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Metric-Based Approaches and IT Tools Development for Tracking and Communicating Energy Transition's Multi-Dimensional and Multi-Scale Impacts

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2024

Declaration

I hereby declare that the contents and organization of this dissertation constitute my own original work and does not compromise in any way the rights of third parties, including those relating to the security of personal data.

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2024

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Abstract

This dissertation addresses the critical need for science-based support to guide policymaking throughout the complex challenges of energy transition, focusing on decarbonization and electrification to meet the ambitious targets set by the European Climate Law. To achieve a 55% reduction in EU-27's carbon emissions by 2030 and carbon neutrality by 2050, integrated policies and strategic actions are necessary across multiple dimensions (energy, environmental, social, and economic dimensions) and spatial scales. This commitment requires robust scientific evidence to inform policymakers, support data-driven decision and enhance public trust in policymaking. The research emphasizes the importance of bridging the gap between science and policy, by promoting a shift from traditional, selective and curiosity-driven research to a more inclusive, policy-oriented approach, known as 'Science 2.0' or 'Science for Policy'. Metric-based methodologies, ensuring clarity and conciseness of scientific evidence, play a crucial role in synthetising key findings and translating complex results into key policy-relevant insights. To further enhance audience understanding, metric-based methods need to be empowered with effective data visualization and interactive interfaces. The study introduced three novel metric-based methodologies for assessing energy transition trends at different spatial scales (European, national and urban scale), revealing both benefits and worsening across diverse domains. To validate the developed methodologies and demonstrate their wide applicability, three real-case applications are discussed: metric-based scenario analysis to evaluate the impacts of increasing intermittent renewable generation in Europe, assessment of the 'energy trilemma' evolution in Italy through the composite index ISPRED, and monitoring of the urban energy transition in Turin, Amsterdam, Eindhoven, Utrecht, Rotterdam through the composite index UETI. Additionally, the research encompassed the development of three interactive web platforms to support informed policymaking and improve public trust and awareness by providing clear and timely insights on real-word issues: ET@IT designed for monitoring national energy transition in Italy, E3 devoted to evaluate large-scale renewable energy impacts and benefits at the European level, and SERT aimed at assessing the energy risk of energy supply corridors and perform risk scenario analyses. By developing these platforms, this study makes a significant and tangible contribution to empowering evidence-informed policymaking. It exemplifies a novel, more inclusive approach that enhances audience understanding, promotes data-driven decisions, and fosters transparent policies, ultimately increasing public acceptance and trust in policymakers.

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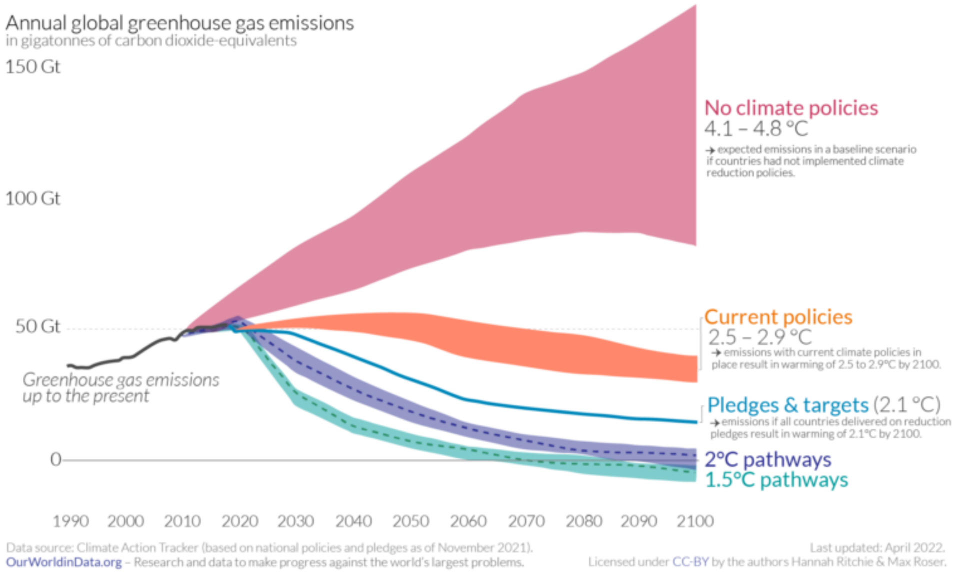
Chapter 1

1 Introduction

1.1 Evidence of global warming and worldwide climate impacts

In 2014 the Intergovernmental Panel on Climate Change (IPCC) published the fifth Assessment Report (AR5) [1] showing the evidence of human-induced global warming and warning about the serious worldwide impacts associated with climate change. On this line, during the 21st Conference of the Parties (COP21) held in Paris in 2015, world leaders of 195 countries reached a breakthrough in fighting climate change: the Paris Agreement, the first legally binding international treaty on climate change under the United Nations Framework Convention on Climate Change (UNFCCC) [2], the main international agreement on climate action adopted at the Rio Earth Summit in 1992 [3]. However, before the Paris Agreement, in 1997 the UNFCCC concluded the Kyoto Protocol the first ever legally binding emission reduction targets for developed countries, expired in 2020. With the Paris Agreement, countries renewed their commitment to tackle the climate change and to limit the global warming to well below 2°C, preferably to 1.5°C, compared to the pre-industrial levels [2]. In 2023 Synthesis Report (SYR) [4] concludes the Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC), synthesizing the overall IPCC findings on climate impacts analyses, vulnerability studies, adaptation and mitigation assessments [5], [6], [7]. The main evidence is that the impacts of the climate change are already widespread and underway. The sea level rise, the glaciers retreat, the acidification of ocean and consequent biodiversity loss are some of the main proves of the ongoing global warming. Moreover, compared to the 2018 Assessment Report, the effort required to tackle the climate change has become even greater due to the continuous increase of greenhouse gases (GHGs) emissions [8]. Each GHG, namely carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O) and F-gases (HFCs, CFCs, SF6), is characterized by the Global Warming Potentials (GWPs) expressed in units of CO2 equivalent (CO2e). In 2022 the global GHGs emissions reached 38.5 Gt CO2e, +1.2% compared to 2021, +13.8% compared to 2010. Indeed, the trend of global GHGs emission has been continuously growing since 1990 [8].

Climate policies are crucial to reverse this trend and limit the increase of global temperature which would lead to irreversible damage on global scale. Although UNFCCC member states increased their efforts to limit climate change, IPCC stated that the ongoing policies (orange area in Figure 1) are not sufficient to achieve the target set by the Paris Agreement in 2015 (i.e., to keep the global warming below 1.5°C compared to the average 1990 temperature). This finding is supported also by the continuously rising trend of global CO2 concentration in the atmosphere the issue is that, in the last decades, not only the CO2 concentration has been increasing, but also the rate of accumulation remains constant over time.



Data source: Climate Action Tracker (based on national policies and pledges as of November 2021).
OurWorldinData.org – Research and data to make progress against the world's largest problems.
Last updated: April 2022.
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Figure 1: Global GHGs emissions and global warming scenarios (Source: CO_2 and Greenhouse Gas Emissions in Our World in Data [9]*)*

As well as for the CO2 concentration trend, the average global temperature is steadily increasing (about +0.1°C per decade [10]). The global average temperature is currently around 1.1 °C above the pre-industrial levels (1990), therefore if this rate continues, the Paris Agreement threshold equal to 1.5°C will be reached by 2040 [10].

The link between GHGs concentrations and global temperature is the so called "greenhouse effect", the natural process performed by the GHGs that trap the sun heat, keeping the lower part of the atmosphere warmer and suitable for life. However, the excessive concentration of GHGs leads to the extreme "greenhouse effect", main driver of the climate change. IPCC stated that the human activities have significantly increased the concentration of GHGs in the atmosphere and consequently the phenomenon of the extreme "greenhouse effect". Nevertheless, the global warming is just one of the various adverse effects of climate change.

Every increment in global temperature results in a higher frequency and severity of extreme weather events (e.g., heat extremes, heavy rainfall and droughts), as well as faster sea level rise, glacial retreat and ocean acidification [4]. The SYR emphasizes that many irreversible damages and losses already occurred, and the actual climate impacts are more widespread and intense than expected, therefore urgent counteractions are needed.

Mitigation and adaptation are two distinct approaches to address the climate change. Mitigation actions aim to slow down the progression of climate change by decreasing and limiting the GHGs emissions through widespread decarbonization across all sectors (power, industry, transport and buildings)[11]. On the other hand, adaptation measures address the ongoing and incoming effects of climate change by enhancing the resilience and security of existing infrastructure such as coastal protection, water management to cope with drought either heavy rainfall, as well as by improving the disaster preparedness and resilience to heatwaves, flooding, and other climate-related risks.

Transitioning from fossil fuels -based to renewable energy sources (RES) based energy system is a key mitigative countermeasure, intervening at the source of emission. Indeed, the energy sector produces the most of global GHGs emissions: according to the Nature's Monitoring Global Carbon emissions in 2022 [12] the power sector accounted for 39.9% of global CO_2 emissions, followed by industry 28.9%, transportation (21.9%) and residential sector (9.9%). Apart from the energy transition, improving the energy efficiency of buildings, vehicles and industrial processes, as well as promoting sustainable agriculture and breeding, represent other valid solutions to limit the global GHGs emission. In addition to this, economic interventions such as carbon pricing and incentives play a crucial role in the worldwide decarbonization process.

In 2022 the global CO2 emissions consumed 13%-36% of the remaining carbon budget set to limit the global warming to 1.5 °C and 2.0°C respectively, suggesting that if the current growth rate of emissions persists, the 1.5°C budget will be exhausted within only 7.1 years, whereas the 2.0°C budget within 25.8 years (4.2 years earlier than previous estimates [13].

Among the mitigative actions, carbon capture technologies (Carbon Capture with Utilisation, CCU and Carbon Capture and Storage, CCS) can offer support in the decarbonization process. They encompass also natural and biotic approaches exploiting natural carbon removal performed by plants in the air (reforestation) and seaweeds in the ocean.

In order to track the emissions of countries worldwide, the Joint Research Center (JRC) developed the Emissions Database for Global Atmospheric Research (EDGAR), the global database of anthropogenic GHGs emissions and air pollution. By using international statistics and a consistent and transparent methodology [8], EDGAR provides emission estimates according to information reported by European Member States or by Parties under the UNFCCC.

According to EDGAR statistics, the trend of global GHGs emissions has been increasing over the last ten years, apart from the pandemic period: because of the COVID-19, global emissions decreased by 3.7% in 2020 compared to 2019, followed by a sharp rise after the peak of the pandemic. In 2022 the global emissions reached 53.8 Gt CO2eq, +2.3% compared to 2019 and

+1.4% compared to 2021. The main GHGs emitters in 2022 were China, USA, India, the EU-27 and Russia [14](Figure 2).

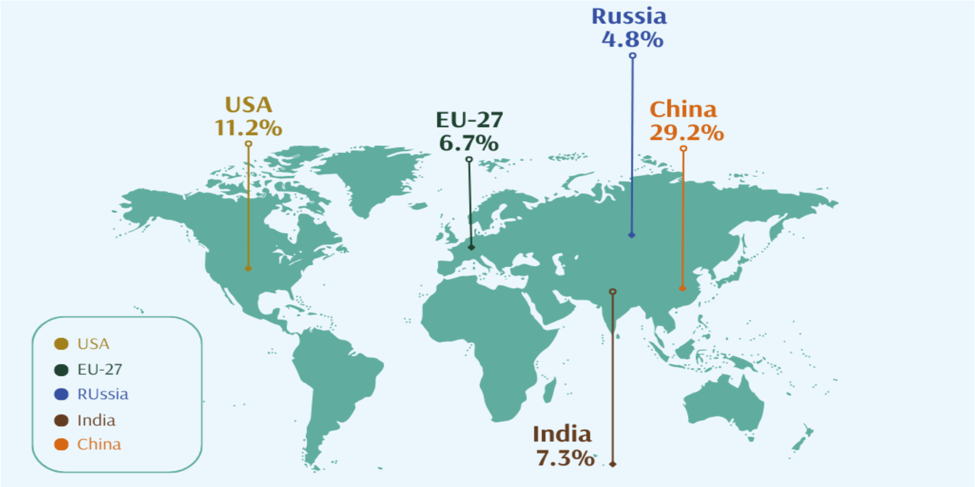

Figure 2: The word main GHGs emitters in 2022 (Source: Elaborated data from EDGAR [8]*)*

Although EU27 is still one of the world's main emitters of GHGs, its commitments have paid off: according to the statistics (Figure 3), in 2022 the EU-27 CO2 emissions from fossil fuels combustion is dropped, -26% compared to 1990 levels. Although the Power Industry[1] sector registered a sharp decrease (-37%) between 1990 and 2022, its share still accounts for the 30% of total fossil CO2 emissions, followed by the Transport[2] sector. Indeed, the share of Transport gained more relevance in the EU-27's fossil CO2 emission, rising from 17% in 1990 to 27% in 2022. On the contrary, Industrial combustion & Processes[3] share dropped from 24% in 1990 to 20% in 2022 (-40% compared to 1990), Buildings[4] share reduced significantly (-32%) compared to 1990 but still accounting for 17% in 2022, whereas the 2022 share of Other sectors[5] in fossil CO2 emissions of EU-27 stayed constant at 6% (the same of 1990).

On the other hand, the global emissions of fossil CO2 registered an overall increase of 71% compared to 1990 levels, highlighting that the efforts to reduce CO2 emissions need to be further intensified.

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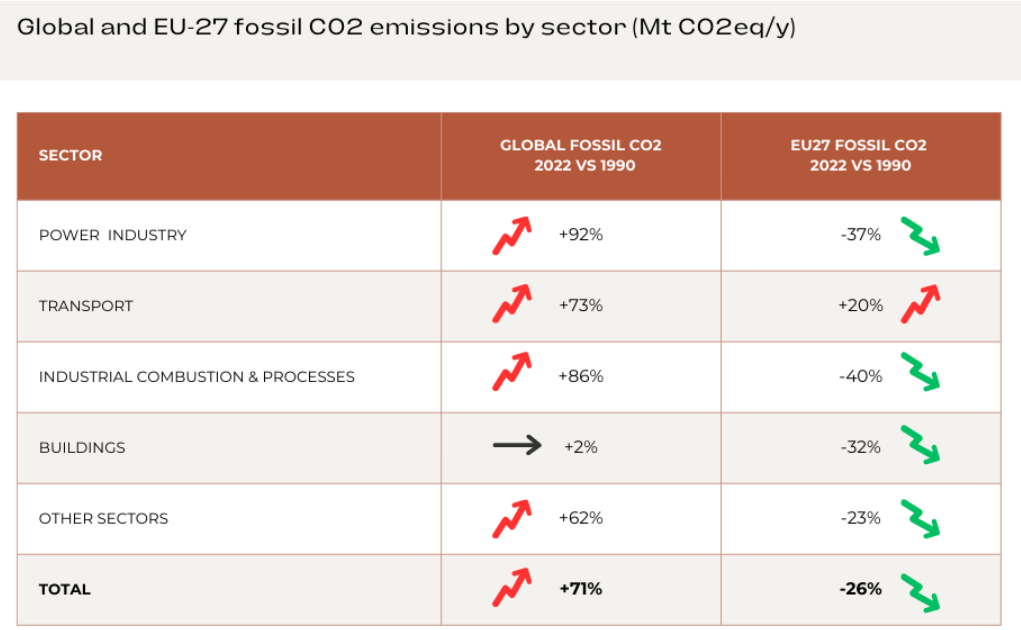
[1] Power industry includes power and heat generation plants.

