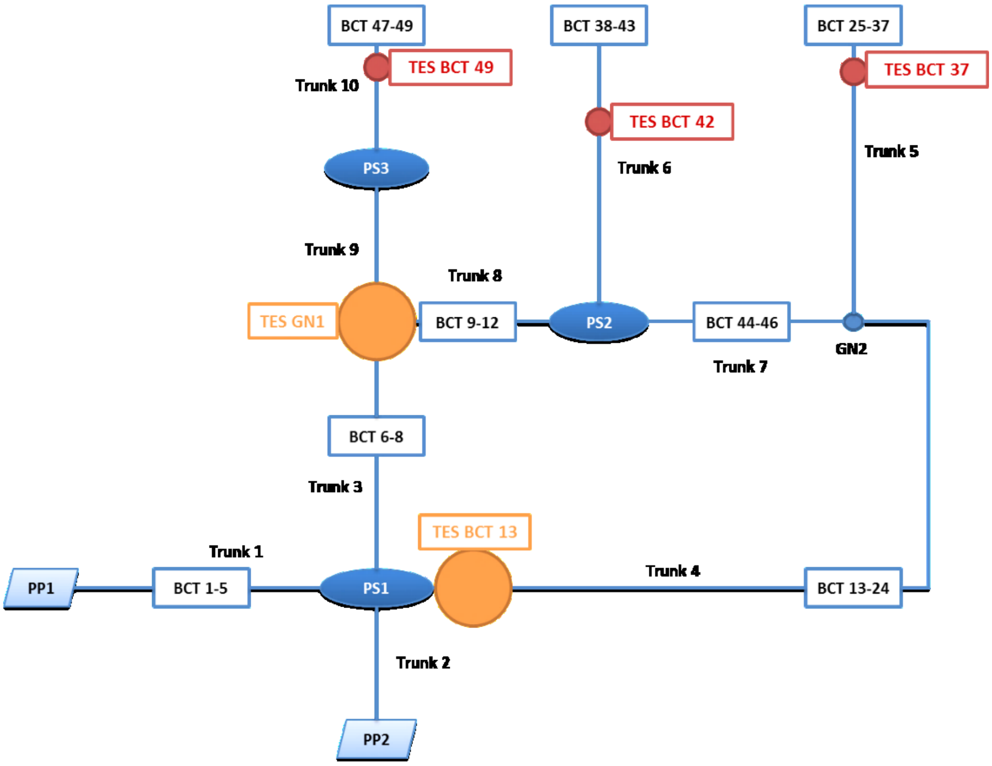


Figure 49: Scenario 2 – Distributed TES localization

Different configurations of Scenario 2 have been analysed, modifying the water flow rates and the volumes of storages. Among the considered configurations, the one shown in Table 24 corresponds to the lowest SAIDI value, with 2 centralised TESs and 3 distributed TESs located on the peripheral trunks of the grid.

Table 24: Best configuration and results for decentralised TES

Storage	**Volume [m^3]**	**Flow Rate [kg/s]**
BCT 37	635.5	63.6
BCT 42	1150.6	115.1
BCT 49	472.1	47.2
GN1	4700	670
BCT 13	3950	560
Parameter	**Result**	**Variation in comparison to Scenario 1**
SAIFI	0.00135 (2.9 failures over t_m)	-36%
SAIDI	0.0154 (33.3 h of disruption over t_m)	-58%

In this configuration, the volumes of the local storages allow to fulfil the BCT needs for about 2 hours and 47 minutes. The choice of these volumes can be justified by taking into account the characteristics of the system failure. In the investigated case study, the majority of failures lasts less than 2-3 hours, and the related unavailability could be faced by storages. Only a limited number of failures lasts about 20 hours, thus resulting not manageable.

Furthermore, larger centralised storages have also been analysed, but they do not lead to a relevant growth in the availability and reliability of the whole system. This put into evidence the opportunity of planning and designing local and centralised storages according to their different purposes. In particular:

- Small storages have to face possible short service disruptions
- Large storages have to be sized for covering the peak demand.

Focusing on the local SAIDI values (Figure 50), it can be noticed that the adoption of local storages can allow a relevant reduction (about 50%) of the hours of service disruption for the most critical BCTs with respect to Scenario 1.

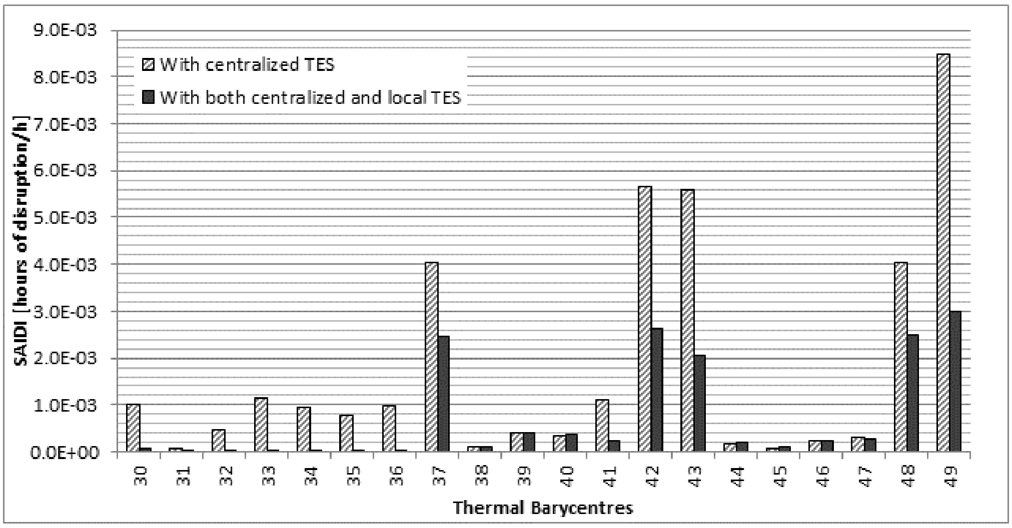


Figure 50: Comparison of the SAIDI values for the best configuration of Scenarios 1 and 2

These analyses highlight how a combined use of large central and small local storage systems allow a more efficient management of complex district heating networks, and a reduction in the number of hours of service disruption from 206 to 66.

In general, the obtained results have shown the crucial role of storages and their impacts on the thermo-hydraulic behaviour and on the network reliability. It has been observed that large centralised storage systems are effective in peak shaving, while small local storage systems (with a capacity of few hours) allow to counteract the unavailability caused by the most common short service failures.

The comparison of various grid configurations emphasised that a proper location and sizing of TESs and the inclusion of reliability analyses in the network design phase could be beneficial from the point of view of the demand fulfilment and of the service quality.

As previously said, in the scientific literature only few studies are focused on the topic discussed in this analysis. Due to this reason, an effective comparison of the results obtained in this case study with those obtained by similar methodological approaches is not possible. The most comparable method is the one developed by Rimkevicius et al. [182]. However, the objective of the study (related to the district heating network of Kaunas city, Lithuania) analysed by the authors is mainly devoted to the reliability assessment for the grid. It takes into account the failure rates of the pipelines, their mechanical fractures, the critical sections and the effects of a failure on the final users. In the proposed study, instead, even if the reliability aspects are important, the main goal is to evaluate how different grid designs (especially taking into account location and sizing of storages) can impact on the service quality, quantified by means of reliability considerations.

It has to be further highlighted that the developed approach has been tested by means of the case study related to an Italian city previously discussed, but it can be used for analysing different types of DHNs and scenarios. For instance, by means of the Monte Carlo approach, the daily load profile could be modified according to historical data. Moreover, starting from the current values of SAIDI and SAIFI parameters for each barycentre, the storage location and sizing could be optimised for minimising the values of these indicators for critical BCTs (as hospitals), on the basis of their need of suffering short or few service disruptions). Finally, taking into account the impact of each specific failure on SAIFI and SAIDI, the most critical sections of the network can be identified, thus defining maintenance priorities and more effectively plannning the related investments.

Among the possible improvements, the implementation of load profiles variable with the ambient temperature and the modelling of pipeline leakages can be mentioned. The use of the proposed methodology in cooperation with network managers for diagnostic purposes could be also useful for obtaining feedbacks on the grid management procedures and on the actual reliability data.

Future steps include the implementation of an integrated planning tool able not only to link the reliability and the thermo-hydraulic aspects but also to include the optimisation of the layout of the grid from an economic perspective, thus integrating the developed methodology with the already well-stated design approaches.

5.3.2 **Fifth case study**

For the development of this case study, aiming at assessing the possible role of **hydrogen penetration** in future **urban energy systems** and its effect on the **security** of energy supply (i.e. at a wider scale), the global forecasting optimisation model **REACCESS**, based on the TIMES model generator, has been adopted.

The "Risk of Energy Availability: Common Corridors for Europe Supply Security" (REACCESS) model – as mentioned in Chapter 5.1 – was built under the 7th Framework Programme (FP7) of the European Commission, with the goal of developing a forecasting tool for the quantitative assessment of the energy supply security for the European Union [235].

This tool is based on the link among 3 bottom-up optimisation forecasting TIMES energy models [46]:

- the Pan European TIMES (PET36) model
  which represent the energy system of 36 European countries (the 28 EU Member States plus Switzerland, Norway, Iceland and the Balkans);
- the TIAM-World model
  which represents the energy system of the other 15 world macro-areas (Africa, Australia, Canada, Central Asia and Caucasus, Central and South America, China, India, Japan, Middle East, Mexico, Other Developing Asia, Other Eastern Europe, Russia, South Korea, USA)
- the REACCESS CORridor (RECOR) model
  which describes the energy corridors (both captive and open sea, in operation and planned/possible) for the transport of the different energy commodities (hard coal, crude oil, natural gas and LNG, refined petroleum products, nuclear material, biomass and biofuels, electricity from CSP, and hydrogen).

In particular, in the **RECOR model** each corridor is assumed to be composed by several branches, in order to better define its physical dimension and to consider its route. The model allows the complete traceability, through an ad hoc coding system, of each commodity, from the extraction field (characterised by extraction costs and capacity data and by information on the expected proven, probable and possible resources) to the entry points of the various countries.