[2] Transport includes road transport, rail transport, shipping and aviation.

[3] Industrial combustion & Processes includes combustion for industrial manufacturing and industrial processes

[4] Buildings includes small-scale non-industrial combustion.

[5] Other sectors includes fuel exploitation (i.e., extraction, transformation, refinery processes), agriculture, waste (solid waste and waste water management, waste incineration)



Global and EU-27 fossil CO2 emissions by sector (Mt CO2eq/y)

SECTOR	GLOBAL FOSSIL CO2 2022 VS 1990	EU27 FOSSIL CO2 2022 VS 1990
POWER INDUSTRY	↗ +92%	-37% ↘
TRANSPORT	↗ +73%	+20% ↗
INDUSTRIAL COMBUSTION & PROCESSES	↗ +86%	-40% ↘
BUILDINGS	→ +2%	-32% ↘
OTHER SECTORS	↗ +62%	-23% ↘
TOTAL	↗ **+71%**	**-26%** ↘

Figure 3: Comparative chart of fossil CO_2 emissions in 1990 and 2022: global and EU-27 estimates (Source: Elaborated data from EDGAR [8]*)*

Apart from IPCC, other organizations address the issue of decarbonization and regularly publish reports and outlooks on this topic. The International Energy Agency (IEA) is generally considered one of the most reliable sources for global energy data and statistics and annually it publishes the World Energy Outlook (WEO) proving projections and scenarios of the global energy trends. Similarly, the International Energy Outlook (IEO) is published every year by the Energy Information Administration (EIA), covering various aspects of energy trends. However, since the IEA is an autonomous energy agency within the Organisation for Economic Co-operation and Development (OECD), the goal is to evaluate the global energy trends with an emphasis on both OECD and non-OECD countries. On the other hand, being the EIA an independent agency within the U.S. Department of Energy, although the IEO's findings come from international scale analyses, its primary focus is on tracking the energy trends of United States. Moreover, while the IEA's outlook includes scenarios that explicitly explore the impacts of different policies (e.g., National Trends, Global Ambition, Distributed Energy), EIA declares to not assume any future policies in its outlooks therefore the final output cannot be interpreted as forecast but rather as baseline projection. In addition, the International Renewable Energy Agency (IRENA) periodically publish the World Energy Transition Outlook (WETO), providing an in-depth long-term analysis of renewable energy sources benefits in achieving climate goals.

1.2 The role of electricity in decarbonization process: the "electricity triangle"

The major organizations and experts agree that electricity will play a central and indispensable role in achieving decarbonization goals. Due to the expected growth of global population and increasing energy demand from developing countries, meeting the global GHG emissions threshold appears even more difficult. However, it is widely recognised how important the role of electricity is in addressing this challenge. In particular, the implementation of the so-called "electricity triangle" [15], [16], including three main vertices (Figure 4): power generation from renewables, electrification of final uses and exploitation of electricity as the main energy carrier, can play a central role in limiting global carbon emissions in short-term and in achieving the ambitious long-term goal (i.e., global net-zero CO2 emissions by 2050). Although the electricity triangle is a general concept, it concisely represents the idea of using electricity as a tool to implement energy transition and speed-up decarbonisation processes worldwide.

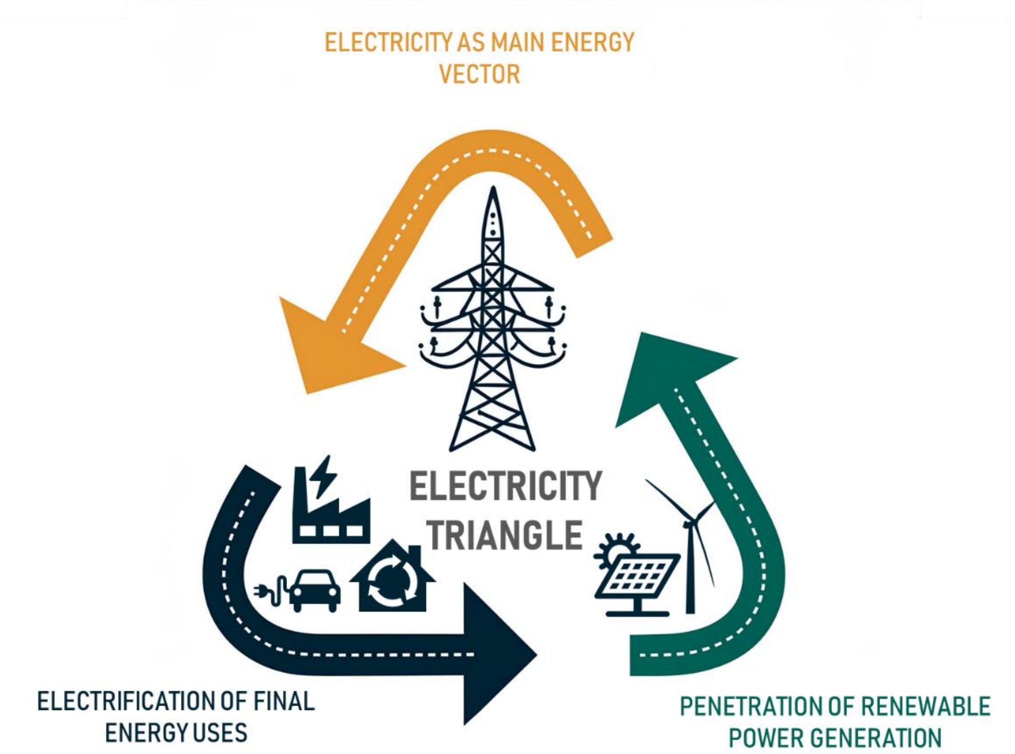


Figure 4: Schematic representation of the electricity triangle concept (Source: Elaborated data from [16]*)*

1.2.1 Power generation from renewables

One of the three vertices composing the electricity triangle is the penetration of renewable energy sources (RES) in the European energy mix, by increasing the share of RES electricity generation in the power sector which is currently mainly dependent on fossil fuels. As power sector is one of the main causes of European carbon emissions, shifting to RES generation plays a crucial role in decarbonisation process. In particular, increasing solar and wind generation is considered one of the most important solutions proposed in the FIT55 plan [17]. However, due to their intermittent and non-predictable generation, increasing the share of RES in the power sector leads to serious challenges for the security of the future European power network. In fact, on one hand the growth of RES generation decreases the carbon and air pollutant emissions produces by fuel combustion in conventional power plant, on the other hand, they introduce a further degree of unpredictability of power generation, consequently leading to problems in consistently ensure the balance between load and generation. Moreover, their intermittency causes fluctuations in frequency and voltage, resulting in disturbances for the power system. Furthermore, unlike conventional power plants, solar and wind installations do not provide any inertia to the power network, hence, since it is planned to shift toward a RES-based power sector, it is expected a sharp decrease in thermal plants and consequently in the overall power system inertia.

On the other hand, the increase in power generation from RES will help in reducing Europe’s energy dependence on third countries to supply raw fossil fuels such as natural gas and crude oil. Indeed, as evidenced by the consequence of the energy crisis following the Russia-Ukraine war, Europe must enhance its energy self-sufficiency in order to avoid supply issues caused by external geopolitical conflicts. Hence, RES penetration can play a fundamental role not only in the European decarbonisation process but also in increasing energy autonomy of European countries. In 2022 The REPowerEU plan [18] focused on the crucial topic of energy security and outlined the necessity to adopt measure aimed at decreasing energy dependency from third countries; in particular, a series of actions are presented in order to rapidly reduce the EU’s dependence on Russian fossil fuels. One of the three pillars of REPowerEU plan is diversifying energy carriers and energy suppliers; the other two pillars are saving energy by enhancing energy efficiency and circular economy and by increasing clean energy from RES.

The Climate Law [19] in 2021 increased the previous 2030 RES target for EU (32% according to the Renewable Energy Directive 2018/2001/EU) to at least 40% of the total power generation installations by 2030. The REPowerEU plan further increased the target up to 45% by 2030. Indeed, to speed-up the process of RES penetration, the European Commission agreed to accelerate the procedure of RES projects permit-granting and to facilitate power purchase agreements [20]. The last version of the target was revised in the Renewable Energy Directive

EU/2023/2413 which set a minimum target equal to 42.5% up to 45% of total power plants by 2030. By shifting to a global perspective, the IEA Net Zero Scenario (NZS) [21] provides an extensive overview on how achieving global carbon neutrality by 2050. To reach this ambitious goal, the current global energy mix which still relies on fossil fuels (more than 60% of world electricity production is generated from coal, natural gas and oil), must shift to a renewables-based power system, in which RES generation covers almost 88% of the global electricity production by 2050. Wind and solar PV generation are expected to increase the most: up to 23,469 TWh (33% of global electricity production) for solar PV and 24,785 TWh (35% of global electricity production) by 2050. The solar installed capacity is projected to reach 14,458 GW PV (43% of global electrical capacity) and 8,265 of wind (25% of global electrical capacity) onshore and offshore.

To achieve decarbonisation targets by 2030 and by 2050s, two main policy directions can be distinguished: distributed RES penetration and centralised RES penetration. The first policy promotes the development of distributed renewable sources, in order to maximize the deployment of local RES, while reducing the distance between generation and load and limiting the power losses. Conversely, the second policy consists of large-scale installations located in area characterized by abundant renewable resources, in particular wind and solar sources. This solution would centralize power generation in specific areas suitable for power generation (e.g. Northern Europe suitable for wind farms and Northern Africa for photovoltaic installations), hence, it would require large amount of electricity transmission from the generation areas to the load areas. The higher is the distance to be covered to reach the load, the higher the loss. The existing transmission grid primarily operates on alternating current (AC), less efficient than high-voltage direct current (HVDC) for long-distance electricity transmission; therefore, when considering the centralized generation of large-scale RES installations, the HVDC technology can be a better alternative to HVAC to reduce losses in electricity transmission over long distances between the generation bus and the load bus. Since the HVDC technology is generally more expensive than HVAC, it is necessary to compare the two alternative solutions and evaluate whether the HVDC technology results more cost-effective than HVAC. Due to the relevance of this topic, many studies have been devoted to the assessment of alternative solutions to implement large-scale RES integrated with the enhancement of the European power network: EWEA discuss the large scale wind offshore generation in the North Sea [22], DESERTEC investigates the combination of photovoltaic generation (PV) with Concentrate Solar Power (CSP) technology able to store electricity as thermic energy in Northern Africa [23], ABB presents a meshed HVDC network composed by 40 nodes as cross-border connection to transmit power generation from the large-scale RES installation (i.e., 30 GW solar power from the Sahara Desert, 2.2 GW hydroelectric power in Northern Europe and 7.8 GW wind power from Western Europe) to the European load centres, with limited power losses compared to the HVAC system [24].

ENTSO-E, the European Network of Transmission System Operators for Electricity, including 40 Member TSOs (Transmission System Operator) from 36 countries presented in 2020 the first version of Ten-Year Network Development Plan (TYNDP) which addresses a wide range of topics related to the impacts of energy transition in the European power network. This comprehensive study is based on three main scenarios, encompassing both centralised large scale RES generation and distributed small scale generation, as well as including the ongoing national policies. A detailed comparative analysis of these scenarios is presented in section 4.1 and are used as reference to evaluate multi-dimensional impacts of different policy directions in the context of energy transition.

1.2.2 Electrification of final uses

The second vertex composing the electricity triangle is the electrification of final energy uses, namely replacing the traditional fossil energy vectors (e.g., oil products in transport sector) with electricity. Electrification, coupled with the growth of renewable power generation, is a fundamental element to speed up the decarbonisation process as it involves various sectors, such as transportation, industry, and buildings (e.g., heating and cooling, cooking, etc.) traditionally relying on fossil sources and therefore contributing significantly to the global carbon emissions.

Since some sectors are characterized by higher electrification potential than other (e.g. transport and building sectors), this process is expected to involve all sectors but with different magnitude as illustrated in Figure 5, Figure 6, and Figure 7. For instance, in the IEA’s NZS building sectors, including residential and services sectors, are expected to significantly decrease the overall energy demand disfavouring fossil consumption while increasing electricity consumption. Hence, despite the moderate increase in absolute terms of electricity consumption compared to 2020, the electricity share in the building sector’s energy demand is expected to shift from 33% (in 2020) up to 66% by 2050. Among the main measures to reach this target, replacing traditional heating systems with electric heat pumps is a key action in the strategy to electrify the buildings sector.

Industry and transport electricity shares result equal to 46% and 44% of their energy mix by 2050 [25]. Although transport shows the lowest electricity share by 2050, it is actually the one that drastically change its energy mix: from a fossil-based energy mix (96% of the total transport consumption in 2020) it is expected to decrease oil and gas shares up to 12% by 2050, while electricity will account for 44% of the transport energy demand. The remaining energy demand will be covered evenly by bio-fuels (16%) and hydrogen (16%). As regards the industry energy mix, electricity contribution is expected to shift from 22% of total final consumption (in 2020) up to 46% in 2050, whereas coal from 28% to 6%, natural gas from 20% to 10% and oil from 20% to 15%.

Unlike the other two sectors showing a significant reduction in the overall final consumption thanks enhanced energy efficiency, industry shows instead a growth and fossil fuels maintains a relevant share (31%) in the energy mix. This disparity arises from the greater complexity of industrial electrification compared to other sectors. This complexity stems from the fact that the majority of industrial energy demand originates from "heavy industries," where transitioning from traditional fuels (e.g., coal, oil) to alternative low-carbon fuels (e.g., hydrogen) often necessitates process changes. These modifications incur higher costs for design, implementation, and testing, rendering them economically uncompetitive and unattractive. Furthermore, certain industries, such as chemicals, cement, and steel, require extremely high temperatures for operation, further complicating their electrification at a feasible cost.

The relevance of this topic is evidenced by the number of studies focused on industry electrification [26], [27], [28], [29], [30]. How to further decarbonize the 'hard to abate' sectors such as industry remains an open question on which several research activities are currently ongoing [31], [32].