Moreover, the RECOR model includes **risk parameters** for the evaluation of the security of all the energy supplies. These risk indicators are related to each corridor and are calculated as the probability of failure of the corridor itself, considering the risk indexes related to each country crossed by the considered corridor. These risk indexes are hypothesised steady over time and range between 0 (safe country) and 100 (unsafe country). They were calculated by means of factor analysis methodologies and taking into consideration 4 dimensions related to the geopolitical security of a given country: the political-institutional, the socio-political, the energetic and the economic ones [279]. The country risk indexes are supposed to represent the probabilities that a corridor crossing a certain country fails [231]. Finally, the risk related to each supply is quantified by multiplying the corridor risk index by the flow of commodity (called "activity" and measured in energy units) carried out by that corridor. Through this approach, the risk is therefore considered as a sort of pollutant emission, and so it is possible to perform scenario analyses including constraints on the risk value, like a fixed percentage risk reduction in a given year for a single country or for a set of countries or a maximum risk level.

Focusing on the emissions, the REACCESS model calculates, by means of emission factors, the GHG emissions deriving from the use of technologies fuelled by fossil commodities and related to the entire energy system. Consequently, by implementing ad hoc constraints it is possible to investigate decarbonisation scenarios that describe environmental policies and goals (like those defined by the EU roadmap 2050).

Risk scenarios and environmental scenarios can be also combined in order to analyse the possible future energy pathways created by the adoption of different policies related to the penetration of new technologies, as those concerning hydrogen.

The REACCESS model allows to carry out scenario analyses over a mid-/long-term time horizon. For each run (i.e. for each different scenario), it finds the system configuration that corresponds to the minimum total system cost (i.e. the minimum value of the objective function), under the set of constraints.

In the model, each **technology** is described by:

- economical parameters (investment costs and fixed and variable operation costs)
- technical parameters (availability factor, specific consumption, efficiency, life, etc.)

and the topological link among commodities and technologies is represented in the Reference Energy System.

The whole set of model equations (including the objective function and the constraints) is made by linear equations. Consequently, from a mathematical perspective, the model can be considered a **Linear Programming** (LP) problem.

In particular, the **objective function** is defined, for each model region (i.e. a single country or a world macro-area), as the sum of different cost component [46], according to the following relationship:

$$\begin{aligned} OF_r(z) = \sum_y D(y,z) \\ \cdot [IC_r(y) + IT_r(y) + ID_r(y) + FC_r(y) + FT_r(y) \\ + VC_r(y) + EC_r(y) - LR_r(y)] - S_r(y) \end{aligned} \tag{54}$$

Where:

- *r*: model region
- *y*: model year
- *z*: year at the beginning of which the total system cost is discounted
- *D*: discount factor
- *IC*: investment cost

- *IT*: taxes and subsidies related to the investment
- *ID*: decommissioning cost
- *FC*: fixed operating and maintenance costs
- *FT*: taxes and subsidies related to the installed capacity
- *VC*: variable costs
- *EC*: costs related to the loss of welfare (in comparison with the baseline run) due to the change in the demands when elastic demands are used
- *LR*: late revenues from materials and energy embedded in some processes, which are released after the end of the time horizon
- *S*: salvage value related to the unused part of the technical life for those investments that exceed the end of the time horizon

The single regional objective functions are summed together for calculating the overall objective function, which has to be minimised by the solver (in turn, based on the Simplex algorithm).

Within the model, **hydrogen** is produced by dedicated processes, which simulate the variety of synthetic gas production technologies. This is the main source of hydrogen for non-industrial use. Hydrogen for industrial use (mainly in the petrochemical sector) is supposed to be self-produced by means of the reforming of natural gas already supplied to the plant. This hydrogen is not merchant hydrogen but self-produced and used hydrogen and, for this reason, it is included in the hydrogen Reference Energy System (RES) (Figure 51). Instead, according to the perspective penetration of hydrogen in the economy, new hydrogen sources have been analysed and represented in the model. The REACCESS project, starting from the results obtained in previous analyses like DLR advanced studies on CSP or ENCOURAGED, identified some possible production sites for hydrogen that could be supplied to Europe. The general idea was to exploit inefficient fossil sources or widely available but intermittent renewable potentials for producing high quantities of hydrogen to be delivered to Europe for using them in the end-use sectors, like the commercial, industrial, transportation and agricultural ones.

Among the outcomes of the project, a database identifying the possible corridors supplying hydrogen to Europe.

In particular, the exploitable potentials are:

- cheap lignite in Ukraine basins,
- spread biomass (originated from agricultural residues) in Turkey,
- solar radiation in Algeria and
- off-shore wind in Morocco.

Detailed data related to the analysed potentials are available in [280].

Twelve **corridors** were defined and the versatility and complexity of hydrogen as energy vector were taken into account by means of the various considered pathways (from production to final supply).

The **lignite** potential was described to be converted into hydrogen through gasification and then carried in form of gaseous compressed hydrogen via pipeline to the eastern European countries (Poland, Czech Republic, Hungary and Romania). This potential is small and so the model can select a country to supply, but not all the four.

The **biomass** potential in Turkey was supposed to be exploited through reforming in a distributed generation grid. One hunderd small and medium reforming plants were assumed to be installed in barycentric zones of Turkey and then linked for reaching the expected production volume. Two alterntive pathways were imagined:

- one that transfers hydrogen from the central part of Turkey to the Ceyhan port on the southern costs, where natural gas liquefaction plants were planned and an industrial port is already in operation
- one that transport hydrogen via pipelines to Bulgaria.

This LH_2 was supposed to be supplied to Greece and Italy.

The **solar** potential was assumed to be exploited by means of a CSP plant coupled with a thermo-chemical cycle, splitting the water molecule into hydrogen and oxygen without the use of electricity. The gaseous hydrogen is then carried via pipeline to the Algerian coast, where it is liquefied in existing industrial and port facilities. From these ports, LH_2 ships reach the coasts of Italy, France and Spain, where the commodity is regasified and distributed.

The **wind** offshore potential in Morocco can be interesting due to its strength and constancy. This potential could be exploited through an offshore wind farm, which produces electricity. This electricity is used in a large-scale electrolysed plant onshore and the produced gaseous hydrogen is shipped to the liquefaction plant located in another site next to a port. From this port, ships reach both the Atlantic and the Mediterranean coasts of Spain.

The PET model includes two commodities identifying hydrogen:

- one for gaseous hydrogen and
- one for liquid hydrogen.

Gaseous hydrogen can be generated through gasification or pyrolysis of biomass, gasification of black liquor, electrolysis, coal gasification, partial oxidation of heavy fuel oil, steam methane reforming and solar methane reforming.

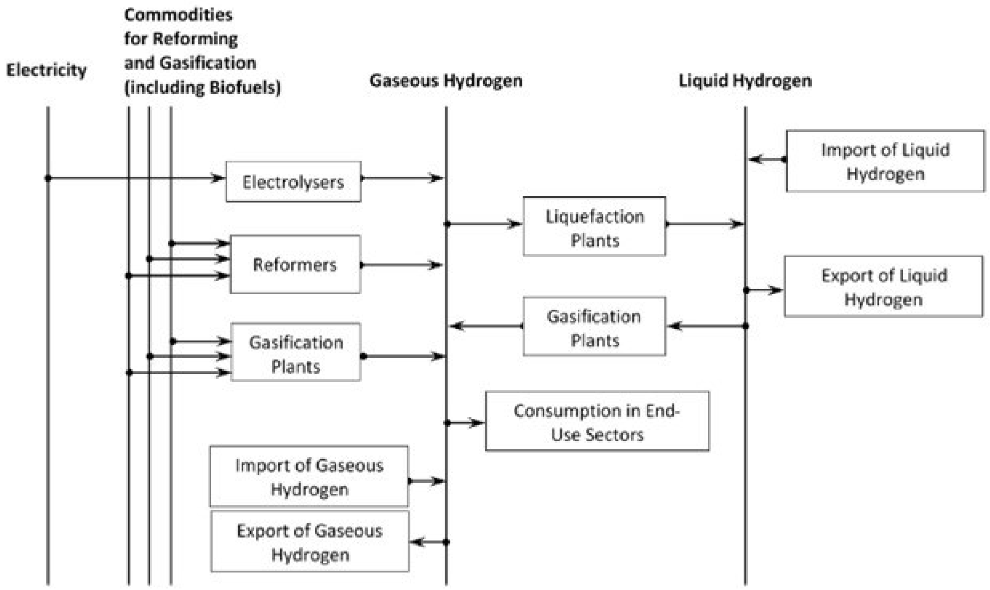


Figure 51: Reference energy system for hydrogen generation in the PET36 model

Figure 51 graphically describes a simplified representation of the Reference Energy System for the **hydrogen chain** implemented in the PET36 model , which takes into account local production, import and export, transformation and end-uses.

The model can use hydrogen (either in liquid or gaseous form) for the fulfilment of several demands, like residential, commercial, industrial, mobility and agricultural.

In the **residential** sector some of the several technologies available for satisfying the final services demand, like burners, can be directly supplied with hydrogen, while fuel cells (as SOFC) are mostly supplied via natural gas for CHP applications.

The **mobility** sector, apart from the modelling results represents a crucial entry option for the success of hydrogen economy. Numerous projects (as, in Europe, the Hy-Fleet Cute project) have demonstrated the technical feasibility of public transportation fleets supplied by hydrogen at urban scale, particularly if environmental constraints are considered.

The range of vehicles fuelled by hydrogen, even if increasing during the years, is still below the one of ICE vehicles. Furthermore, it has to be underlined the difficulty in implementing a capillary infrastructure for refuelling. Due to these facts, the applications of hydrogen technologies in the mobility sector are limited to urban and suburban areas. The models allows to consider urban and suburban application through the possibility of implementing ad hoc technologies for satisfying the mobility demand.

The coupling with the RECOR model previously described is achieved by considering that the corridors end points are located near cities (Athens, Warszawa, Marseille, Bratislava), which can allow the implementation of a public (or private) transportation scheme considering vehicles fuelled by hydrogen. It has to be noticed, however, that the city level is not a spatial detail planned for the REACCESS model.

Focusing on the public transport sector, the reference energy system of the PET36 model includes, among the possible "new" technologies, fuel cell hydrogen buses. These technologies compete each other for satisfying the mobility demand, as it can be observed in Figure 52, related to the urban buses sub-sector. The same types of vehicles are also available for the intercity buses.

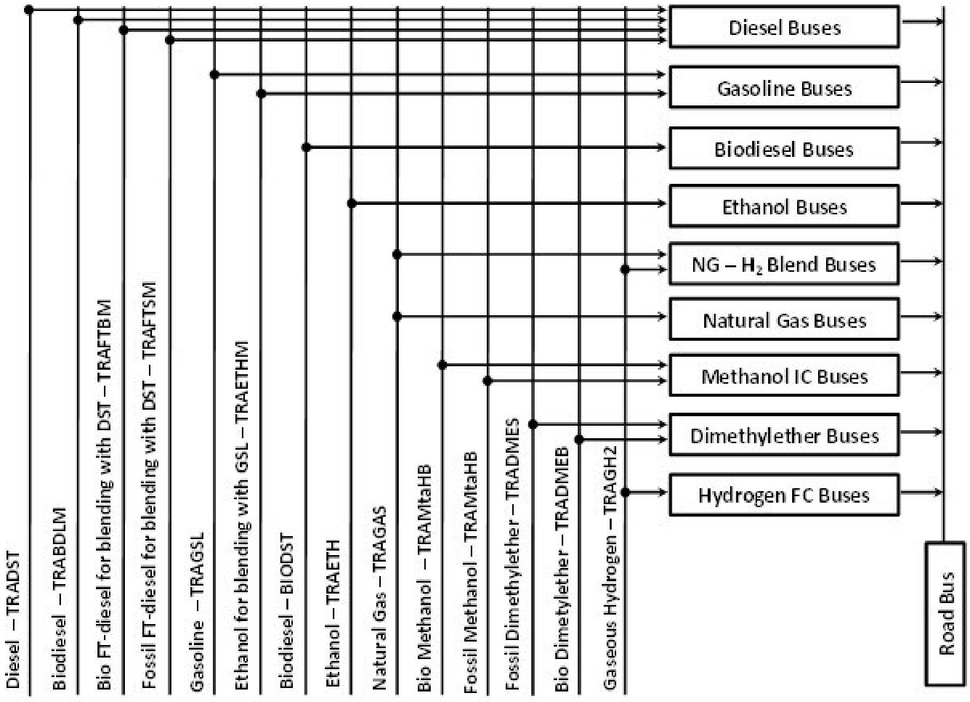


Figure 52: Reference energy system for urban public transport **[281]**

The different mobility demands, (which, in particular, include those related to passenger cars, urban and intercity buses and road freight) are measured in Mpass·km for passenger mobility or in Mton·km for freight mobility. These demands represent an exogenous input to the model: for this reason, the modal split is fixed "a priori" and it is not modified by the solver during the optimisation.

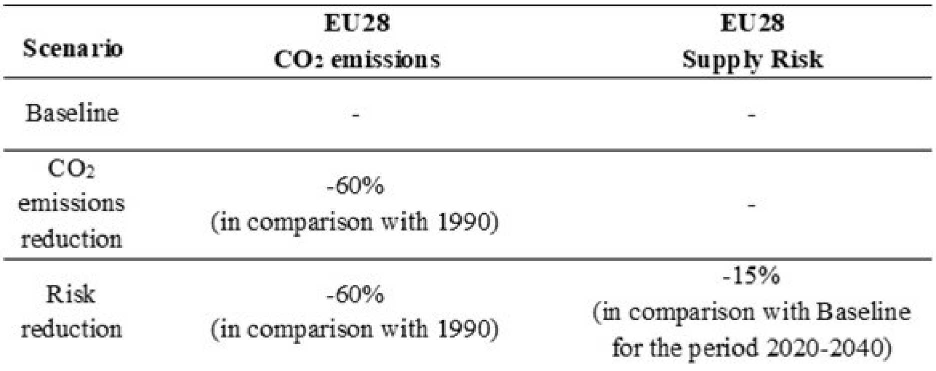
For carrying out the study, 3 scenarios (over the time period 2015-2040) have been hypothesised:

- a Baseline scenario, considering all the technologies fed by hydrogen but not including environmental constraints;
- a CO_2 emissions reduction scenario, which sets a CO_2 emissions reduction by 60% in 2040 in comparison with the 1990 value. It thus introduces in the model a constraint coherent with the one planned by the EU Roadmap, i.e. a 80% reduction in 2050);
- a Risk reduction scenario, in which the overall risk value for the European Union is reduced by 15% over the period 2020-2040 with respect to the

Baseline value, in addition to the previously defined constraint on CO_2 emissions.

The main hypotheses for the 3 scenarios are summarised in Table 25.

Table 25: Analysed scenarios



Scenario	EU28 CO_2 emissions	EU28 Supply Risk
Baseline	-	-
CO_2 emissions reduction	-60% (in comparison with 1990)	-
Risk reduction	-60% (in comparison with 1990)	-15% (in comparison with Baseline for the period 2020-2040)

The scenario analysis has been focused on the penetration of hydrogen technologies in the end-use sectors, in particular in the residential and transport ones, at European scale. Due to this, the activities (i.e. the energy fluxes, measured in PJ/y) related to the processes that correspond to the hydrogen chain have been taken into account.

The motivation of the choice of focusing on the hydrogen penetration for the European context has to be found in the urbanization pattern, which is increasingly relevant in other parts of the world (like India and China) but that also in Europe still show a slow discrete centripetal population movement.

Considering the **residential** sector, the obtained results show that hydrogen devices for low voltage electricity and heat generation are not installed and used by the model in all the scenarios, even if available over the assumed time period. This can be explained because investment and operating costs are higher than the ones of other technologies (like heat pumps for buildings heating), that are thus preferable under a least cost perspective. The hydrogen option seems valuable only in small countries like Cyprus and Malta, which do not have relevant local resources and, as a consequence, can find convenient the adoption of these technologies. For quantitatively assessing the impacts of the investment cost on the role played by hydrogen burners in the satisfaction of space heating demand, a sensitivity analysis has been carried out, by setting a reduction by 20%, 50% and 90% in this cost. The results put into evidence that only a reduction in the investment cost by 90% can allow a substantial penetration of this technology in the residential sector (urban and rural) (Figure 53).

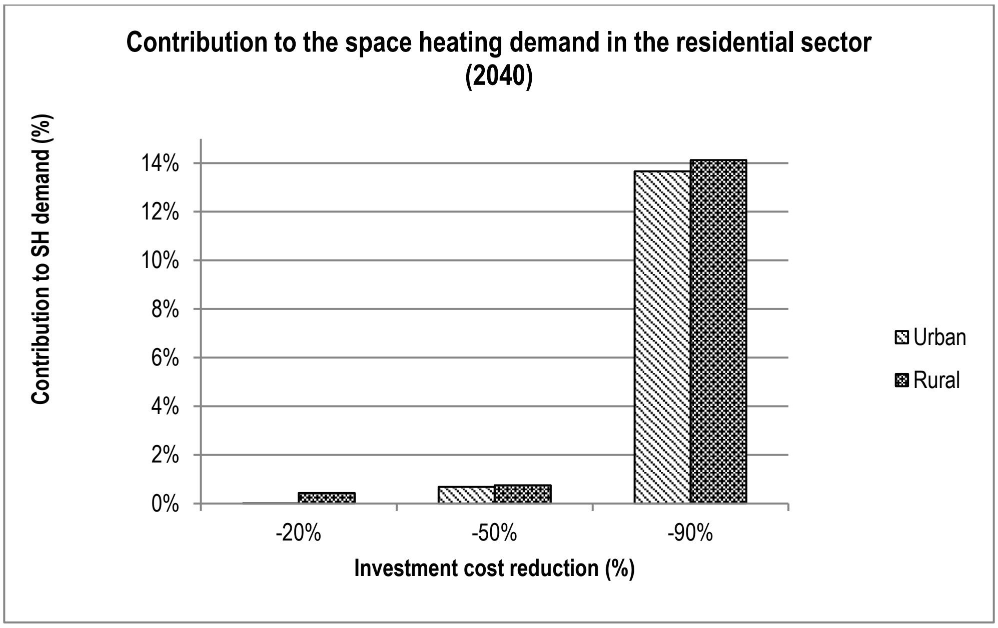


Figure 53: Contribution of hydrogen devices to urban and rural space heating demand changing the investment cost

In the **commercial** sector a more significant growth in the installed capacity of SOFC CHP in 2040 can instead be observed in the case of the CO_2 emissions reduction scenario. Also for this scenario, however, the diffusion is limited to small or relatively small countries like Cyprus, Latvia, Estonia and Czech Republic. For this scenario and for the entire EU-28, in the commercial sector the contribution of hydrogen to the low voltage electricity production accounts for 1.88% (this value increases to 3.42% only if direct generation – i.e. without transformation from medium voltage to low voltage – is considered), while for the low temperature heat demand this contribution is equal to 5.26%.

The most relevant findings are related to the **transport** sector when environmental goals are introduced. In particular, Figure 54 compares the total hydrogen consumption in the transport sector for the Baseline scenario and for the CO_2 emissions reduction scenario, measured in energy units.