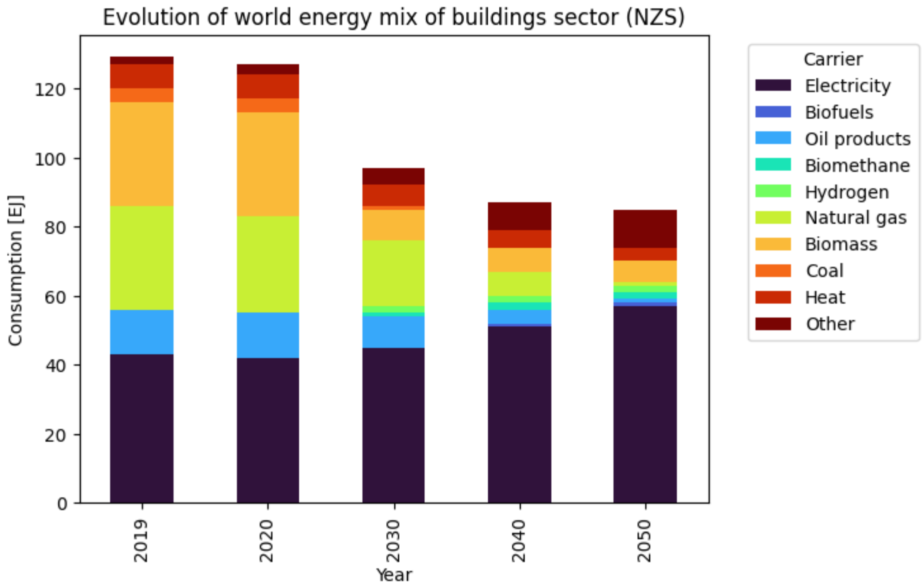


Figure 5: Evolution of world energy mix of buildings sector's final uses (Source: Elaborated data from IEA's Net Zero Scenario [21]*)*

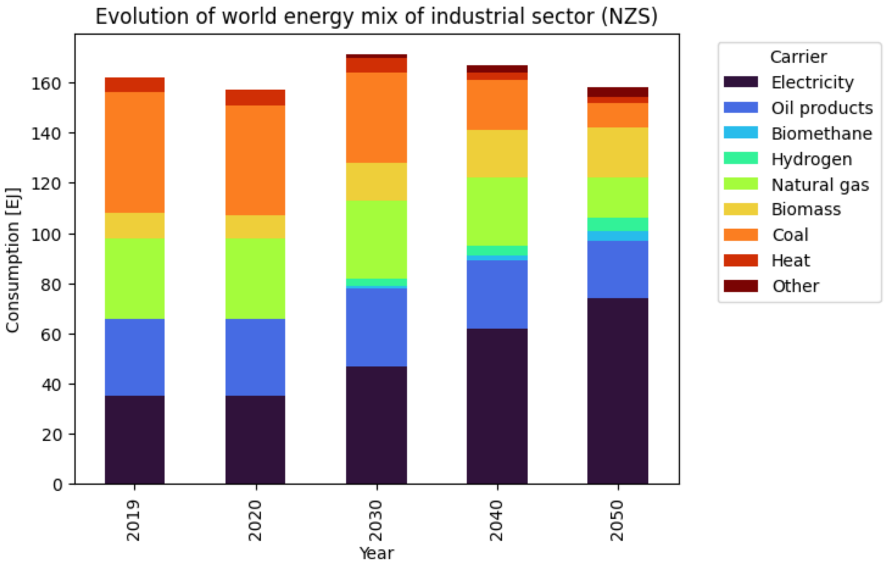


Figure 6: Evolution of world energy mix of industry sector's final uses (Source: Elaborated data from IEA's Net Zero Scenario [21]*)*

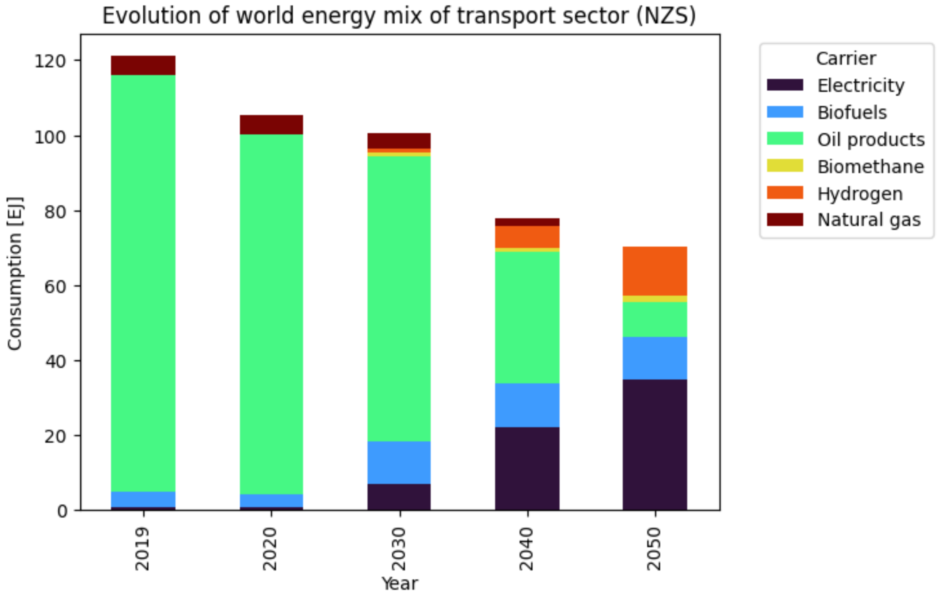


Figure 7: Evolution of world energy mix of transport sector's final uses (Source: Elaborated data from IEA's Net Zero Scenario [21]*)*

1.2.3 Electricity as main energy carrier

The third vertex of the electricity triangle entails leveraging electricity as the primary energy carrier. This implies a reduced significance for the traditional energy sources, notably coal, oil, and gas, in favour of electricity. As a result, infrastructure associated with the supply chain of these fossil fuels will become less relevant in the context of energy security: by decreasing dependence on these energy vectors, traditional supply corridors such as oil and gas pipelines, as well as oil tankers, will also diminish in importance. Moreover, unlike fossil reserves unevenly distributed among countries, RES generation enables to enhance country's self-sufficiency by means of local RES generation such as wind and solar, favouring those countries traditionally characterised by high dependence on imported fossil fuels.

As a result of electrification, power system infrastructure (i.e., cross-border lines and distribution lines) would emerge as central components of the new energy paradigm. Overall, the third vertex can be identified as the link between the first and the second vertex of the electricity triangle: indeed, to enable effective RES power generation combined with electrification of final uses, electricity infrastructure must be capable of ensuring electricity supply to all the final users in a cost-effective way, even in presence of disturbances or under abnormal conditions. Therefore, it is necessary to modernize and improve existing power networks. As a consequence of the electrification of final uses, the load is expected to increase significantly in the next years, therefore the existing infrastructure must be adequately extended and improved. The improvement of European electricity network is discussed in detail in the System Needs Study provided by ENTSO-E [33].

Additionally, as a consequence of the increase in intermittent and non-programmable generation from wind and solar, the future power network must be able to handle stability issues caused by the unpredictability brough by the penetration of renewables in the power generation mix. This aspect will be discussed in detail in section 4.1.2 by focusing on the fluctuations of residual node related to different policy scenarios developed in the last version of the TYNDP study [34] for evaluating the impacts of energy transition in the ENTSO-E countries in 2030, 2040 and 2050.

Chapter 2

2 Developing science-based tools for informed policymaking

2.1 Ambitions and challenges of European Union to fight the climate change

European Union has been actively dealing with climate change and has consistently advocated for ambitious climate actions for several decades. Since 1992, EU played a crucial role in the UNFCCC negotiations at the Earth Summit in Rio de Janeiro, one of the main key milestones in the global response to climate change. Indeed, after the Earth Summit in 1992, the first Conference of Parties (COP) took place in 1995, followed by the subsequent annual COP meetings. In 2015, the Paris Agreement introduced the so-called Nationally Determined Contributions (NDC) [35], [36], individual country-level commitments, mandatory for 195 members of UNFCCC and updated every five-years, which outline the country climate action plan to cut emissions and adapt to climate impacts in line with the Paris agreement goals. The operational details for the Paris Agreement implementation were agreed on at the 24th COP (COP24) in Katowice (Poland) in 2018 and finalized during the COP26 held in Glasgow (Scotland) in 2021. Each successive NDC is meant to reflect a higher level of climate ambition compared to the previous version. Since the NDCs works on five-years cycle, in order to frame the strategies to achieve the long-term goals, the Paris Agreement also invites the member countries to formulate the long-term low greenhouse gas emission development strategies (LT-LEDS). Unlike the NDCs, the LT-LEDS are not mandatory. Among the UNFCCC members who signed the Paris Agreement, the EU has emerged as a prominent and proactive leader in shaping the collective vision and committed itself to even more ambitious targets. Indeed, EU presented its first NDC [36] in 2015, setting the target to reduce the European GHGs emissions by at least 40% compared to 1990 levels by 2030. The long-term vision, also known as "European Green Deal", was presented by the European Commission in 2019, setting a new ambitious goal: achieving EU's carbon neutrality by 2050 (i.e., net-zero GHGs emissions). Consistently with the vision of the Green Deal, the successive NDC version submitted by the European Commission in 2020 [37], updated the previous target equal to -40% of GHGs emissions by 2030 compared to 1990 levels to at least 55% reduction. To financially support the Green Deal, the European Commission presented the Sustainable Europe Investment Plan (2020) aiming to collect at least €1 trillion of public and private investment by 2030 [38].

EU-27 made many steps towards reducing emissions between 1990 and 2022, by operating in several sectors simultaneously. One of the main tools adopted by the European Commission to cut emissions is the European Union Emission Trading System (EU ETS), launched in 2005. It works on trading phase, in 2021 started the fourth trading phase and it will in 2030. According to the EU ETS, each emitting entity needs emission allowances (i.e., carbon credits, emission quotes) to emit CO2. If the allowances available to the emitting entity are insufficient, the missing allowances are purchased from other entities. Therefore, emission allowances can be traded among entities (carbon market), but the overall emissions cannot overcome a fixed cap. This cap is reduced annually in order to progressively cut GHGs emissions.

On July 2021, the European commission presented FitFor55, a package of proposal to reform the EU climate policy, including the EU ETS [17]. The Fitfor55 is a large package of actions, detailing how to reach -55% of GHGs emissions (compared to 1990 levels) by 2030. This commitment turned into law on 29th July 2021 with the so-called European Climate Law [19], which legally bound EU-27 to achieve carbon neutrality by 2050 (long-term goal) and it also set the intermediate target for 2030 of at least -55% of carbon emissions compared to 1990. To track the progress of EU-27 member states towards the 2030 and 2050 goals, the Climate Law adopts the existing systems of monitoring through the National Energy and Climate Plans 2021-2030 (NECPs) and periodic report by the European Energy Agency (EEA). The NECPs were introduced by the "Clean energy for all Europeans package"[39], in order to implement the Energy Union Strategy presented in 2015 and to comply with the Regulation on the Governance of the Energy Union and Climate Action (EU 2018/1999 [40]). To frame the actions up to 2050, the EU 2018/1999 set out a process to support the Member States in preparing the National Long-Term Strategies, aimed at achieving the overall carbon neutrality of EU-27 by 2050 by operating across five domains simultaneously: decarbonisation, energy efficiency, energy security, energy market, research and innovation. Moreover, the Member States are required to consult and involve citizens, local authorities and stakeholders. Therefore, the European Commission is aware of the need to engage policymakers at all levels (international, national, regional, municipal). In particular, the contribution of municipalities is crucial to speed up the process of carbon neutrality at larger scale: with the launch of the "100 Cities Mission" [41] the European Commission invites 100 EU cities to reach climate neutrality by 20230 and inspire other cities to follow suit by 2050. In addressing the carbon neutrality challenge, which involves reducing greenhouse gas emissions to net-zero society, policy makers are the ones responsible for setting clear and ambitious targets coupled with robust and effective regulatory frameworks, encouraging the adoption of sustainable practices and technologies by means of incentives and/or taxes (e.g., ETS), investing in new low-carbon and energy-efficient technologies and employing them for renovating the existing infrastructure into more sustainable and more accessible ones. In addition to mitigation efforts policy makers need to find solutions to face the climate change impacts already underway (e.g., extreme weather events, sea-level raise, etc.). Moreover, huge amount of data and statistics are necessary to track the progress with respect to the final target, to highlight eventual weaknesses or side-effects, and to assess the overall performance of ongoing policies. Monitoring and reporting are indeed two key elements to inform policymakers and support them in making data-driven decisions.

2.2 Informed-Policymaking powered by scientific evidence

"*Effective evidence-informed support to policymaking goes beyond simply communicating research evidence, towards identifying options, helping policymakers understand the likely impact of choices, distinguishing facts and values in the debates and providing policy advice from a scientific viewpoint*" [42].

To deal with the complexity and magnitude of the issue, the scientific and policy-making communities should communicate and cooperate effectively. The scientific contribution to policymaking can cover a wide range of technical, economic, environmental and social topics. The core element which differentiates the science-based approach from the traditional policymaking is that scientific methods rely on objective evidence and data-driven outputs. Moreover, scientists and policymakers define problems with different aims: one as a problem to solve technically, the other as a social process of negotiating solutions supported by public opinion [43].

Aware of the important contribution of the scientific community in the decision-making process, the European Commission charged the JRC with promoting and implementing the so-called "evidence-based policy making" [44], by improving research evidence use in policy. Especially in case of crises and emergencies, evidence use is crucial to deal with severe impacts and need of constantly review countermeasure as demonstrated by the coronavirus (Covid-19) pandemic. Indeed, during the most serious periods of the pandemic's spread, the scientific expertise was put to the forefront in policymaking to deal with the pandemic emergency, involving multiple variables, various uncertainties and worldwide impacts. However, evidence-based policymaking does not imply that policy decisions should be taken solely based on scientific evidence (i.e., technocracy) [44], on the contrary it consists of selecting the best solution, balancing expert advice, feasibility and effectiveness of action, and taking into consideration the public acceptance too (i.e., democratic evidence-based policymaking). Thus, the actual challenge for policymaking lies in finding trade-off between evidence and societal context including expectations, values and preferences of the entire society (scientific community, citizens, media, and stakeholders).

Science for Policy Handbook [45], published by JRC in 2020, encompasses a wide range of topics and issues related to different attitudes and ways of thinking of politicians and scientists, highlighting the actual barriers which separate the two environments and make communication poorly effective. However, this book also highlights the need of promoting the collaboration between science and policy to face the complexity of ongoing global interconnected issues and develop robust and successful policies. Indeed, the magnitude and scale of unintended consequences brought by errors due to an ineffective evidence-based decision making are too large. In this line, advice and good practices to overcome the science-policy gap are reported in this book, highlighting the potential opportunities resulting from effective cooperation between policy and science.

2.2.1 Bridging the science-policy gap

"Scientists and policymakers define problems differently: one as something to solve technically, the other as a much more social process of negotiating solutions that have majority support" [43].