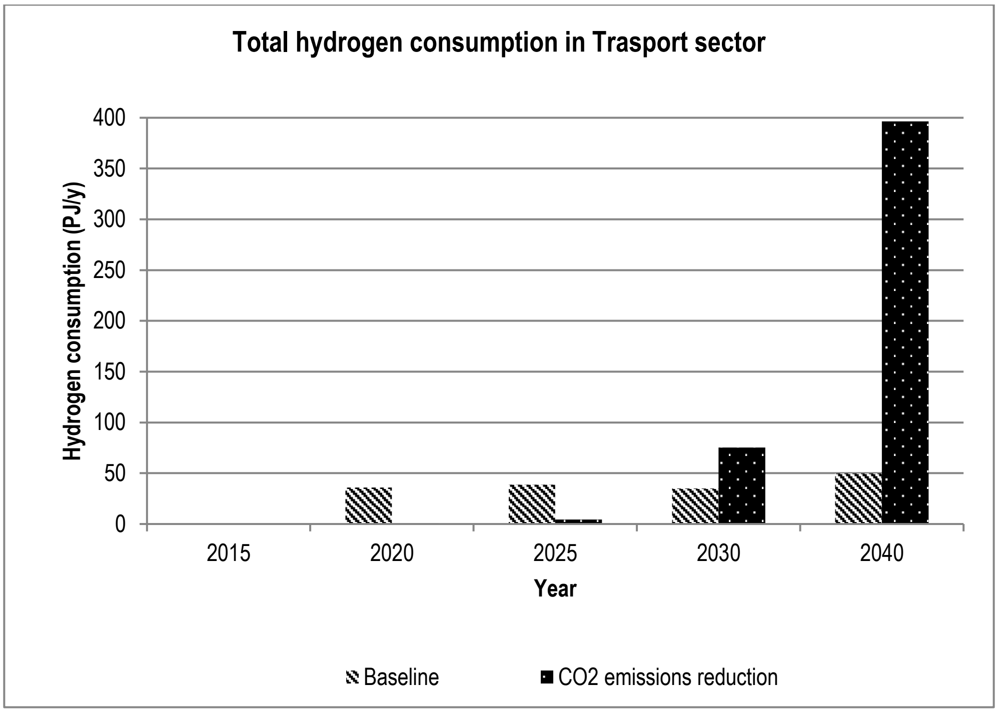


Figure 54: Hydrogen consumption in transport sector

In particular, it can be noticed that the most significant penetration of hydrogen vehicles involves the public transport, namely the urban and intercity buses. The forecasted trends for the consumption of gaseous hydrogen by urban and intercity buses for the Baseline and the CO_2 emissions reduction scenarios are reported in Figure 55 and Figure 56.

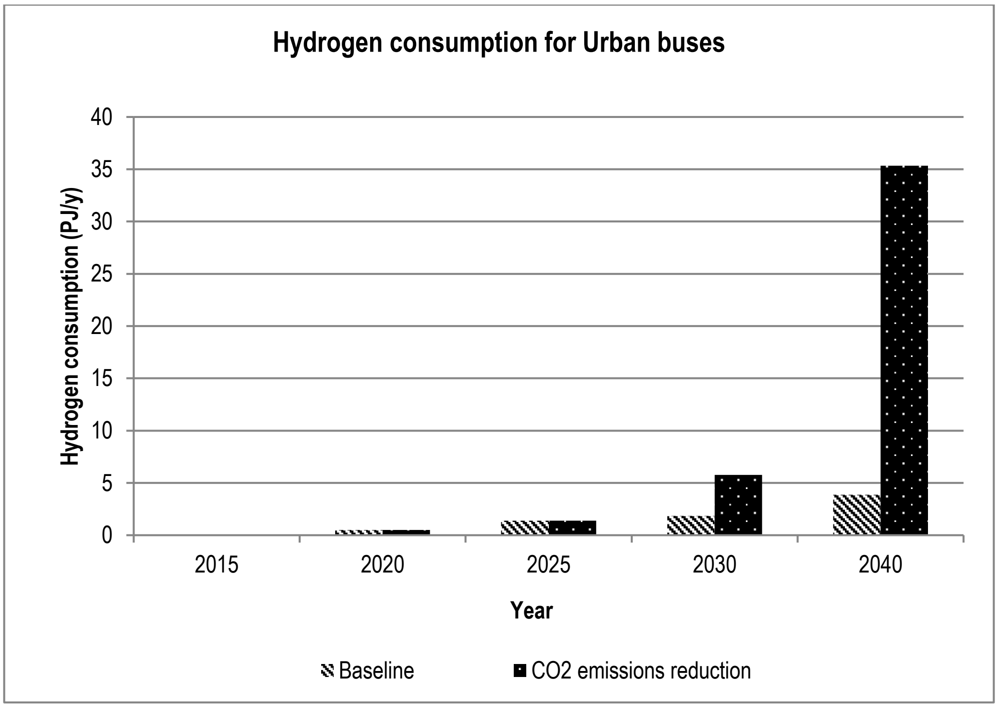


Figure 55: Gaseous hydrogen consumption for urban buses

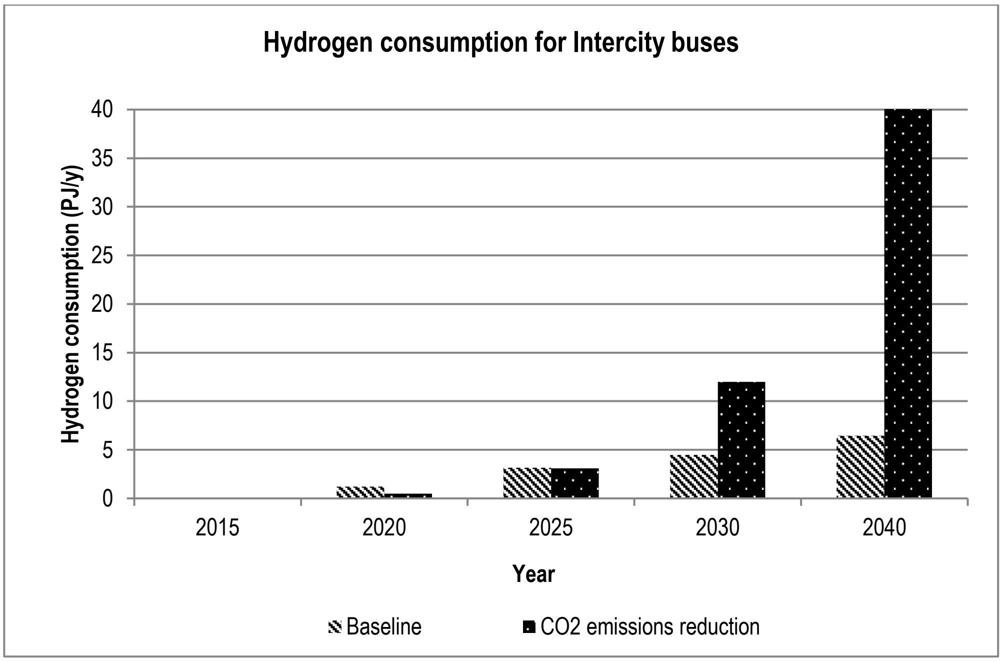


Figure 56: Gaseous hydrogen consumption for Intercity buses

It can be noticed that the penetration is especially significant at the end of the analysed time period. This relevant growth allows to hydrogen buses to fulfil the majority of the related mobility demand in the EU-28.

For assessing the fuel mix used in order to fulfil these demands, the following relationship has been adopted:

$$\chi_{f,i} = \frac{A_f}{M_i} \tag{55}$$

Where:

χ : percentage contribution of technologies fed by fuel f to the fulfilment of the mobility demand i

A : activity performed (i.e. share of demand fulfilled) by technologies supplied with fuel f (expressed in MPass·km)

M : mobility demand for subsector i, expressed in MPass·km

f : fuel

i : subsector of mobility demand (in the present case study, urban or intercity)

Figure 57 and Figure 58 show the obtained percentage contributions by commodity in 2040 in the case of the CO_2 emissions reduction scenario. In this scenario, a relevant fuel shift from fossil fuels to hydrogen and biofuels can be observed, coherently with the environmental constraints introduced.

The remaining amount of gaseous hydrogen used in transport sector in the CO_2 emissions reduction scenario is consumed by freight vehicles. By comparing the values reported in Figure 54, Figure 55 and Figure 56), it can be seen that in

2040 this quantity is the most relevant one. Despite this, the relative weight of hydrogen in this subsector is lower that the one in public transport, and it accounts for only 5.21% of the whole freight mobility demand (measured in Mton·km).