In order to bridge the gap between scientific and policy environments, it is important to fully understand which are the barriers which divide them. Firstly, there is a large difference in their approach to deal with a problem and find the solution (technically correct vs socially accepted), however there are further differences. Firstly, scientific research generally operates without strict deadlines, allowing for thorough investigation of the problem, collection and selection of data, validation of output and detailed discussion of results; on the other hand, policy often addresses immediate issues, requiring prompt decisions and immediate actions in any situation, even when scientific knowledge is insufficient to understand the phenomenon (e.g., Covid-19 outbreak). Due to the lack of time policymakers expect simple and clear messages. In contrast with the typical scientific approach, consisting of thorough reports and detailed analysis, the request from the real-world policymaking is quick, simple, and clear evidence. In case of emergency, policymakers miss the time necessary to elaborate and fully understand very detailed and complex notions. On the other hand, the scientist finds it difficult, too simplistic, or even incorrect to reduce the complexity of the results to a few simple pieces of information. Therefore, scientists tend to overestimate the level of detail needed to policymakers, simply because investing the problem thoroughly is intrinsic to the nature of the scientific approach. Moreover, scientific research often focuses on long-term solutions and understanding, whereas policymakers have to cope with the fast pace of policy and social needs, therefore they prioritise short-term goals and solutions. In addition, the limited duration of their mandate (e.g., ministers) is a further constraint influencing the choice of short-term solutions allowing to show the effectiveness of their policies.

Another crucial barrier between science-policy interaction is their attitude towards uncertainty. Policymakers refuse uncertainty and they demand ‘certain’ solutions from scientists, considering uncertainty as a threat which can undermine the success of the proposed solution. On the other hand, scientists accept uncertainty and include it in their methods since they are aware that all the outputs present a certain level of uncertainty. The lack of effective communication of the inherent uncertainty of scientific findings leads to misunderstanding between science and policy. Therefore, informing policy about the scientific uncertainty in a constructive way deserves particular attention from the scientific community [43].

The JRC’s Knowledge management for policy (KMP) initiative synthesised eight skills [46] useful to establish an effective science for policy (Figure 8), aimed in particular at researchers for overcoming barriers and bridging the science-policy gap:

- “Synthetising scientific evidence”: policymakers require clear and reliable quick solutions. Researchers often overestimate the level of details requested by the policymakers and underestimate the potential contribution of synthesis when prompt decisions are necessary. The first step is therefore to move research questions and analysis closer to the real needs of policymakers. Secondly, to meet the need of policymakers of quick and short proposals, the technical and detailed report should be coupled with a “shortcut” version, containing the key insights of the analysis.
- “Strengthening collaboration across experts”: in order to deal with complex and worldwide issues, interdisciplinary network can offer a valid solution to share ideas and experience, leading to a shared solution in accordance with the specific needs and reality of policymaking.
- “Understanding policy environment and needs”: enhancing the impact of science in policymaking requires a profound understanding of the policy process, goals and expectations. For this reason, as a preliminary step, researchers have to recognise policy context and drivers, identify the target audience and adapt the expertise to develop scientific insights tailored to the level of knowledge and understanding of the audience.
- “Enhancing interpersonal skills”: apart from the technical (hard) skills, researchers should develop interpersonal (soft) skills to foster effective communication and cooperation between multidisciplinary experts, policymakers and stakeholders.

- “Promoting stakeholders engagement”: effective evidence-based policymaking, aware of the importance of multiple perspectives and fields of knowledge, also promotes the engagement of stakeholders and citizens in the decision-making process.
- “Advancing evidence communication skills”: to foster the science impact in policy, data visualisation is a crucial aspect to consider. The combination of infographic design, interactive platforms and ‘storytelling’ method allows to transmit evidence from experts to non-specialist audience effectively, preserving public interest and understanding.
- “Monitoring effectiveness of informed policymaking”: evaluating the impact of research evidence on policymaking helps improve the influence of evidence on policymaking, thus researchers have to track the effectiveness of scientific contribution in policymaking by means of metrics and evaluating if any modification is needed.
- “Gaining policymakers’ trust”: researcher’s responsibility encompasses not simply communicating research evidence but also helping policymakers to understand the likely impact of their choices and providing policy advice from a scientific point of view. In this way, policymakers perceive the scientific community as a reliable advisor.

Figure 8: Framework of skills to enhance science for policy (Source: Elaborated data from Chapter 4 of Science for Policy Handbook [42])

2.2.2 Effective communication of scientific findings

"*Evidence does not speak for itself – it must be communicated*" [47].

Understanding thoroughly the nature of the issue raised by policymakers is an essential step, preliminary to the problem solving performed by researchers. However, assumed that the research activity is successfully executed and leads to relevant insights, selecting the most pertinent ones and effectively communicating to the audience should be prioritised over the other skills. Indeed, a common mistake of scientific community is to assume evidence as self-explanatory, or even take for granted the interpretation of results. Transmit the evidence in an understandable way is actually responsibility of researchers. This aspect is even more important if the goal is to inform broader audiences (e.g., citizens, journalists, and stakeholders) about ongoing policy challenges and objectives, with the aim of raising public awareness and understanding of complex topics like energy transition, decarbonization process and climate change impacts.

Depending on the audience, the same evidence can generate different messages, relevant and appropriate for the target audience. For instance, long and detailed reports are intended for an expert audience, whereas short summary providing the most relevant findings are more appropriate for politicians. For a better understanding of citizens, summaries reporting real-life examples and impact on citizens' lives is a valid solution to inform and engage them into the context of ongoing policies. Social media is a further communication channel which requires

mostly infographics: eye catching insights, short and easy to understand, aimed at capturing the attention of broader audiences, and hopefully encouraging them to explore the topic further. However, since the scientific community has always been accustomed to communicating through scientific papers, researchers encounter some problems communicating to non-expert audience. For this reason, JRC's Handbook emphasises the importance of strengthening the scientist's skill of clear writing, intended as the capability of explaining findings in a way that non-expert audience can understand. Among the good practices suggested by JRC, planning how to visually arrange the most relevant information is a crucial step in any scientific report destined for a wide public. Visual communication is indeed a powerful tool to effectively communicate to broader audiences.
Firstly, it is important to define in advance some aspects:

1) content and objective of the message to be communicated: what do you want your audience to learn or do?
2) Which is the target audience and its characteristics (i.e., environment, level of knowledge and interest, biases, and communication habits)?
3) Which is the most effective format of communication (i.e., printed/digital format, interactive report, animation, etc.)?
4) What type of interactions with audience?

Once clarified these core elements, choosing the narrative style and length of the text are essential to catch the attention of the audience and to pass the message effectively. Visual storytelling is a powerful combination of visual communication and storytelling narrative. It allows to achieve policy impact and to transfer scientific evidence to various kinds of audiences, since it can be easily understood and trigger policy thinking and stakeholder's engagement. In addition to this, infographic elements are successful in communicating through social media, which lately is becoming an additional channel for disseminating scientific information. Therefore, according to JRC's instructions, due to the relevance of visual communication (i.e., target audience, message, length, narrative, and infographics), it is necessary to track improvements towards an enhanced policy impact by developing a set of metrics [47] to assess the effectiveness of communication.

2.2.3 Metric-based methodologies as a tool to support evidence-informed policymaking

"Composite indicators can be powerful practical tools that can help policymakers summarise complex and interdependent phenomena that are not directly observable" [48].

Monitoring policy impact of scientific research is itself evidence to justify the investment in research [49] and it can help researchers identify critical points and how to handle them. Since

policy impact is not directly measurable, it is necessary to define and develop ad hoc metrics able to objectively measure the scale of policy and social impact of scientific contribution.
Metrics are successful tools in summarising and explaining complex phenomena not directly measurable (e.g., climate hazards at various spatial and temporal scales, economic and environmental impact of energy transition, etc.). Among the metrics, composite indicators are characterized by the capability to synthetize and capture the overall picture of the phenomenon, to catch the public interest and to meet the requirements of effective visual communication. In addition, metrics allow comparative analyses between countries, regions and cities, and they provide monitoring support and help assessing future (i.e., ex-ante) policy options.

In the dynamic landscape of addressing global challenges such as the energy transition and the multifaceted impacts of climate change, the utilization of metric-based methods plays a pivotal role in tracking and comprehending these intricate processes. Metrics offer a systematic and quantifiable means to monitor and analyse complex phenomena, providing valuable insights into multi-dimensional and multi-scale aspects. By translating complex data into accessible and comprehensible metrics, scientists can engage a broad spectrum of audience and foster their understanding.

Metrics can serve as valuable tools not only to communicate scientific findings across diverse audiences, including those without specialized expertise, but also to enhance evidence informed policy-making. By offering a basis for objective assessment, metrics help policymakers to evaluate the effectiveness of implemented strategies and to make data-driven decisions. This evidence-based approach also enhances the credibility of proposed policies and straighten public trust in the decision-making process. Furthermore, metrics enable the establishment of clear benchmarks and goals, aiding in the monitoring and evaluation of long-term policy outcomes. By setting measurable targets, policymakers can track progress, identify areas that require attention, and adapt strategies accordingly. This iterative process allows for dynamic and responsive governance, crucial in the face of evolving challenges posed by energy transitions and climate change impacts. Additionally, metrics contribute to accountability by providing a transparent means to assess policy performance. Policymakers can be held accountable to the public, fostering, on one hand a sense of responsibility and encouraging the implementation of effective, evidence-backed measures, on the other, enabling more citizens' engagement.

In addition to this, by providing a common language and standardized framework, metrics can be also used for comparing various scenarios, enabling comparison between diverse policies and constructive competition in achieving sustainable goals. This not only encourages the sharing of best practices but also promotes a sense of collective responsibility in addressing shared challenges on a global scale.

2.2.3.1 Simple and Composite Metrics

Metrics serve as a powerful tool to translate intricate information into simple key messages, facilitating the promotion of sustainable policies, garnering support from public opinion and contributing to the advancement of environmentally conscious decision-making on a global scale. Researchers commonly employ two main approaches: simple metrics with focus on a specific aspect, and composite metrics which instead aggregate multiple aspects into a unique index. Each method has its advantages and drawbacks, and the choice between them depends on many factors such as the concept (phenomenon) to be measured, the objective of the study (e.g., ranking between systems, scoreboards, tracking performance of single system over time, etc.) and the target audience (e.g., researchers, data analysts, politicians, citizens, etc).

Simple metrics are easy to comprehend, calculate, and interpret, offering a clear snapshot of specific aspects and facilitating quick assessments and initial insights. However, their limitations become apparent when dealing with intricate phenomena that involve multiple dimensions, as they may fail to capture the holistic picture. Scoreboards are commonly used for visualizing simple metrics, but their efficacy diminishes ad the number of showed metrics increases. The main purpose of a scoreboard is to provide a concise and easy to understand insights by means of a limited set of key metrics. Nonetheless, when dealing with intricate phenomena, like energy transition and climate change, a wide range of simple metrics are needed to perform a comprehensive assessment. To avoid misinterpretation or an incomplete understanding due to information overload, composite metrics can serve as a tool to ensure clarity and conciseness of scoreboard without omitting relevant aspects of the complex phenomenon under study.

Composite metrics, indeed, overcome the limitations of simple metrics, by summarising diverse factors into a single index which concisely provides the ‘big picture’ of the complex phenomenon. Despite their advantages, creating composite metrics demands careful consideration of weighting, normalization, and the selection of appropriate indicators. Furthermore, the complexity of composite metrics building may pose difficulties in interpretation and communication to a non-expert audience.

Although the use of composite metrics increased exponentially in the last 20 years [48], their use still raises many doubts and criticisms, because composite indicators may provide misleading policy messages if they are poorly constructed or misinterpreted. Furthermore, no agreement has yet been reached on how to construct the composite indicator (i.e., normalization, weighting allocation and aggregation approach), thus a wide variety of methodologies is available in literature.

2.2.3.2 COIN guidelines to build composite indexes

The JRC's Competence Centre on Composite Indicators and Scoreboards (COIN) is renowned for its research activity focused on developing methodologies to build metrics allowing policymakers to capture the 'big picture' of real-word phenomena and to measure progress towards the policy goals. Although there is no universally accepted method, the JRC-OECD's Handbook [50], providing detailed instructions on how to build composite indicators in ten steps, has become a relevant reference for developing composite indicators.

Step 1 - Defining the conceptual framework of the composite index. At this stage it is crucial clearly identifying the objective of the index, namely which is the phenomenon (concept) under study. The literature review of existing indicator frameworks is preliminary to the process of final formalisation of hierarchical structure, composed by domains and sub-domains. In this step, it is advised to involve stakeholders (i.e., citizens, public entities, etc.) through workshops and webinars.

Step 2 – Selecting indicators. Once defined the conceptual framework, it follows the choice of indicators. According to COIN's guidelines, a minimum of 3 indicators by domain is acceptable and 5-7 indicators is a good practice. The selection is based on specific criteria such as: relevance with respect to the aspect to be measured, reliability and credibility of the data source, and data availability. Some indicators like population, surface and GDP can be used to rescale indicators and performing objective comparison across different systems (e.g., countries). When considering data availability, the selected indicators should have at least 65% of input data coverage. During this stage, it is important to keep track of characteristics of all indicators in a summary table containing useful information like data coverage (spatial and temporal distribution), brief description, data-source, and year.

Step 3 – Data cleaning. This step involves identification and management of inconsistencies in input data (e.g., outliers, duplicates, missing data). Data visualization by means of scatterplots and histograms is a valid way to identify possible outliers (i.e., values significantly different from the majority of data) in datasets. According to COIN's instructions, to check the presence of outliers is sufficient to verify one of these conditions: kurtosis > 10; or kurtosis > 3.5 and the absolute skewness > 2.0.

Step 4 – Normalization of indicators. Before aggregating indicators into a composite metric, it is necessary to perform the normalization of values into a common scale (e.g., 0 to1, 0 to 100, etc). Furthermore, the consistency of indicator scores must be included in the normalization process, so that higher scores correspond to better performance and lower scores to worse performance. Min-Max normalization is indicated as one of the most adopted methodologies, which rescales the values into a common scale by using the maximum and the minimum values of the data series.

Step 5 – Weight allocation. The choice of weighting method depends on the objective of the composite index. In literature, equal weighting, factor analysis, expert opinion and the budget allocation are the most adopted methods. Sophisticated and intricate methods may hinder the effective audience comprehension of the weighting scheme, thus simpler methods can be more effective in this respect.

Step 6 – Aggregation. As for normalization, the choice of aggregation approach also depends on the objectives of the composite index and the more complicated the method, the more challenging it is to explain and communicate the aggregation scheme to the audience. Arithmetic and geometric average, Borda and Copeland methods are mentioned as some of the most popular aggregation methods. Depending on the adopted aggregation methodology, it must be kept under consideration the compensability among the high and low scores of aggregated indicators. For instance, additive aggregation is characterized by perfect compensability whereas the geometric aggregation is less affected by compensability effect.