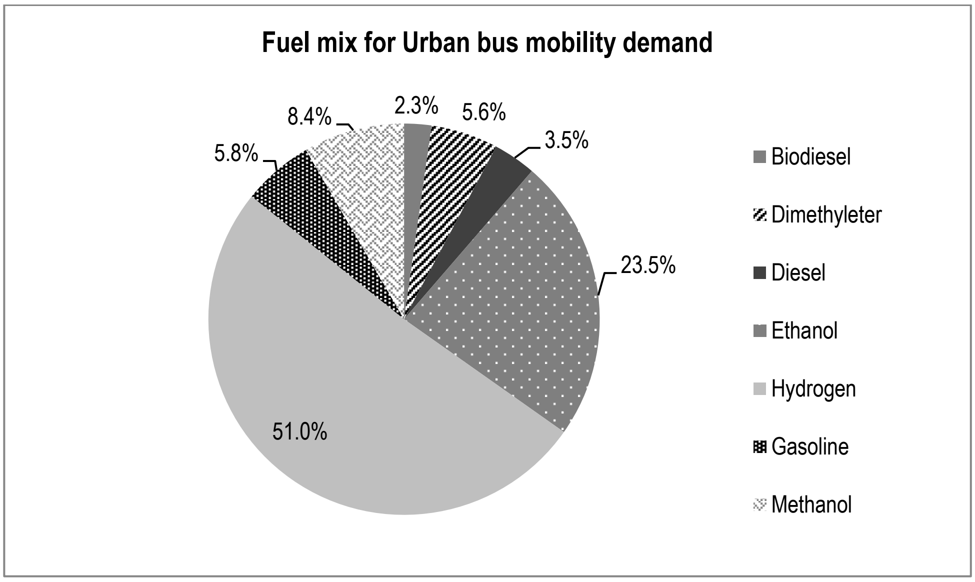


Figure 57: Fulfilment of urban bus mobility demand by energy commodity in 2040

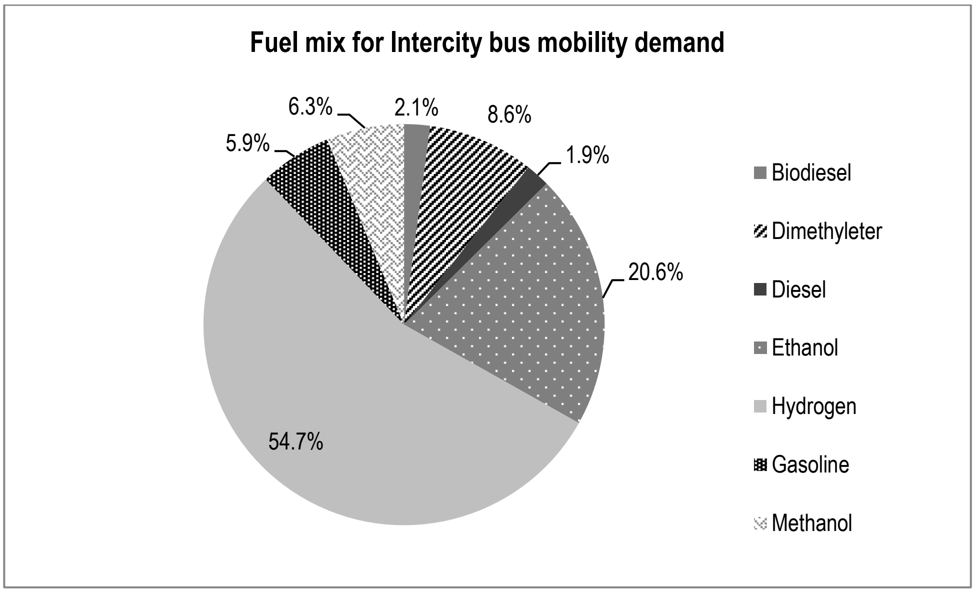


Figure 58: Fulfilment of intercity bus mobility demand by energy commodity in 2040

In order to explore a more effective option for supporting the transition towards a high hydrogen penetration in the mobility sector, a new typology of short distance cars and urban buses has been introduced into the model and tested with specific runs for the Baseline and CO_2 emissions reduction scenarios. These vehicles are fed with **hydrogen-methane blends**: according to [282], the assumed shares are 70% methane / 30% hydrogen for cars and 85% methane / 15%

hydrogen for buses (a blend value successfully tested also during the MHYBUS EU project).

The results highlight that, in both the scenarios, blends are not a relevant option in the optimal mix for urban buses over the assumed time period, even if, in the CO_2 emissions reduction scenario hydrogen still remains the main commodity in 2040. On the opposite, in the CO_2 emissions reduction scenario blends could play a high role for cars used for fulfilling short distance mobility demand. In fact, in this case the contribution of hydrogen-methane blends in 2040 is equal to 27.5%, as it can be seen in Figure 59.

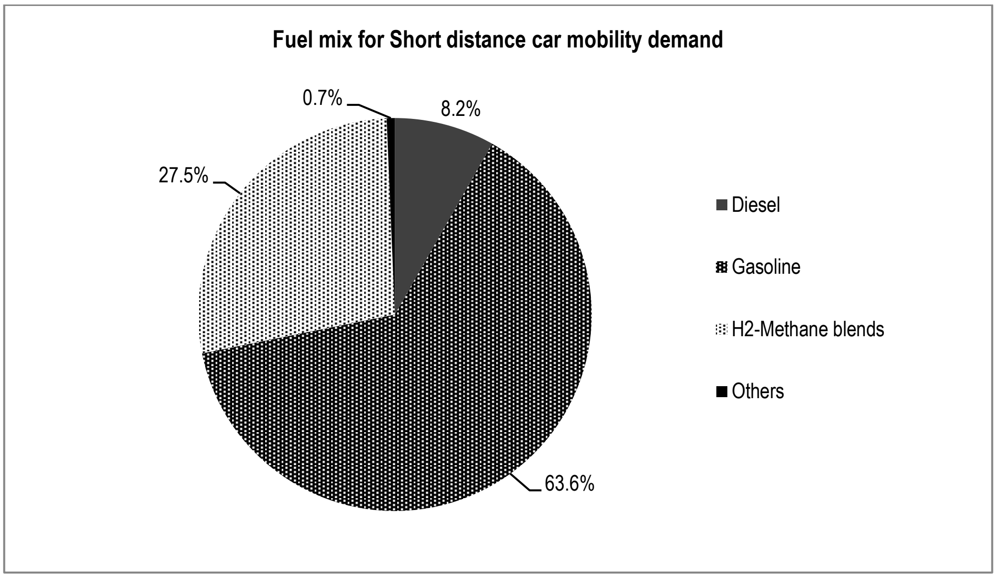


Figure 59: Fulfilment of short distance car mobility demand by energy commodity in 2040 (CO_2 emissions reduction scenario)

Referring to the third scenario (the one coupling the constraint on CO_2 emissions with a constraint on the overall energy supply risk) no relevant impacts on the use of hydrogen can be observed. In fact, the hydrogen import via energy corridors for both the liquid and gaseous form is the same in the two scenarios.

In particular, in the Risk reduction scenario in 2040 the supply of gaseous hydrogen via corridors is equal to 3.72% of the total availability, while for the liquid hydrogen the entire supply is via corridors, but the absolute value of this quantity is small and equal to 32% of the imported gaseous hydrogen. The values are almost identical also for the CO_2 emissions reduction scenario.

This fact seems to suggest that, in future scenarios, hydrogen could play a role regarding the energy supply security not as alternative commodity imported through energy corridor able to replace other “unsafe” commodities, but as a fuel locally produced if the related costs will reduce.

Despite the technological advancements, hydrogen penetration remains still limited because of the difficulties related to the infrastructure diffusion, which is associated to the investment requested in a unstable economic framework. However, if the transition towards decarbonised energy systems will be a key goal for decision maker, hydrogen could represent a viable choice especially in urban areas. Being versatile, hydrogen can be used for covering mobility and residential electricity and heat demands.

According to the proposed modelling exercise, a relevant share of the European urban and intercity public mobility could be satisfied with buses fuelled by hydrogen, particularly if environmental constraints (coherent to the set of requirements of the 2050 European Energy Roadmap) are introduced. The model seems to suggest that the infrastructural weakness could be overcome by reducing the range of application. Centralised plants in urban areas may produce the required amount of hydrogen, either using conventional fossils, or, most probably and conveniently, electricity generated in large renewables power plants. The analysis has shown that these plants could also make the most of renewable potentials set far from the demand centres, and that electricity or hydrogen could then be transported by means of technical solutions already available.

Moreover, it has been demonstrated that hydrogen cannot determine significant benefits in terms of energy supply security at European scale. The model put into evidence the limited influence of this vector, because it is a commodity that can be produced in relevant quantities only from fossil fuels (that are imported) or from renewables (that, in significant proportions, are imported too).

Chapter 6

Conclusions

The project aimed at assessing the role of energy **infrastructures** in the framework of the energy transition towards decarbonized energy systems. In particular, it focused on their integrity, intended as the capability of a certain infrastructure to perform its function according to what is requested and to be properly managed from several points of view, including safety, environmental protection, maintainability, productivity, etc.

The **integrity** is strictly related to the **development** of the infrastructures themselves. In fact, this concept should be more and more embedded in the planning and design phase, in order to ensure a self-compliancy of the infrastructures to security, service quality, economic and environmental aspects.

In particular, the focus has been on the **multidimensional** characteristic that is inherent in the integrity analysis. The integrity involves different layers. The most relevant of them are the

- the technological,
- the geopolitical,
- the environmental and
- the economic ones.

The **technological** dimension mainly refers to the physical delivery/distribution of energy commodities according to the quantities requested for satisfying the internal needs of the considered zone (country, region, local area, etc.). It thus encompasses the availability, reliability, safety and resilience of the infrastructure under a technical perspective.

The **geopolitical** dimension is mostly related to the political scenarios that can affect the international energy supply dynamics, i.e. the scenarios that can influence the exchanges (imports/exports) of energy commodities among countries. Furthermore, however, the geopolitical level can also concern the policy decision-making about strategical choices in the energy sector internal to a country.

The **environmental** dimension considers the different energy targets and the way in which they can be achieved by acting on the energy sector and, consequently, by planning and investing in energy infrastructures. An example can be represented by the constriction of power networks (at high voltage for long distance transmission or smart grids for local distribution) in order to exploit electricity generation from renewables and electrification of the energy final uses.

The **economic** dimension refers to monetary value of the energy commodity and to the fact that a loss of energy can correspond to a loss in GDP for a country. As expected, the economic dimension spreads over all the types of infrastructures, from large corridors for external supply to distribution networks, and the loss of integrity of one of these infrastructures leads to damages that can be also quantified in monetary units.

All these dimensions can be related to different kind of **threats** that can impact on the infrastructures, namely

- the natural,
- accidental and
- intentional ones.

Natural threats refer to extreme natural events (like floodings, earthquakes, wildfires, tsunamis, etc.) that can potentially damage energy corridors or infrastructures. This type of threats, in particular, requires the evaluation of the resilience of the involved infrastructures and the definition of ad hoc emergency plans, mitigation actions (that can include the redispatching of the lost energy flows through other available infrastructures, which can operate as back-ups) and actions devoted to the restoration of their functions.

Accidental threats are instead related to unexpected and unintentional technical failures that cause the unavailability of the considered infrastructure and that, as a consequence, lead to technical and/or economic instabilities in the analysed energy system.

Finally, **intentional threats** refer to deliberate actions, like sabotages and physical and cyber attacks, against a given infrastructure. As the natural threats, they require the assessment of the resilience of the infrastructure and the definition of emergency plans, mitigation and restoration actions. It has to be underlined that accidental threats, because of their technical nature, are more common and characterised by higher frequencies of occurrence. Due to this fact, historical databases are available, providing data on parameters like failure and repair rates for several components. The availability of statistical values allows an easier adoption of scientific approaches in the quantification of the consequences related to this kind of threats with respect to the other considered threats. The natural and intentional threats, in fact, are related to unpredictable and low-frequency events, that cannot permit the implementation of purely probabilistic methodologies.

Referring to the **spatial scale** of the infrastructures, they can be classified into three main macro-categories:

- energy corridors (oil and gas pipelines, maritime routes, power lines, etc.),
- transmission / distribution networks and
- local distribution grids.

All these typologies can suffer the above mentioned threats, which can determine negative effects on their integrity that, in turn, can cause impacts on one or more of the described layers.

The analysis of all the possible combinations of spatial scales and threats impacting on the integrity is out of the scopes of the present work, which instead focused on five of them, considered as representative of a sufficiently large set of options. These configurations have been analysed by means of **five case studies**.

First Case Study:

Goal: quantitative evaluation of the energy security at country level under a geopolitical perspective.

Spatial scale: energy corridors

Threats: intentional threats like geopolitical tensions, international crises or terroristic attacks, able to modify the integrity status of the considered infrastructures.

Dimensions: geopolitical and economic levels

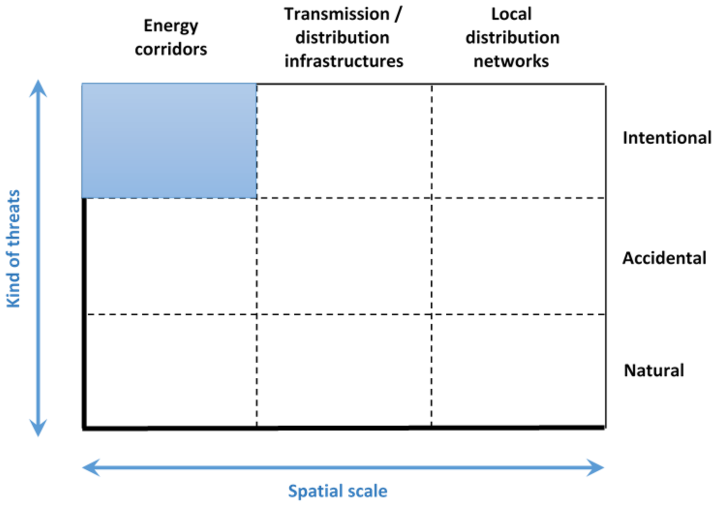


Figure 60: Schematic representation of the first case study

The proposed methodology links the representation of the detailed **energy inflows** of a country, the calculation of the **geopolitical risk** related to them and a cost-benefit analysis of the possible actions and **countermeasures** to be implemented for:

- in the short term: allocating resources and efforts with the goal of protecting a given infrastructure
- in the mid/long term: planning and implementing different supply options, also involving new infrastructures.

The approach has been implemented and tested with reference to the **Italian case**, especially with respect to the natural gas supply, a commodity strategical for the energy balance of the country and characterised by a high level of import dependency.

The analysed **scenarios** has been related to

- the increase in the activity of terroristic groups in North African countries,
- the deterioration of the diplomatic relations between Italy and Qatar (the main national LNG supplier),
- the presence of antagonistic groups in Libya, with the disruption of the Greenstream natural gas pipeline, and
- the enhancement in the political tensions between Russia and the Ukraine (with an increase in the country risk and the disruption of the natural gas and oil corridors from Russia and crossing Ukraine).

The analysis of the obtained results put firstly into evidence the role played by the **spatial dimension** of energy corridors under the geopolitical security perspective for high energy-dependent countries like Italy. The length of the corridors, their routes and the political security level of the crossed countries can in fact significantly affect the risk related to the energy imports.

Furthermore, the study has highlighted the relevance and effectiveness of **diversification** of energy supply sources and corridors in decreasing the overall external risk. In this sense, taking into account the importance of natural gas as “risky” commodity, the strategical investment in LNG (by increasing and diversifying the supply routes and building new terminals or increasing the capacity of the ones already existing) can have positive effects on the national energy security.

Additionally, the possibility of comparing possible alternative **countermeasures** (modelled as different scenarios) to be implemented as reactions to geopolitical threats allows to assess their effectiveness and the related economic impacts to be assessed in terms of reduction in GDP losses. In the same way, the possibility of numerically evaluating the benefits deriving from investments in preventive actions for counteracting terroristic attacks to sensitive targets (like oil and pipelines) can be relevant from the point of view of policy **strategical planning** and **decision-making**. Also in this case, in fact, it is possible to avoid the loss of a significant amount of GDP consequently to a sudden unavailability of a certain supply of energy commodities.

Second Case Study:

Goal: analysis of the resilience of critical infrastructures with respect to natural hazards

Spatial scale: transmission/distribution infrastructures

Threats: natural extreme events (earthquakes, floods, wildfires, storms, landslides)

Dimensions: technological, economic and environmental levels.

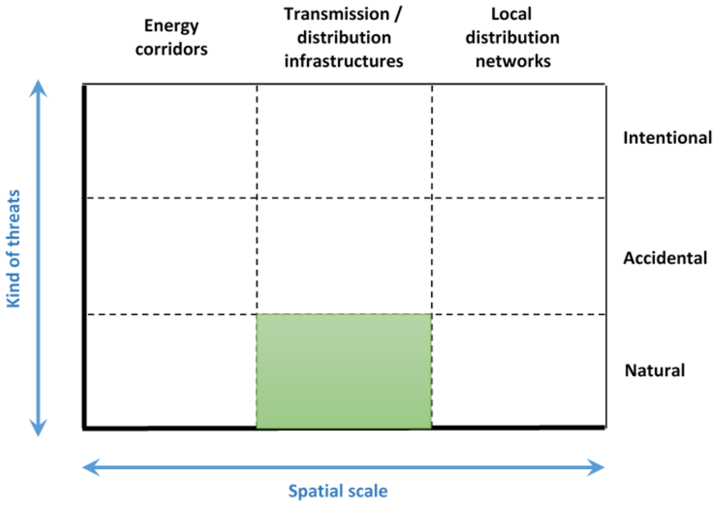


Figure 61: Schematic representation of the second case study

One of the most relevant aspect of this methodology is – like in the first case study – the introduction of the spatial dimension of the considered infrastructure in the quantitative assessment procedure. In this case, in particular, the **spatial position** along the infrastructure is one of the parameters that is included in the proposed criticality index. In this way, the evaluation of the criticality status or of the distance from a criticality condition for each section of the infrastructure can be computed.

The proposed **criticality index** takes into account four classes of **parameters**, related to

- the natural hazard,
- the infrastructure,
- the availability of backups and
- the users involved by the event,

also considering the interdependencies among them.

The index allows to quantify (in monetary units) the **socio-economic damage** caused by different extreme natural events on the analysed infrastructure.

Furthermore, it can be used for evaluating the **maximum acceptable frequency** of the event and the corresponding intensity, which can be thus compared to the design features of the infrastructure.

In general, it can be effective in identifying and **prioritising**

- the criticalities,
- the needed investments,
- countermeasures,
- civil protection plans and
- mitigations actions.

For this reason, it can support **public administration** and **companies** in ensuring the maximisation of the infrastructure integrity (especially regarding transmission and distribution infrastructures) and, consequently, the minimisation of the negative impacts on the end-use sectors that can arise from the disruption of a certain section of the infrastructure and of the related economic effects.

The application of this approach to a simplified case study has underlined its potential advantages, in particular if a reassessment of the limit of risk acceptability is considered. In fact, it permits to clearly identify the **safety margin** with respect to the design characteristics or the need for structural tests, assessing in this way the resilience of the infrastructure.

Moreover, the above mentioned possibility of calculating the index value for non-critical sections allows to develop **monitoring plans** for those sections that are closer to a critical condition, thus implementing preventive actions.

Future **developments** of this approach

- require the definition of detailed environmental and technological databases for the quantification of the considered parameters
- could include multi-risk analyses, based on scenarios characterised by the simultaneous occurrence of at least two extreme events, thus assessing the resilience in the worst, low-frequency situations.

A particular attention, in the case of wide-scale applications, should be payed to the identification of the **boundaries** of the systems, especially when meshed networks (for instance, natural gas distribution grids or power grids) are considered.

Third Case Study:

Goal: analysis of the effects of high penetration rates of non-programmable renewable sources in the power generation

Spatial scale: transmission/distribution infrastructures

Threats: accidental threats, related to the amount of energy that cannot be immediately consumed and the possible related issues, like grid instabilities or the need for disconnecting base load plants in order to avoid damages

Dimensions: technological and environmental levels.

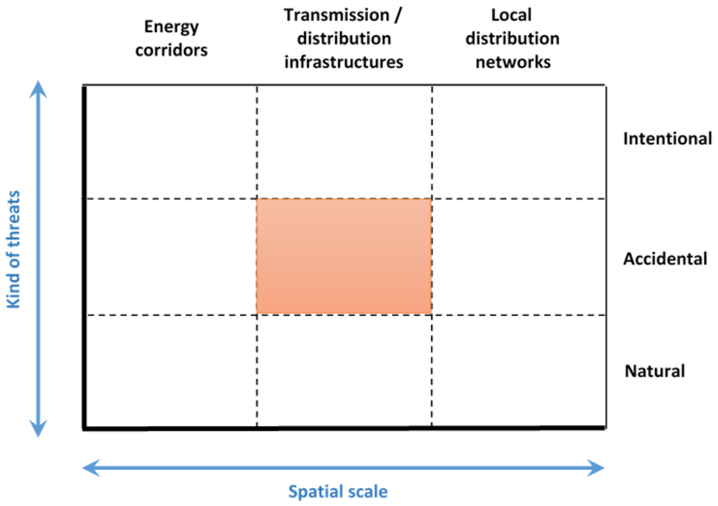


Figure 62: Schematic representation of the third case study

If alternative options like storage systems or ad hoc interconnections among different zones are not available, high penetration rates of non-programmable renewables (for instance, 70% or more) can lead to significant amount of energy that cannot be immediately consumed and this can represent a **limitation** in the enhancement of renewables integration in the power system of a country.

Three **alternatives** can be implemented in order to reduce this amount of energy that cannot be instantaneously consumed.