Step 7 – Correlation Assessment. To better understand the influence of individual indicators in the overall composite index score, COIN's instructions suggest performing the correlation analysis by calculating the Pearson index (r) for each indicator composing the aggregated index. By analysing the Pearson index values, it is possible to detect whether indicators are over-represented or under-represented by the composite index score: for instance, if the absolute value is below 0.3, it means that the indicator is under-represented by the score of the composite index.

Step 8 – Sensitivity analysis and uncertainty assessment. Firstly, it is crucial to identify the main sources of uncertainty such as indicators selection and methodological choices (e.g., normalization, weighting allocation, and aggregation). The sensitivity analysis allows for verifying the robustness of composite index framework, and it also serves to detect which assumptions lead to the most uncertainty.

Step 9 – Storytelling design. To effectively communicate with the audience, data visualization must be organized according to a linear narrative, coherent with the objective of the composite index. Correlation analysis cannot be used to assume causality links between variables, nonetheless, if a consistent sample of time series is available, specific causality tests can be performed.

Step 10 – Data visualization. In this step, storytelling and visualization tools are combined to communicate the findings to the target audience. Powerful and well-designed narrative can enhance data visualisation tools (e.g., graphs, symbols, etc.), focused on communicating specific key messages without hiding important information neither overloading the audience with non-vital information, and preferring self-explanatory graphics rather than long texts.

To simplify the process from step 3 to step 8, COIN developed an online Excel-based tool for constructing composite indicators and scoreboards by following a series of simple steps described in detail in the COIN Tool User Guide [51]. The COIN tool is intended for a wide range of users: it is aimed to provide a powerful yet accessible and user-friendly platform to develop, analyse and adjust composite indicators. Users can also analyse relationships between indicators, check robustness of composite indicator and test the effect of different methodologies in the overall score. This tool is deliberately developed in Excel, as it aims to be accessible to the widest range of users.

Nonetheless, COIN Excel tool exhibits certain limitations, such as the maximum number of input data and aggregation levels, which influence the usability and applicability in specific scenarios. Firstly, the restriction of 300 input data points may pose a challenge when dealing with extensive datasets (e.g., when dealing with hourly data over a year or with urban data over a whole country). In these situations, the limited capacity of COIN tool forces to reduce the amount of input data, for instance by selecting a subset of characteristic data, or by shifting from a finer to a coarser resolution of dataset (e.g., from hourly data to daily, or from city scale to provincial scale), leading though to a loss of information. Furthermore, a maximum of 99 metrics can be calculated, and four levels of aggregation can be performed, therefore those projects with a higher degree of complexity in the hierarchical structure or a broader range of variables may find this constrain very restrictive. For this reason, it's important for users to be aware of these limitations and assess whether the COIN Excel tool aligns with their datasets and analytical requirements, or if alternative tools might better suit their needs.

The COIN tool, while providing valuable insights for building metrics, lacks an essential function – an automated system for collecting input data from diverse sources and subsequently calculating the indicators that form the basis for constructing composite metrics. The construction of a composite index often requires a large number of diverse data, available across different datasets, in various formats, and with differing spatial and temporal resolutions, making them challenging to access and collect. An automated data collection system would significantly reduce the processing time for composite index calculation, enabling analysts to avoid the delays and errors associated with manual data input and updates. However, developing such an automation system requires a comprehensive understanding of all datasets and data providers characteristics, including knowledge of their content, data format, and update frequency. Knowing which data to extract and how to organize it effectively is crucial for subsequent processing into indicators. Automation not only accelerates the composite index calculation but also mitigates the risks associated with manual data collection, ensuring accuracy and reducing the potential for errors. With a well-designed automated system, analysts can focus more on the interpretation of results and decision-making, rather than spending significant time on the manual compilation of data.

Normalization step

The first step of building composite metrics involves the choice of normalization approach. Indeed, due to the diverse nature of indicators, normalization process is imperative before proceeding with their aggregation into a single metric. Indeed, normalization involves converting data into a standard scale to remove discrepancies in units of measurement and scales. The most employed methods include z-score normalization, Min-Max normalization and distance to a reference [50], [52]:

- Z-score normalization entails dividing the difference between the raw indicator and the mean by the standard deviation, resulting in all indicators being scaled to a common scale with an average of zero and a standard deviation of one. While widely used due to its robustness and simplicity, it may not accurately represent the original data if the distribution is not normal or if sample sizes are small [50].
- Min-Max normalization is a straightforward method, involving rescaling values relative to the minimum and maximum of the dataset. Unlike z-score normalization, it is suitable for a wider range of distributions, but it only retains the relative ordering of values post-normalization. Additionally, outliers can alter results and it necessitates recalibration when new data is introduced.
- Distance to reference normalization scales raw indicators based on a benchmark, though the choice of benchmark can introduce subjectivity to results. Similarly, categorical-scale normalization assigns numerical or qualitative scores to raw indicators based on reference thresholds based on experts' judgement.

Among these methods, Min-Max normalization is the most adopted [53], [54], [55], [56]. Indeed, Min-Max normalization enables comparative assessments from two perspectives: the individual system perspective, focused on highlighting the improvements and worsening of a specific system over time, and the multiple systems perspective, used to identifying the best and worst performances in a group of systems, fostering healthy competition and emulation of the best-performing system. In the first case, the normalization involves scaling the values with respect to the minimum and maximum values recorded by a single system (e.g., country, region, city). As regards the second perspective, the minimum and maximum are obtained from the best and worst performances of the systems group (e.g., EU-27 countries) in a certain time unit (e.g., year, month)

Numerous studies lack normalization, weighting, and aggregation procedures [57], [58], [59], [60], focusing solely on criteria to select appropriate indicators according to the phenomenon under study (e.g., sustainable development, energy transition, energy security etc.). Other studies, such as the Carbon Neutrality Capacity Indicator System (CNCIS) [61] and Uniform Smart City Evaluation (USCE) Framework [62], employ hybrid approaches for aggregation, normalization, and weight allocation. The CNCIS's approach combines the best-worst method (BWM) with the entropy method (EM) while USCE couples the distance to a reference method with the categorical-scale method and uses both the Budget Allocation (BAL) and the equal weight (EW) weighting methods among different sub-index levels. Similarly, the Urban Energy Sustainability Index (UESI) [63] is obtained by assigning a different weight according to the type of indicator (i.e., basic, instrumental, and complementary indicator). Although these intricate and sophisticated methodologies may be more accurate from a scientific perspective, their complexity can hinder comprehension and communication to non-expert audience. Conversely, prioritizing clarity of findings and transparency in methodology can improve understanding and effective communication to diverse audiences, enabling broader engagement and greater trust and confidence of stakeholders and citizens in the scientific evidence.

Since these studies are often intended to support policymaking, it is not reasonable to develop methodologies beyond the policymakers' comprehension, therefore less sophisticated methods should be preferred.

Weighting and aggregation steps

As regards the weighting allocation, two main approaches can be identified: objective approaches and subjective approaches [64]. Among the objective approaches, equal weighting assigns equal weight to all indicators under the assumption that no single indicator is inherently more significant than the others [65]. Statistic-based methods such as Principal Component Analysis (PCA), Factor Analysis (FA), data envelopment analysis (DEA), and regression analysis (RA) [40,46] are included in the category of objective (data-driven) normalization approaches: it derives weights from statistical properties of data composing the indicator. Among the subjective weighting methods, the Analytic Hierarchy Process (AHP), the conjoint analysis (CA), and the Budget Allocation Process (BAP) are commonly used, especially when dealing with qualitative input data or in case of data scarcity. However, since they rely on opinions and experiences of experts and stakeholders, weights might be sensitive to personal opinions and biases of individuals, making them less objective and potentially difficult to replicate [50].

Some studies adopt hybrid weighting methods combining subjective and objective approaches [61], [66]. Nonetheless, some weighting methods can affect the choice of certain normalization and aggregation approaches due to their compatibility limitations [50]: for instance, the Min-

Max normalization is adaptable to the majority weighting and aggregation methods, whereas z-score normalization cannot be combined with geometric aggregation or the Benefit Of Doubt (BOD) weighting method [50].

Ultimately, when dealing with building composite metrics, equal weighting results the most straightforward objective method. It is commonly used in the literature and is often employed as a reference for comparative analyses [53], [65], [66], [67], [68], [69], [70], [71], [72], [73]. Among aggregation approaches, though it exhibits "perfect compensability", namely underperformance in one component is perfectly compensate by overperformance in another [50], [74], additive aggregation is the most used, often combined with equal weighting. Although its incompatibility with certain normalization methods (i.e., z-scores normalization), the geometric aggregation, based on the product of variables rather than their sum, is less sensitive to perfect compensability compared to additive aggregation [74] . Moreover, it encourages improvements in weaker components since it tends to penalize unbalanced performances more heavily than additive aggregation.

Chapter 3

3 A novel approach for data formalisation

In the pursuit of supporting evidence-based policy decision-making, the continuous provision of updated information is paramount. Particularly in the realm of monitoring through indicators and composite metrics, a significant challenge lies in the collection, cleaning, and validation of the multitude of data required. This process often occurs manually, demanding substantial time and resources and leading to major risks of errors due to manual data collection, or without any thorough and clear methodology. The COIN guidelines, while explaining in detail how to design a robust composite metric framework, provide no indication of how to manage the process of data collection and update preliminary to indicators calculation, which is often more time-consuming than the composite index calculation itself. The need of a new systematic approach to handle this preliminary step is even more relevant in the current landscape where digitalization is spreading, and the amount of data continues to grow. The utilization of digital platforms capable of providing real-time and continuous information to users, will play a central role in the next decades, enabling the continuous exchange of information and the implementation of measures such as the Demand-Side Management (DSM) [75], involving the strategic adjustment of energy consumption patterns by end-users to order to optimize energy usage, enhancing grid stability and short-term flexibility. Nonetheless, digitalization cannot be pursued without and effective system of methodologies and tools capable of handling big amount of data. The following sections will delve into the detailed explanation of the methodology developed: on one hand the aim is to address the challenge of collection and organization of information into a unique database, characterising each data and understanding the hierarchical inter-index relationships, on the other hand the objective is to setting the foundations for a digital platform capable of automatically processing and updating indicators and composite metrics, accessible to the user through a single and user-friendly interface.

3.1 Data categories and hierarchical structure

Central to the optimization of the collection, processing, and continuous updating of metrics is a dynamic and well-structured database. A database, defined as a systematic collection of organized data, acts as a centralized repository designed for efficient data retrieval and management. It serves as the foundation for any automated system, providing the essential infrastructure to store and organize diverse datasets cohesively. Before delving into the intricacies of designing a unified database structure for the categorization and organization of data, a critical preliminary step involves establishing a robust method for formalizing both the data and the datasets in use. This includes creating a clear hierarchy among the data, constructing a structured framework that facilitates seamless "traceability" of input data. This traceability is indispensable, allowing for the straightforward tracking of raw data back to the derived output data, such as composite index, and vice versa. Therefore, the formalisation of data and the establishment of a well-defined hierarchy become the keystone in subsequent stages of database design. This pivotal initial step ensures a systematic approach to structuring the database, particularly vital for managing a substantial amount of data, continuously updated. This becomes especially pertinent in the context of calculating composite indicators and metrics, where the need for a dynamic but robust database is paramount. In this era of rapid digital evolution, the emphasis on this aspect cannot be overstated, as it serves as key tool for handling vast datasets, ensuring accuracy, and facilitating real-time decision-making through the effective computation of up-to-date indicators and composite metrics.

A core element of the novel approach developed is the distinction of five macro-categories for the classification of data organised within the database. The distinction among these categories is integral to establishing a comprehensive hierarchy that not only facilitates the traceability of information but also serves as the cornerstone for subsequent stages of data processing. The five macro-categories include Raw Data, Basic Figures, Indicators, Simple Indices, and Aggregated Indices (Figure 9).

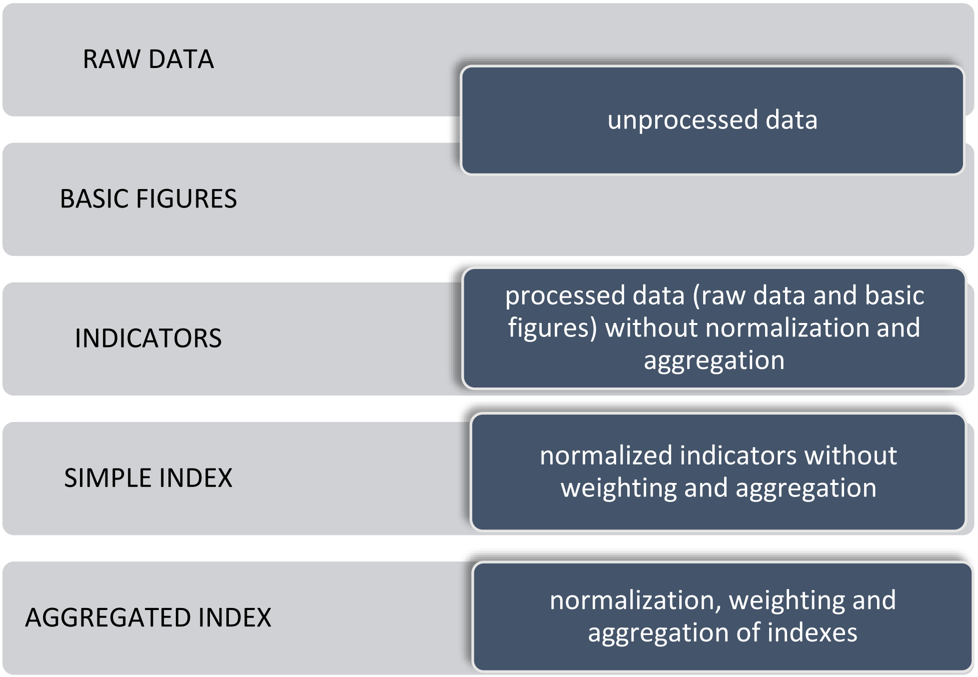


Figure 9: Classification of data into 5 macro-categories

Raw data: this category includes all data collected from other data providers. It includes only measured and unprocessed data without any meaning as an indicator: these data, by themselves, simply cannot characterise and explain the behaviour or a property of the system under study but they can be further processed and combined with each other to construct indicators. They generally have a specific unit of measurement as shown in the examples below:

- Number of inhabitants of a country [inhab]
- Surface area of a country [km^2])
- Hourly electricity generation by type of generator [MWh]
- Hourly electricity demand by bus [MWh]
- Installed capacity by power generation technology and by bus [MW]

Basic figures: data already processed by external sources, which serve to characterise the behaviour or a property of the system under study and can also be used in combination with raw data to build new indicators. Like raw data, basic figures are generally characterised by a unit of measurement, otherwise, it means that they have been obtained through normalisation and aggregation steps (e.g., Worldwide governance indicators [76]).