- One is the **increase in the flexibility** of the system, which can be achieved by modifying its structure and substituting traditional base load plants with more flexible plants as load-following ones. The methodological approach applied to the Italian case study, however, put into evidence that this option could be not particularly effective under a cost-benefit perspective. This is due to the high investments requested and to the fact that, even in the case of the maximum flexibility, a significant quantity of energy from non-programmable renewables cannot be still immediately consumed, especially in some of the six macro-areas (like Southern Italy, Sicily and Sardinia) in which the Italian power system is divided.
- The other option is represented by the **increase in the electricity transmission** between the different zones. This solution requests huge investments, however it allows an increase in the quality and reliability of electricity dispatching.
- The last alternative is the **implementation of storage systems**, which can be significantly effective in the case of power generation mainly from photovoltaic and with renewables penetration rates of about 60%.

Each of these alternative is characterised by pros and cons, and probably the best option is represented by a proper mix of the three.

Moreover, it has to be highlighted that the **power generation mix** and the single contribution of renewables to the overall production can relevantly affect the amount of excess electricity. In particular, a good balancing between solar and wind contributions can provide a significant reduction of this amount, without requiring relevant investments in new plants.

Finally, the amount of electricity from non-programmable renewable sources that cannot be instantaneously consumed seems independent from the load profile, even if this result should be confirmed through the development of additional case studies related to various countries.

Furthermore, sudden load changes, on the time scale of minutes, seconds or less, should be investigated, also considering the role played by different storage technologies like ultracapacitors and flywheels, that can be useful in those cases of quick load variations.

Fourth Case Study:

Goal: assessment of the service quality of district heating networks

Spatial scale: local distribution infrastructures

Threats: accidental threats, related to possible technical failures that can affect the grid components

Dimensions: technological level.

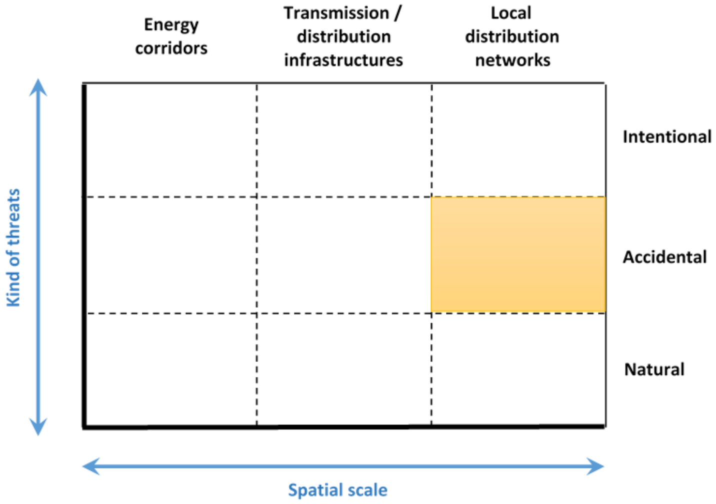


Figure 63: Schematic representation of the fourth case study

The proposed methodology, in particular, allows to link two different aspects that are crucial in the analysis of these networks:

- the **energy** aspects, evaluated through a thermos-hydraulic module

- the **reliability** aspects, which are assessed by means of a Monte Carlo module, used for simulating failure and repair processes.

The two **reliability indexes**, i.e.

- SAIFI, that quantifies the number of failures, and
- SAIDI, that quantifies the number of hours of service disruptions for the analysed grid,

have been considered with reference to a real case study and to three **scenarios**:

- a baseline without load profiles and thermal energy storage systems;
- a scenario including load profile and centralised storages;
- a scenario with load profile and both centralised and local storages.

The obtained results put into evidence the relevant role played by the **thermal energy storage** systems, not only in improving the heat demand fulfilment, but also in increasing the service quality by lowering the time duration of service unavailability. In particular,

- small local storages are effective in facing the short service failures, while
- large centralised storages are useful in peak shaving.

Therefore, the comparison between possible configurations of the grid showed that the inclusion of the reliability analysis in the design phase of the grid and a proper sizing and location of TESs could be beneficial from both the demand coverage and the system quality point of view.

The reliability considerations have been consequently used for assessing how different **design options**, with the introduction and sizing of local and/or centralised thermal energy storages, can impact on the **quality of the service**.

Further applications can involve:

- the modification of the considered load curve;
- the optimisation of the location and sizing of the thermal storages by minimising the values of the SAIFI and SAIDI parameters for the most relevant barycentres (as hospitals), also taking into account the specific needs (short of few interruptions in the service) of these critical users;
- the identification of the most critical sections of the grid according to the effects on the SAIFI and SAIDI values caused by different failures, in order to plan investment priorities and maintenance actions.

The introduction of load profiles variable with the ambient temperature, the modelling of leakages and the definition of an integrated procedure able to link the already defined procedure with the economic optimisation of the network can represent future development steps of the proposed methodology.

The application of the tool to real district heating networks in cooperation with the grid managers could also allow to obtain feedbacks on the management procedures and on the reliability data.

Fifth Case Study:

Goal: effects on the energy systems caused by the penetration of an innovative energy vector like hydrogen

Spatial scale: local scale, especially urban, involving the residential and – above all – the transport sectors

Threats: intentional threats, related to the analysis of the consequences on the security of supply at European level of hydrogen penetration

Dimensions: geopolitical and economic levels.

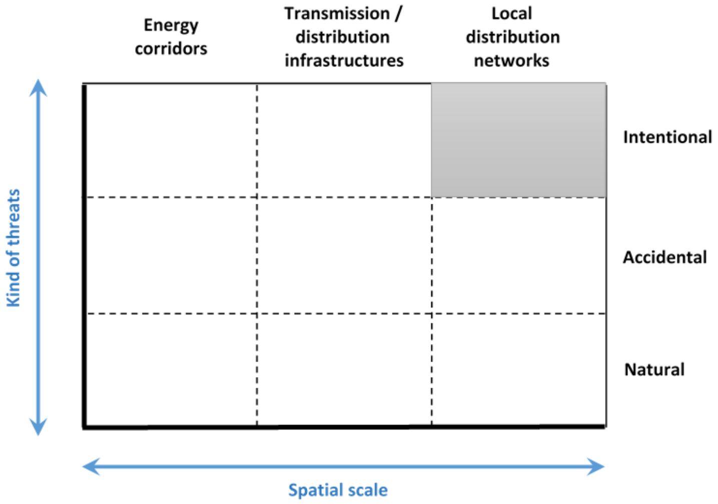


Figure 64: Schematic representation of the fifth case study

This study is mostly related to the local scale, but it also analyses – through a forecasting optimisation energy model – how the effects of a **local change** in the energy systems **spread at wider scale**, having an impact on the geopolitical layer and on the security of supply.

The study showed that hydrogen could represent an effective choice in the framework of the implementation of decarbonisation strategies, due to its versatility and the possibility of using it for mobility and residential electricity and heat demands.

However, significant **investments** are required in distribution infrastructures, which still suffer a lack of diffusion, especially if compared with the advancement in hydrogen production and use technologies.

The performed modelling exercise put into evidence that hydrogen could provide a significant contribution to the fulfilment of **urban and suburban mobility** needs in the European Union. This contribution becomes especially relevant if **environmental constraints**, like those planned in long-term decarbonisation pathways (as the 2050 European Energy Roadmap), are set.

These results seem to suggest also a possible strategy for enhancing the role of hydrogen in the energy mix and – at the same time – for overcoming some of the above mentioned limitations related to the weakness of hydrogen infrastructures, i.e. restraining the application spatial range to **urban areas**. In these areas, the requested fuel could be produced by means of centralised plants using fossils or – more conveniently – electricity generated in large renewable power plants.

On the opposite, the analysis of the effects of hydrogen penetration on the security of energy supply has shown that the increase in the role of hydrogen could not correspond to an enhancement in the **geopolitical energy security**. Only if hydrogen is produced not using fossil commodities (largely imported in the European Union) but by exploiting renewable resources locally available, there could be a positive effect on this aspect.

As a consequence, in future scenarios forecasting significant penetration rates, hydrogen could be mainly considered not an alternative vector imported through ad hoc corridors, but a **commodity locally generated**, of course if the related production costs will reduce making this option not only technically but also economically feasible and sustainable.

Analysis of the multidimensional and multiscale approach

The analysis of the whole set of obtained results allows first of all to make some consideration with respect to the different integrity dimensions involved. Each of these dimensions, in fact, can be correlated to specific **energy targets**, namely:

- the economic affordability;
- the environmental sustainability;
- the geopolitical security;
- the technical feasibility.

The **economic affordability** corresponds to the possibility of obtaining on the market (and at market prices) the energy needed for the fulfilment of the final demands of the users.

The **environmental sustainability** identifies a configuration of the energy systems in which production, distribution and use of energy commodities are able to satisfy the current and future needs without negatively affecting the people's quality of life and the availability of resources, and allowing social equity and economic efficiency.

The **geopolitical security** identifies the capacity of ensuring the amount of energy commodities requested for satisfying the final uses through local production and internal distribution infrastructures or through the import via energy corridors.

The **technical feasibility** defines the possibility of planning or implementing a certain strategy by using technological options in different segments of the energy chain (production/import of energy commodities, transformation, distribution and end-uses) that can be effectively adopted.

The achievement of each of this target, which can be considered relevant and positive in the framework of an effective long-term energy transition perspective, can however be **conflicting** with the others, especially with respect to the different infrastructural choices that can be implemented.

An **example** can be the one related to the **increase in penetration of renewables**, which is one of the pillars of the energy transition and which has been investigated in the third case study:

- This increase is coherent with the environmental sustainability and can also lead to positive effects on the geopolitical security if it is mainly implemented through the adoption of local micro-grids based on renewables. This solution, in fact, allows to reduce the dependency on the import of fossil commodities by exploiting locally available resources.
- On the opposite, the increase in the role of renewables by means of large-scale interconnections can be effective from the point of view of the environmental sustainability, but it can determine negative consequences on the supply security, because these infrastructures can be more easily subject to intentional threats, both physical and cyber.
- Furthermore, as previously mentioned, high non-programmable renewables penetration rates could cause instabilities in the power systems, due to the decrease in the system inertia and to the difficulty in balancing production and demand. In this case, the environmental sustainability is thus in conflict with the technical feasibility.