- Gross Domestic Product of a country, GDP [$]
- Title Transfer Facility of natural gas, TTF [€/Smc]
- West Texas Intermediate, WTI [$/bl]
- Worldwide governance indicators [-]: Rule of Law, Voice and Accountability, Political Stability and Absence of Violence/Terrorism, Government Effectiveness, Regulatory Quality, Rule of Law, Control of Corruption

Indicators: they are obtained by further processing and combination of raw data and/or basic figures. They can describe the behaviour or a property of the system under study and they are generally characterised by a unit of measurement. A key distinction between indicators and basic figures lies in the fact that indicators can be derived through processing open-source data available in datasets, whereas basic figures are not easily recalculable; external sources typically provide only the final processed value, lacking sufficient information for reconstructing the exact value. All elaborations and combinations between raw data, basic figures and other indicators are allowed to build indicators with the exception of normalisation, as the latter distinguishes the category of indicators from the category of indices.

- Carbon intensity of electricity generation [$kgCO_2$/kWh]
- Annual final consumption by sector [TJ]
- Carbon emissions per capita [tCO_2/inhab]
- Annual per capita electricity consumption [MWh/(y*inhab)]
- Annual energy supply by GDP (MJ/thousand 2015 USD)

Simple indices: they lack specific measurement units and are generated through a normalization process. A simple index can be obtained by rescaling indicators to a predetermined scale, typically falling within the range of 0 to 1 or 0 to 100.

Aggregate index: a dimensionless value with a predefined graduated scale, obtained from the combination of simple or aggregate indices. Different degrees of aggregation are distinguished (hierarchy structure):

- 1st level aggregated index: obtained by aggregating at least one simple index with other metrics;
- 2nd level aggregated index: obtained by aggregating at least a 1st level aggregated index with other metrics;
- Nth level aggregated index: obtained by aggregating at least a N-1th level aggregated index with other metrics.

Table 1 summarises the typologies of data categories, including their origin and the symbology adopted.

Table 1: Type of data categories: name, source, symbol

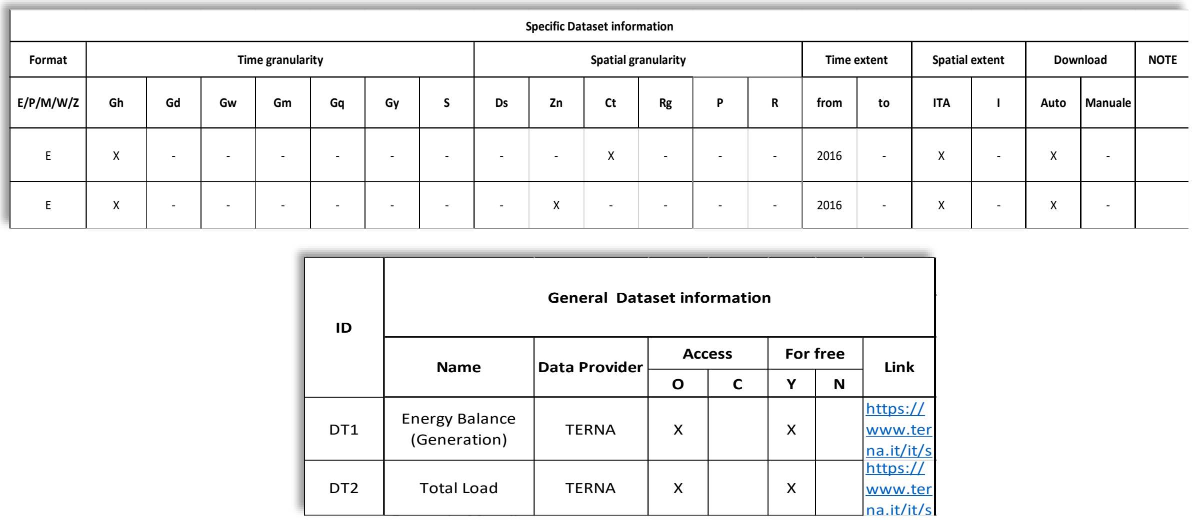
Data category	Origin	Symbol
Raw data	Collected data	d
Basic figure		b
Indicator	Internally Calculated data	i
Simple index		I0
Aggregated index of Nth level		IN

3.2 Attributes for data characterization

Creating a unified and dynamic database capable of updating data collected from various data providers, as well as independently processing and calculating aggregated indices, requires the development of a comprehensive characterisation system. This system extends beyond merely categorising input and output data; it also involves characterising datasets and data providers supplying the required information. Characterising data and mapping datasets and data providers is a fundamental step to gain a complete overview of the information encompassed within the composite index framework. Some datasets provide links for direct downloading or API (Application Programming Interface) which provide a standardised way to retrieve information directly from data source, streamlining the process of accessing and extracting data, therefore simplifying the extraction of desired data. Conversely, other datasets without any download links or APIs available, require the development of peculiar code (script) for data extraction: the crawler. A crawler (web crawler or spider) is a program designed to systematically browse and extract information from websites. It works by navigating through web pages, following links, and collecting data according to predefined rules or patterns. These automated scripts simulate the user's actions browsing the web, but at a much faster pace and with the ability to process large volumes of data without the risks of manual errors. Crawlers are valuable tools for collecting data from websites that do not provide direct download links or APIs. When designing an automated system of crawlers for data downloading, the update frequency of datasets must be considered too.

Another crucial aspect distinguishing datasets is their spatial and temporal resolution (granularity). Some datasets offer finer resolutions, such as hourly data, while others provide coarser resolutions, such as annual or global data. In general, finer resolution is preferred because it allows to perform more detailed analyses and evaluation, whereas coarser resolution forces assumptions to be made in order to derive the desired granularity. The spatial and temporal extent of a dataset is also significant; a broader extent yields more information, enabling more robust statistical evaluations (e.g., correlation analysis, sensitivity analysis).

The characterisation system is implemented through a tabular format (Figure 10), where general and specific information is structured in columns and presented in the form of "attributes", providing a standardized way of reporting distinct property of element being characterized (e.g., dataset, unprocessed data, indicator, etc.). Each attribute corresponds to a specific feature or quality of the data, allowing for a detailed and systematic description of the elements within the database in a concise and structured way.



Specific Dataset information																				
Format	Time granularity							Spatial granularity						Time extent		Spatial extent		Download		NOTE
E/P/M/W/Z	Gh	Gd	Gw	Gm	Gq	Gy	S	Ds	Zn	Ct	Rg	P	R	from	to	ITA	I	Auto	Manuale	
E	X	-	-	-	-	-	-	-	-	X	-	-	-	2016	-	X	-	X	-	
E	X	-	-	-	-	-	-	-	X	-	-	-	-	2016	-	X	-	X	-	

ID	General Dataset information						
	Name	Data Provider	Access		For free		Link
			O	C	Y	N	
DT1	Energy Balance (Generation)	TERNA	X		X		https://www.terna.it/it/s
DT2	Total Load	TERNA	X		X		https://www.terna.it/it/s

Figure 10: Example of dataset characterisation in a tabular form: general and specific information sections

This characterisation method also addresses the need of achieving a comprehensive understanding of all the datasets and data sources used for downloading and updating data. As shown in Figure 10: Example of dataset characterisation in a tabular form: general and specific information sections, each dataset is assigned an identification code (ID). The ID code is composed by a string consisting of two letters, depending on the type of element, followed by a sequential number. The two initial letters for datasets correspond to "DT", for unprocessed data correspond to "dd" and for processed data correspond to "ee". This code associates each data with its source dataset and provider, ensuring a thorough traceability of every item within the database and therefore enhancing the overall transparency and reliability of data. Furthermore, since the characterisation system is designed to handle data collection from diverse datasets and to manage continuous updates in the calculation of indicators and indices, it incorporates the classification of processed and unprocessed data into categories (introduced in section 3.1). Indeed, data category is one of the aspects characterising alphanumeric code (section 3.2.1), a more elaborate version of the ID code which provides the key information of characterisation process in a concise way.

3.2.1 Alphanumeric code for data identification

When dealing with a vast number of indicators and indices and diverse levels of index aggregation, navigating through the database becomes more intricate for the user. To address this complexity, a more sophisticated ID code has been developed. This code condenses key information into a string that can be effortlessly interpreted by a program capable of "scanning" the code. Consequently, the program promptly returns to the user all the essential details, also indicating the level of aggregation of composite indices. The alphanumeric code is composed by a specific structure (Figure 11) comprising a prefix, a root, and a suffix: prefix and suffix provide information about the data, while root is designed to uniquely recognise the data within the database.

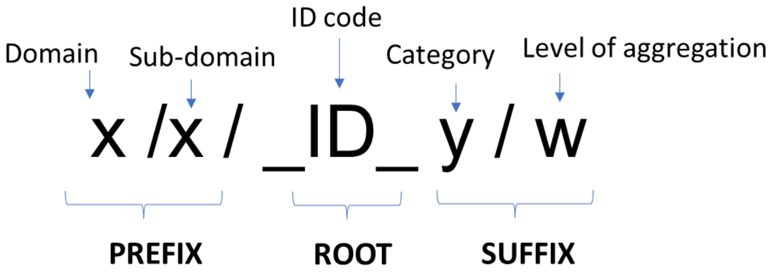


Figure 11: Structure of alphanumeric code for data identification

As shown in Figure 11, the prefix defines the domain and sub-domain to which the data been allocated during the definition of conceptual framework (Step 1) discussed in section 2.2.3.2; the root indicates the ID code assigned which allows data tracking within the database; the suffix provides information about the data category and N^{th} aggregation level for composite indices. The underscore separator (‘_’) is used to distinguish sections (prefix, root and suffix) from each other, while the slash separator (‘/’) is used as an internal separator within each section.

This alphanumeric code serves as a more elaborate version of the simple ID code, to not only uniquely recognise database items but also to provide further information about it (e.g. domain it belongs to, category of data, and level of aggregation). Nonetheless, it may happen that the suffix cannot be uniquely assigned because that data is utilized in constructing different indicators belonging to different domains/subdomains. In these cases, due to the interplay of raw data and basic figures across diverse domains and subdomains, several versions of code are generated with different prefix but same root (ID code) enabling the uniquely data recognition.

3.3 Application of the methodology to the ISPRED index

This systematic approach of data characterisation has been applied to the existing system of indices used by ENEA (Italian National Agency for New Technologies, Energy, and Sustainable Economic Development) to perform the quarterly assessment of the Italian energy transition. This work [77] is part of a broader joint project "Systematisation and automation of the analysis of the national energy system using the ENEA ISPRED composite index" between ENEA and the Energy Department (DENERG) of Politecnico di Torino. The general goal of this project is to contribute to the enhancement of current ENEA's approach of collecting, handling, and updating all data composing the energy transition index framework. In particular, the research activity involved three main objectives:

1. Applying the developed formalisation approach to systemically map and characterize input data and datasets, including indexes and indicators employed by ENEA to track the Italian energy transition process in the "Analisi Trimestrale" report [54];
2. Reviewing the ISPRED framework and evaluating whether additional indicators can be included in the composite index structure or in the "Analisi Trimestrale" report [54];
3. Designing and developing of an interactive IT tool, available online and intended for a broad range of stakeholders (e.g., institutional bodies, public and private companies, citizens) interested in understanding and monitoring the progress of energy transition in Italy through a user-friendly interface. The prototype version of this web-application – ET@IT, Energy Transition Analysis – Italian Tracker – has been developed in accordance with the COIN's guidelines [51] on storytelling (step 9) and data visualisation (step 10). As a result, the intricate and comprehensive insights presented in the "Analisi Trimestrale" report [54] are transformed into interactive graphics. These graphics effectively highlight key messages and trends, making them easily understandable to users.

ENEA's quarterly report: "Analisi trimestrale del Sistema Energetico Italiano"

The ENEA's "Analisi trimestrale del Sistema Energetico Italiano" report [54] has the primary objective of providing a comprehensive and up-to-date assessment of the national (Italy) energy transition trend. Indeed, this analysis aims to monitor the progress of Italian energy transition, identify potential challenges, and offer science-based insights for strategic decision-making. This quarterly analysis examines the "energy trilemma" coined by the World Energy Council (WEC) [78] in 2010 and addressed by others [79], [80], [81]. The energy trilemma concept comprises three dimensions (i.e. Security, Equity, and Decarbonization) which are combined into the ISPRED (Indice di Sicurezza, PREzzi, e Decarbonizzazione) composite index. In addition to the calculation of the ISPRED, the analysis covers many other aspects of the energy transition using "auxiliary" indicators not included in the ISPRED structure.

Therefore, the quarterly offer a holistic view of emerging trends and issues in the context of energy transition, on one hand, facilitating a prompt and dynamic response from policymakers and stakeholders, on the other, tracking the effectiveness of ongoing initiatives and policies.

However, the quarterly analysis also has its limitations. Currently, the periodic updating of data is performed manually by an operator who directly accesses each individual data source, downloads the dataset and extracts the data of interest, which is then entered into an Excel spreadsheet for the calculation of indicators and indices. This procedure is not only inefficient and time-consuming, but above all increases the risk of errors during the manual updating. Moreover, considering the periodicity of the updates and given the extensive amount of data and computations to be handled, the current approach would significantly benefit from an automated updating system integrated with a structured database containing all input and output data, readily accessible and efficiently organised.

The proposed systematic data formalisation method is paramount for developing an organized and robust structure for the automated updating system, enabling a streamlined and efficient process for handling diverse data and datasets utilized in the quarterly analysis.

Data formalisation methodology has been implemented to ENEA’s index framework also taking into account further aspects essential to develop a web-application, such as evaluating which datasets allow automate data collection through API or web crawlers, periodicity of publication, time and spatial extent of data coverage, etc.). The main two steps performed at this stage are listed below:

1. mapping and comprehensive characterisation of datasets and input data, in accordance with the formalisation approach described in section 3;
2. formal definition of output data, comprising indicators and indexes, including mathematical formulas and the level of aggregation.

Attributes for datasets mapping

To map the datasets used for data collection in ENEA's quarterly analysis, 14 attributes have been identified: seven attributes allocated to the general information section and seven allocated to the specific information section (Table 2).

Table 2: Characterisation attributes for datasets mapping

General information	
ID code	To uniquely identify the dataset
Dataset name	Title of the dataset
Data provider	To indicate the entity or company supplying the data
Access type	To distinguish between accessible datasets (including both paid and free datasets), and blocked datasets
Free	To distinguish between datasets accessible for free, and datasets requiring payment
Download	To indicate whether data download can be performed automatically, or it requires manual intervention
Link	The URL code for direct access to the dataset
Specific information	
Trilemma dimension	To identify the dimension of the energy trilemma (Security, Equity, Decarbonisation) the dataset refers to
Commodity	To specify to which of the four commodity categories identified in the ENEA report (electricity, gas, oil, CO2) the dataset data refers to
Format	To specify the format of dataset (e.g., Excel, PDF, etc.)
Time resolution	To indicate the temporal granularity of the dataset
Spatial resolution	To indicate the spatial granularity of the dataset
Time extent	To indicate the temporal coverage provided by the dataset
Spatial extent	To indicate the spatial coverage provided by the dataset

By adopting this approach, a comprehensive mapping of energy datasets has been performed. Overall, the formalisation analysis has been performed not only for those datasets currently used by ENEA in the Analisi Trimestrale's document, but it has extended also to other datasets such as the World Governance Index by World Bank and Alphatanker by AXS Marine. A total of 47 datasets and 23 providers have been formalised (APPENDIX, Figure 91). As shows in Figure 12, 45% of datasets are provided by Italian sources (i.e., MiSE, MASE, TERNA, UNEM, GME, Staffetta Quotidiana, SARAS, SNAM, and ENEA), while the remaining quote (55%) is supplied by 14 international data providers. Among the 9 Italian data providers, the Italian Ministry of Economic Development (MiSE) provides 11% of the total datasets, followed by the Italian Transmission System Operator (TERNA) accounting for 9% and the Italian Ministry of Environment and Energy Security (MASE) accounting for 9%, with significant contributions also coming from the International Energy Agency (9%) and Eurostat (9%). Among the entire dataset collection, 21 datasets are supplied by Italian data providers, the remaining datasets (26) are furnished by international providers.

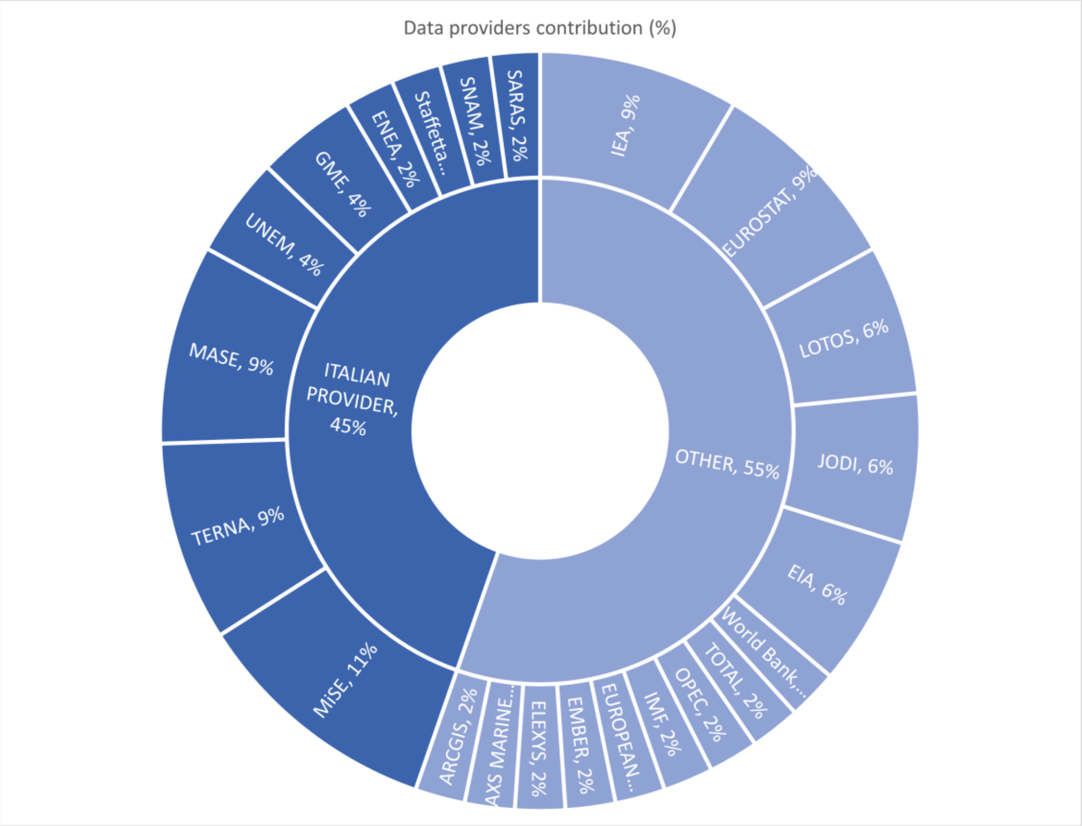


Figure 12: Percentage of dataset coverage (%) of Italian and non-Italian data providers

As regard the temporal resolution, excluding the 3 datasets referring to spot values assumed constant over time, 80% of the datasets employed to collect data for the quarterly energy assessment are updated with a finer frequency than quarterly (e.g., hourly, daily, weekly). These finer temporal resolutions are preferred to the biannual and annual ones (20% of the dataset collection): biannual and annual datasets are often published with more delay compared to those with finer resolution and they need assumptions and further calculations to obtain the estimated value to include in the quarterly assessment. Temporal resolution of formalised datasets is illustrated in Table 3.

Table 3: Temporal resolution of dataset collection

N° datasets	hourly	daily	weekly	monthly	quarterly	biannual	annual
44	4	5	3	20	3	4	5
100%	9%	11%	7%	45%	7%	9%	11%

Attributes for data characterization

Once completed the datasets mapping, follows the characterization of collected data. Similarly to the datasets mapping, the characterization comprises both general and specific information as shown in Table 4:

Table 4: Characterisation attributes for collected data

General information	
ID code	To uniquely identify the collected data
Symbol	To identify data in the calculation formula
Data name	Name of the collected data
ID dataset	To identify the dataset the collected data belongs to
Link	The URL code for direct access to the dataset
Data category	To identify the category of the collected data (raw data or basic figure)
Specific information	
ISPRED	To specify if the collected data is included in the ISPRED calculation
Commodity	To specify to which of the four commodity categories identified in the ENEA report (electricity, gas, oil, CO2) the collected data refers to
Unit of measure	To specify the unit of measure of the collected data
Format	To specify the format of dataset (e.g., Excel, PDF, etc.)
Time resolution	To indicate the temporal granularity of the dataset
Spatial resolution	To indicate the spatial granularity of the dataset
Time extent	To indicate the temporal coverage provided by the dataset
Spatial extent	To indicate the spatial coverage provided by the dataset

The attributes utilized to characterize the collected data are similar to those used for mapping the datasets. However, to avoid repeating general and specific information related to the dataset, the dataset ID is used as a link to the general and specific information of the dataset. Additionally, in the table for data characterization is specified data category according to the formalisation approach defined in section 3. As regards the specific information, it is reported whether data is included into the ISPRED framework, and it is indicated the unit of measurement too. Characterization of data utilized for the ENEA's quarterly assessment includes 14 attributes and encompasses a total of 101 data, reported in APPENDIX, Figure 92. Another essential step following data characterization is the formalisation of indicators and indices calculations. This stage encompasses all data obtained through calculations and processing of collected data. Table 5 summarizes the 14 attributes of characterization of this group of metrics, including indicators, simple indices and aggregated indices. Among the selected attributes, Formula attribute is crucial to understand how the indicator/index is obtained, underscoring the mathematical relationship between the input data and the resulting indicator/index value. This information is crucial for developing an automated updating system capable of independently calculating updated indices and indicators whenever the input data is refreshed with the latest available data. This ensures real-time monitoring, enabling timely insights and informed decision-making based on the most updated data. The output of the complete characterization of indicators and indices, including intermediate calculations, is reported in APPENDIX, Figure 93 and comprises a total amount of 139 processed data.

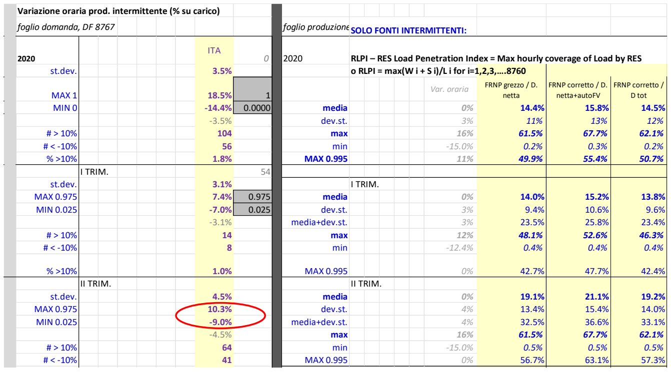
Table 5: Characterisation attributes for processed data

General information	
ID code	To uniquely identify the processed data
Symbol	To identify the processed data in the calculation formula
Data name	Name of the processed data
Description	To explain the meaning of the indicator/index
Data category	To identify the category of the processed data (indicator or index)
Specific information	
ISPRED	To specify if the collected data is included in the ISPRED calculation (yes or no)
Trilemma dimension	To identify the dimension of the energy trilemma (Security, Equity, Decarbonisation) the indicator/index refers to
Commodity	To specify to which of the four commodity categories identified in the ENEA report (electricity, gas, oil, CO2) the collected data refers to
Unit of measure	To specify the unit of measure of the collected data

Formula	It reports the mathematical expression used to calculate the indicator/index
Time resolution	To indicate the temporal granularity of the dataset
Spatial resolution	To indicate the spatial granularity of the dataset
Time extent	To indicate the temporal coverage provided by the dataset
Spatial extent	To indicate the spatial coverage provided by the dataset

Performing the extensive formalisation of datasets, collected data and processed data included in the energy transition assessment is a core preliminary step for developing an IT tool capable of updating the database with the latest input data and automatically calculating the indicators and indices used to consistently and timely track the trends throughout the national energy transition.

Moreover, to better underscore the benefits lead by the adoption of the developed data formalisation, three screenshots are provided: the first one (Figure 13) shows an example of ENEA's worksheet in excel where all calculations are performed by an operator who manually refreshes the input data and updates the outputs. Even with an adequate worksheet organization, manual intervention is time consuming and increases the probability of errors. Moreover, exploring information contained in the worksheets results complicate and disorienting, hence necessitating familiarity with the worksheet structure to locate pertinent information of interest. In the second screenshot (Figure 14) is reported an example of index formalisation, including all intermediate calculation steps from the input data to the final index. This representation facilitates on one hand the understanding of relationships between data, indicators and indices, and on the other underscore the hierarchical structure within the aggregated index. The last screenshot (Figure 15) shows the combination of data formalisation with detailed design of a user-friendly and interactive platform, allowing user to easily explore both collected data, indicators and indices by means of a single interface. Additionally, the platform's automated data collection and processing system prevents human errors and speeds up quarterly analysis updates.



Variazione oraria prod. intermittente (% su carico)

foglio domanda, DF 8767

		ITA	
2020			0
st.dev.		3.5%	
MAX 1		18.5%	1
MIN 0		-14.4%	0.0000
		-3.5%	
# > 10%		104	
# < -10%		56	
% >10%		1.8%	
	I TRIM.		54
st.dev.		3.1%	
MAX 0.975		7.4%	0.975
MIN 0.025		-7.0%	0.025
		-3.1%	
# > 10%		14	
# < -10%		8	
% >10%		1.0%	
	II TRIM.		
st.dev.		4.5%	
MAX 0.975		10.3%	
MIN 0.025		-9.0%	
		-4.5%	
# > 10%		64	
# < -10%		41	

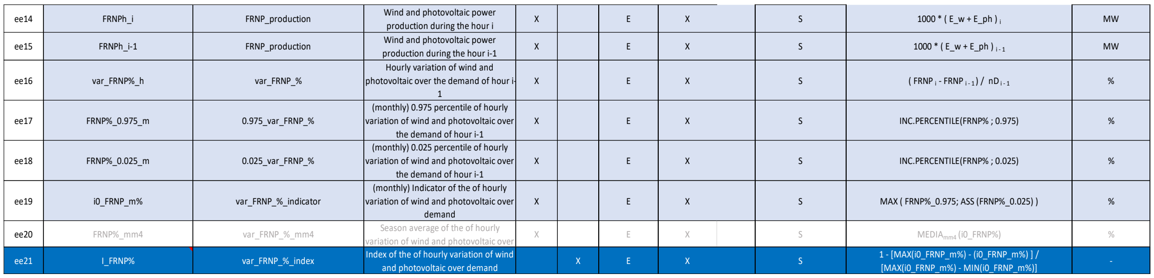
foglio produzione **SOLO FONTI INTERMITTENTI:**

2020 **RLPI – RES Load Penetration Index = Max hourly coverage of Load by RES**

o RLPI = max(W i + S i)/L i for i=1,2,3,….8760

		Var. oraria	FRNP grezzo / D. netta	FRNP corretto / D. netta+autoFV	FRNP corretto / D tot
media		*0%*	**14.4%**	**15.8%**	**14.5%**
dev.st.		*3%*	*11%*	*13%*	*12%*
max		*16%*	***61.5%***	***67.7%***	***62.1%***
min		*-15.0%*	*0.2%*	*0.3%*	*0.2%*
MAX 0.995		*11%*	***49.9%***	***55.4%***	***50.7%***
	I TRIM.				
media		*0%*	**14.0%**	**15.2%**	**13.8%**
dev.st.		*3%*	9.4%	10.6%	9.6%
media+dev.st.		*3%*	23.5%	25.8%	23.4%
max		*12%*	***48.1%***	***52.6%***	***46.3%***
min		*-12.4%*	*0.4%*	*0.4%*	*0.4%*
MAX 0.995		*0%*	42.7%	47.7%	42.4%
	II TRIM.				
media		*0%*	**19.1%**	**21.1%**	**19.2%**
dev.st.		*4%*	13.4%	15.4%	14.0%
media+dev.st.		*4%*	32.5%	36.6%	33.1%
max		*16%*	***61.5%***	***67.7%***	***62.1%***
min		*-15.0%*	*0.5%*	*0.5%*	*0.5%*
MAX 0.995		*0%*	56.7%	63.1%	57.3%

Figure 13: Example of ENEA's worksheet: Intermittent Generation Ramps Indicator (%) (Source: ENEA)



ee14	FRNPh_i	FRNP_production	Wind and photovoltaic power production during the hour i	X		E	X	S	1000 * (E_w + E_ph)$_{i}$	MW
ee15	FRNPh_i-1	FRNP_production	Wind and photovoltaic power production during the hour i-1	X		E	X	S	1000 * (E_w + E_ph)$_{i-1}$	MW
ee16	var_FRNP%_h	var_FRNP_%	Hourly variation of wind and photovoltaic over the demand of hour i-1	X		E	X	S	(FRNP$_{i}$ - FRNP$_{i-1}$) / nD$_{i-1}$	%
ee17	FRNP%_0.975_m	0.975_var_FRNP_%	(monthly) 0.975 percentile of hourly variation of wind and photovoltaic over the demand of hour i-1	X		E	X	S	INC.PERCENTILE(FRNP% ; 0.975)	%
ee18	FRNP%_0.025_m	0.025_var_FRNP_%	(monthly) 0.025 percentile of hourly variation of wind and photovoltaic over the demand of hour i-1	X		E	X	S	INC.PERCENTILE(FRNP% ; 0.025)	%
ee19	i0_FRNP_m%	var_FRNP_%_indicator	(monthly) Indicator of the of hourly variation of wind and photovoltaic over demand	X		E	X	S	MAX (FRNP%_0.975; ASS (FRNP%_0.025))	%
ee20	FRNP%_mm4	var_FRNP_%_mm4	Season average of the of hourly variation of wind and photovoltaic over	X		E	X	S	MEDIA$_{mm4}$ (i0_FRNP%)	%
ee21	I_FRNP%	var_FRNP_%_index	Index of the of hourly variation of wind and photovoltaic over demand		X	E	X	S	1 - [MAX(i0_FRNP_m%) - (i0_FRNP_m%)] / [MAX(i0_FRNP_m%) - MIN(i0_FRNP_m%)]	-

Figure 14: Example of index formalisation showing the mathematical expressions to calculate the index of Intermittent Generation Ramps (-) starting from the Hourly intermittent generation (MW).