In order to summarise these **interdependencies** among the goals related to the single considered dimensions, it can be observed that:

- The **economic affordability** can be coherent with the technical feasibility, but can negatively impact on the environmental sustainability and the geopolitical security, as the achievement of these objectives usually requires significant investments and the adoption of solutions that are not the most economic ones at market level.
- The **environmental sustainability**, for the reasons above mentioned, can be conflicting with the economic affordability. It can be positive or negative from the geopolitical security point of view, according to the examples previously described. In the same way, as said with reference to the proposed example, it can be conflicting with the technical feasibility, as high structural changes in the energy mix like those required by ambitious environmental targets can

require new technological options not already fully developed or available or can cause technical issues (like the above mentioned grid instabilities).

- The **geopolitical security** can be coherent or conflicting with the environmental sustainability. For instance, an increase in the diversification of the fossil fuel supply is beneficial under the security perspective, but can be is not suitable for the achievement of the energy transition targets. On the opposite, an increase in the renewables penetration can be positive or negative for the supply security, on the basis of the adopted paradigm (exploitation of resources locally available or production concentrated in few world macro areas and global interconnections). The enhancement of the geopolitical security can instead determine negative effects on the economic affordability related to the energy commodity market. There is not a relevant relationship with the technical feasibility.
- The **technical feasibility** is coherent with respect to the economic affordability, but it can be not fully compliant with the environmental sustainability strategies, as some more extreme modifications can require technical solutions not yet totally feasible or characterised by possible critical issues. It seems instead not having a significant direct impact on the geopolitical security.

The whole set of interdependencies among the different integrity dimensions (and the related goals) is summarised in Table 26.

Table 26: Interdependencies among the different dimensions and the related objectives

	Economic	**Environmental**	**Geopolitical**	**Technological**
Economic		-	-	+
Environmental	-		+/-	-
Geopolitical	-	+/-		=
Technological	+	-	=	

Where:

- + : coherent
- - : conflicting
- = : w/o significant effects

Referring instead to the analysed **threats**, the three main categories can affect all the spatial scales of the considered infrastructures (supply corridors, transmission/distribution networks, local grids). The relevance of the effects mainly depends on the availability of backup sources. Furthermore

- The **natural hazards** can be, to some extent, expected according to the considered areas, in particular with reference to extreme events like floodings, earthquakes and tsunamis. On the basis of geological surveys and the analysis of historical trends, preventive and mitigation actions can be already planned for the most critical sections a given infrastructure during the design phase.
- The **accidental threats** are mostly related to technical failures of systems or components. For them, databases able to provide probabilistic information about failure and repair rates are usually available. For this reason, the inclusion of reliability and availability considerations coupled with a proper planning of the maintenance actions in the design phase can be effective in reducing the negative impacts of this kind of threats.
- The **intentional threats** are almost always related to unpredictable events. Due to this fact, the preventive actions to be implemented can be related only to quantitative and qualitative analyses able to identify the most critical infrastructures, in order to prioritise the protection investments and efforts. In general, large international corridors and relevant hubs can be considered high-risk targets for antagonistic and terroristic groups, because of the potential large scale of their disruption and the international media relevance.

According to these considerations, it is possible to identify a prioritisation of the **threats** with respect to the **spatial scales**:

- For the **large scale**, the analysis of the intentional threat, as mentioned, can be significantly relevant, as large energy corridors can be most probably identified as relevant targets for malicious physical or cyber attacks (according to the results obtained in the first case study). However, also natural threats can impact on these infrastructures with important consequences. For this reason it could be useful, in future analyses, to apply a methodological approach for the criticality and resilience evaluation, like the one proposed in the second case study, to international energy captive corridors, like oil and gas pipelines. The quantitative assessment of both security and resilience should be embedded in the planning and design procedures of new infrastructures belonging to this category.
- The **intermediate scale** (involving transmission and distribution networks) can be relevantly subject to the negative effects of natural hazards. Due to this fact, the analysis of their criticality status with respect to these hazards (like the one performed in the second case study) is useful for supporting decision makers in defining strategical countermeasures, emergency and redispatching planning and in identifying possible alternative sources to be used in the case of critical situations. Furthermore, also for these networks, the evaluation of the impacts of technical failures on the quality of the service (considering number and time length of unavailabilities), like the one proposed in the fourth case study, could be an important aspect to be included in future multidimensional studies. The malicious threats can be taken into consideration on a case-by-case basis,

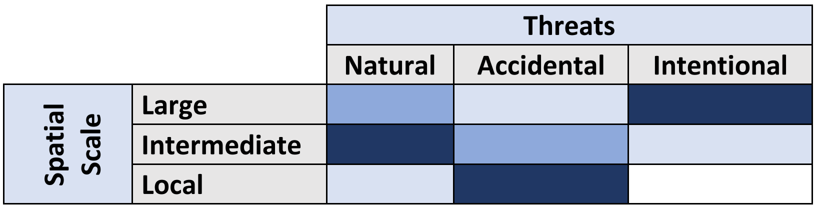
according to the relevance of the analysed infrastructure with respect to the overall energy systems of the considered region or country.

- At the **local scale**, the most relevant threats are represented by the accidental technical failures, which affect the function of the system and its availability (according to what explored in the fifth case study), thus directly impacting on end-users. Consequently, these reliability analyses should be integrated with the commonly adopted technical and economic sizing procedures in order to improve (or optimise) the overall performance of the network, by reducing or minimising the number or duration of the service disruptions. The natural hazards could be taken into account, especially in some areas that can be identified as critical from the geological point of view, however their overall impact from the point of view of the energy system can be less relevant. The intentional threats are instead not particularly significant because local network unlikely can be considered high-risk targets.

These considerations do not allow to define a precise ranking of the different threats with respect to the single spatial scales, but they can by suitable for categorising possible future analyses, in the proposed multidimensional approach, by putting into evidence the ones that could be more relevant for the strategical decision-making process and the management related to the energy infrastructures.

The described **prioritisation** is summarised in Table 27.

Table 27: Ranking of the different threats with respect to the considered spatial scale



		Threats		
		Natural	Accidental	Intentional
Spatial Scale	Large	▩	░	■
	Intermediate	■	▩	░
	Local	░	■	□

Where:

- ■ : high direct impact
- ▩ : significant impact
- ░ : low impact
- □ : w/o significant impact

Considering the different spatial scales, also the **cross-dimensional interdependencies** could be investigated. In particular, it could be interesting, under the perspective of long-term energy planning, to evaluate how changes in the mix and structure of local energy systems can impact on a larger spatial scale (as described, for instance, in the fifth case study) and – vice versa – how a large-scale modification (for instance, a diversification in the supply composition or a commodity shift) can affect the local systems.

Of course, all the considered kinds of threats can moreover **impact on the targets** related to the four integrity dimensions previously described. The effects can have different magnitudes according to the single events. For this reason, it is difficult to comprehensively categorise and rank them, in order to define priorities. However, it can be observed that:

- The **natural threats** can have significant economic consequences, and can also impact on the achievement of environmental sustainability goals, while they have limited effects on the technological feasibility and they do not directly impact on the geopolitical security.
- The **accidental threats** are instead mainly related to the technical dimension, and can determine however economic consequences, even if more limited in terms of extension with respect to the natural extreme events, due to the scientific quality level of reliability analyses that are usually performed. Like the natural threats, they do not directly involve the geopolitical dimension.
- The **intentional threats** are obviously connected to the geopolitical supply security. Their objectives (like the disruption of relevant infrastructures) can also lead to relevant effects on the economic affordability, and can impact – even if to a lower extent – on strategies related to the environmental sustainability. They are instead not connected to the technical feasibility.

As said, these considerations do not represent a precise ranking of the various threats with respect to the single dimensions, like for the spatial scale (Table 27). However, they can by useful for identifying the set of combinations between threat and dimensions that can be most relevant for future investigations, under the holistic perspective proposed in this project.

The above-mentioned prioritisation is summarised in Table 28.

Table 28: Ranking of the different threats with respect to the considered dimensions

		Threats		
		Natural	**Accidental**	**Intentional**
Dimensions and targets	**Economic**	🟫	🟧	🟧
	Environmental	🟧	░	░
	Geopolitical	□	□	🟫
	Technological	░	🟫	□

Where:

- 🟫 : high direct impact
- 🟧 : significant impact
- ░ : low impact
- □ : w/o significant impact

In general, the project has allowed to highlight the relevance of the **multidimensional** and **multiscale** analysis, that has to be taken into account when the possible strategies for the energy transitions towards decarbonised systems are investigated.

The **interdependencies**, the **coherence** and the **conflicts** among the different targets, as well as the **impacts** of the possible threats on the dimensions that are involved should be carefully considered, in order to define effective pathways and avoid possible issues able to vanish the pursued efforts.

In this framework, a key role is played by the **integrity** and **development** of energy infrastructures, which represent the backbone of all the possible strategies to be implemented.

The **integrity** (which is a wider and more comprehensive concept than “security”) with respect to the various dimensions and with reference to the various threats is crucial in ensuring that the energy system performs its functions, and thus in ensuring the achievement of the above-described goals. The assessment of the integrity should be consequently embedded in the planning and design procedures of infrastructures, especially when long-term strategic visions and investments are defined.

The **development** of the infrastructures according to integrity-oriented criteria, in fact, can assure a sort of self-security of them. In this sense, the impact of the single components and elements on the integrity aspects (like the thermal storage for a district heating network, the definition of backup sources in areas not subject to natural extreme events for distribution network, the route of a corridor avoiding the crossing of politically unstable countries) has to be quantitatively analysed through science-based and numerical methodologies.

The proposed case studies tried to cover a part of the possible combinations of threats and spatial scales of the infrastructures and to assess the infrastructure integrity with respect to these threats. As previously shown, they allowed to develop procedures for identifying possible system criticalities and supporting the definition of preventive actions and countermeasures.

Further analyses according to the general scheme proposed in Figure 25 are requested in order to enhance the number of explored options and thus to build **guidelines** for decision-making processes. These guidelines can help in better defining strategical plans for infrastructure management, investment priorities for infrastructure protection and for emergency management in the short-term and for new infrastructure development over a long time horizon, in coherence with the energy transitions objectives.

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