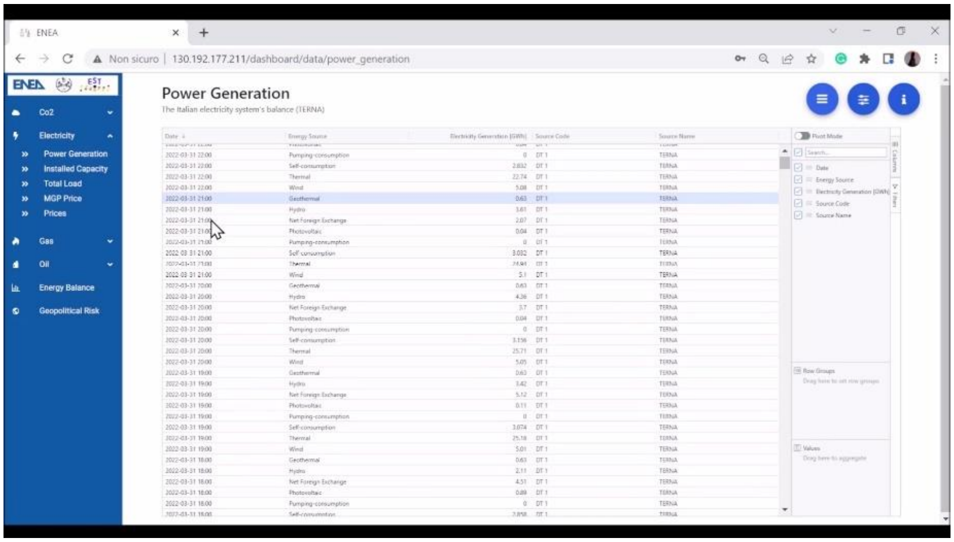


Figure 15: Data interface of the IT tool allowing for exploration of collected data, indicators and indices through interactive tables (Source: ET@IT)

Alphanumeric code for data identification

The key information included in the tables for data characterization (i.e., domain, sub-domain, data category and level of aggregation) can be summarised into the alphanumeric code. The symbology summarised in Table 6 is adopted to distinguish the information included in the prefix of the alphanumeric code: domains and sub-domains of the energy trilemma. In Table 7 are reported the symbols used to distinguish data categories and the level of aggregation of indices, composing the suffix of the alphanumeric code. The root of the alphanumeric code is composed by the ID code used in the formalisation tables. Additionally, to identify indices and indicators not comprised in the ISPRED's framework but included in the ENEA's quarterly assessment, the hash "#" at the beginning of the alphanumeric code is used.

Table 6: Alphanumeric code's prefix information: domain and sub-domain

Prefix information	Name	Symbol
Energy trilemma domains	Decarbonisation	D
	Energy Security	S
	Energy Price	P
Energy trilemma sub-domains	RES Penetration	RR
	CO2 Emission	CC
	Oil System Resilience	OR
	Refinery System Adequacy	OA
	Gas System Resilience	GSR
	Gas System Adequacy	GSA
	Gas Market Adequacy	GMA
	Electricity System Adequacy	ESA
	Electricity Market Adequacy	EMA
	Electricity System Flexibility	ESF
	Electricity Price	EP
	Gas Price	GP
	Oil Price	OP

Table 7: Alphanumeric code's suffix information: data categories and level of aggregation of index

Suffix information	Symbol
Raw data	d
Basic figure	b

Indicator	i
Simple index	I0
Aggregated index of Nth level	IN

As an example, two alphanumeric codes are reported in Table 8: they identify two indices which measure the flexibility of the electrical system, included in the domain of energy security within the electrical context, but one (Uplift index) is included in the ISPRED framework, while the other one (Intermittent Generation Ramps index) is not included in the ISPRED.

Table 8: Example of application of the alphanumeric code

Name	**Code**	**Information**		**Symbol**
Intermittent Generation Ramps Index	Prefix	Energy Trilemma domain	Security	S
	Prefix	Energy Trilemma sub-domain	Electricity System Flexibility	ESF
	Suffix	Data Category	Simple index	I0
	Root	ID code		ee21
	Prefix	Not included in the ISPRED framework		#
	Alphanumerical code	# S / ESF / _ee21_ I0 / 0		
RES In Total Final Consumption Index	Prefix	Energy Trilemma domain	Decarbonization	D
	Prefix	Energy Trilemma sub-domain	RES Penetration	RR
	Suffix	Data Category	Simple index	I0
	Root	ID code		ee132
	Prefix	Included in the ISPRED framework		
	Alphanumerical code	D / RR /_ee132_I0 / 0		

Therefore, the benefits associated with adopting the proposed alphanumeric code are:

- ✓ allowing to identify all the metrics employed in the quarterly ENEA’s assessment
- ✓ summarising key metric-specific information into a single and short string:

1) Domain and subdomain
2) Data category according to the developed formalization method
3) Hierarchical level of the index (i.e., level of aggregation)
4) Whether the metric is included in the ISPRED framework or serves as an auxiliary index to measure a specific aspect useful to better understand the evolution of the national energy transition.

Chapter 4

4 Multi-scale applications of metric-based frameworks

In this chapter, three examples of the application of metric-based frameworks are presented to study trends and identify solutions for achieving ambitious transition and decarbonization goals.

The first application, detailed in section 4.1, examines the effects of the energy transition on the European power system for 2030, 2040, and 2050. This study is based on three main scenarios defined by ENTSOE (TYNDP study [82]) to describe the European policy trajectories up to 2050. One of the innovative contributions provided by this research is the development of a methodology (section 4.1.1) to enhance the spatial resolution of the TYNDP study from a "pan-European scale" to a "single-node scale". The power network developed by Pypsa [83] is used to represent the actual electric grid, offering various degrees of resolution: 1024 buses (higher spatial resolution), 512 buses, 256 buses, 128 buses, and 37 buses (lower spatial resolution). Since higher spatial resolution results in more complex and computationally intensive operations, the choice of resolution must be tailored to the study's objectives. The ability to obtain results at a single-node scale provides greater flexibility in analysing the impacts of renewable energy penetration and the increasing electrification forecasted in European policy scenarios for 2030, 2040, and 2050; indeed, it is possible to aggregate individual nodes to perform assessment on specific areas or regions, as well as at the country level, allowing for comparative analyses among the ENTSOE countries. In addition, the proposed methodology enhances the temporal resolution of results too : from annual to hourly resolution, enabling more detailed analyses and insights on characteristic trends and patterns regarding the impacts of intermittent generation on the power grid (hourly fluctuations of residual load versus total load). Another innovative aspect is assessment of both air pollution emission (not included in the TYNDP documentation) and carbon emissions from power generation; moreover, carbon emission estimation is performed by using two different approaches (Life-Cycle and Activity-Based).

The second example of applying a metric-based framework to support policy-making focuses on evaluating the progress of the energy transition of a country based on the concept of the energy trilemma. This study, discussed in section 4.2, is part of a broader collaboration program with ENEA, which includes various activities such as reviewing the index system used in the "Analisi Trimestrale del Sistema Energetico Italiano" report to monitor the security, economic accessibility, and sustainability of the national energy system during the energy transition process. This section also encompasses new indicators developed during the research activity: dispatched inertia (power system security, section 4.2.3), Suppliers Stability Index, Shannon-Wiener Diversification Index, and Diversification & Stability of Suppliers Index (oil and gas system security, section 4.2.4), Green Electrification Rate, and Power System's Transmission Efficiency (decarbonization, section 4.2.5).

The third example of a metric-based framework focuses on the assessment of the energy transition at the urban scale. The innovative contribution of this research activity is the development of the composite index UETI (Urban Energy Transition Index), resulting from a comprehensive literature review on urban energy transition assessment methods. To enhance the credibility of the composite index, a comparative analysis with other indicators (e.g., Urban Ecosystem Index) is conducted, highlighting differences and common points in the results. Additionally, to increase transparency in the index construction, sensitivity and correlation analysis (Pearson coefficient) results are reported and discussed. To demonstrate the method's applicability, case studies for the city of Turin (Italy) and four Dutch cities (Amsterdam, Eindhoven, Rotterdam, and Utrecht) are presented, highlighting strengths and weaknesses in the transition and decarbonization process, thereby indicating areas that require more effort to align with European energy transition goals.

4.1 Metric-based scenarios analysis of the European power system

With the introduction of the European Climate Law (2021), EU-27 set the ambitious target of reducing European carbon emissions by at least 55% (compared to 1990 by 2030 and of achieving carbon neutrality by 2050. To achieve these long-term objectives, it is necessary to support informed policy decision-making with scientific evidence. Recognizing the crucial need of supporting policy makers in planning tailored strategies and in guiding investments for the development of the European electricity infrastructure, ENTSOE published the Ten-Year Network Development Plan (TYNDP) in 2020. The TYNDP, updated every two years, aims to provide a comprehensive view of the challenges and needs that such decarbonization objectives pose for the European electrical system. In fact, the FIT55 plan [17] refers to a rapid replacement of fossil-fuel generation by renewable energy sources, coupled with an enhancement in electrification of final consumption (e.g., transport, residential, and industry sectors), and in energy efficiency. However, all these actions need to respect a fundamental condition: the reliability of the European power system, i.e., the ability of the electrical system to provide the required amount of electricity to all customers continuously and in a cost-effective way, ensuring supply quality and network stability, even in the presence of disturbances due to imbalances between generation and demand.

To ensure the reliability of the European power system in the context of multi-sectoral and large-scale decarbonization processes, it is important to formulate a pan-European development plan that allows for efficient development of the power network. In support of the formulation of such a plan, the TYNDP documentation includes the System Needs Study, focused on assessing the needs of the electrical system in terms of additional capacity of electrical infrastructures, particularly cross-border capacity, storage systems, and peaking units. The System Needs Study evaluates whether and where the installation of these infrastructures is economically justified from a pan-European perspective.

It is expected that the process of electrification of final consumption, coupled with a growing population and the improvement of lifestyle quality, will inevitably lead to a significant increase in electrical demand, requiring greater electrical production. Furthermore, as a consequence of decarbonization policies, the share of renewable sources, particularly solar and wind, will increase, leading to a greater intermittent and non-programmable generation, affecting the stability of the power system. To address fluctuations in intermittent generation, it is possible to exploit storage systems that allow for the storage of energy during periods of overgeneration, avoiding interventions of renewable energy source curtailment, and releasing it when necessary.

A relevant issue addressed in the System Needs Study is the capacity of cross-border transmission lines: indeed, the higher the demand and generation, the greater the flow through the transmission lines and consequently the higher the risk of congestions. To avoid congestion issues, it is necessary to increase the cross-border lines capacity.

Therefore, to support and guide the development plan of the European electrical infrastructures, the System Needs Study offers a comprehensive evaluation of the transmission and storage capacities necessary to ensure the reliability of the future European electrical system in a cost-effective manner.

The TYNDP 2022’s document [82] presents the key findings of the study, highlighting not only the challenges and needs of the system but also the benefits of investing in the development of the European electrical system. This study discusses intervention priorities to ensure a reliable power system at the European scale, underscoring the system needs and cost of investments, as well as the opportunities and benefits that such investment can bring.

The High-level report [82], included in the TYNDP 2022’s package, is devoted to describe the conceptual framework underlying the TYNDP study and the three scenarios used to represent the main potential trajectories of European energy policies: National Trends (NT), Distributed Energy (DE), and Global Ambition (GA). The scenario-building process is an integral part of the TYNDP study, involving both ENTSOE and ENTSOG and engaging a wide range of stakeholders.

The scenarios have been defined based on three fundamental criteria:

- The scenarios must reflect the latest version of National Energy and Climate Policies (NECPs) in line with the European decarbonization goals defined in the Climate Law (2021) and the FIT55 plan.
- Renewable penetration and enhancement in energy efficiency must play a crucial role in the decarbonization process.
- The scenarios must acknowledge also the negative impacts associated with decarbonization actions, such as relying on energy imports (energy dependence issue) and the network security issues due to pushing renewable penetration to the maximum.

In line with these criteria, the National Trends scenario is derived from the latest national energy policies (e.g., National Energy and Climate Plans-NECPs, national long-term strategies, etc.) of European countries, in combination with gas and electricity datasets provided by TSOs of ENTSOE's member countries. Unlike the Distributed Energy and Global Ambition scenarios, only the 2030 and 2040 time-horizons are included in the NT scenario as data availability for the 2050 time horizon is not sufficient.

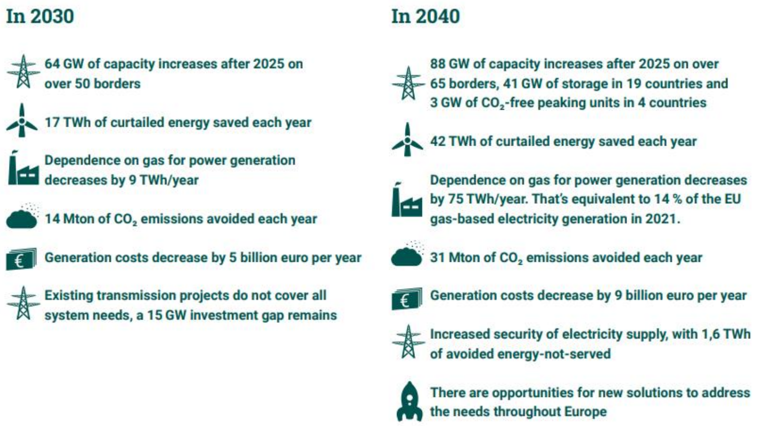
DE and GA scenarios seek to cover a wide range of possible future evolutions of European energy policies up to 2050. They share the same target (-55% carbon emission compared to 1990 by 2030 and European carbon neutrality by 2050) but they include different combinations of actions to achieve it. The main differences between GA and DE scenarios are summarised in Table 9:

Table 9: Storylines differentiation of DE and GA scenarios (Source: Elaborated data from TYNDP 2022)

	Distributed Energy scenario (DE)	Global Ambition scenario (GA)
Target	At least -55% reduction in European carbon emissions by 2030 and climate neutrality by 2050	
Energy transition driving forces (FIT55 plan's objectives)	RES penetration on the national scale by means of small-scale RES installations (distributed RES generation)	RES penetration by means of large-scale installations planned on a pan-European scale (centralized RES generation)
Energy-autonomy driving forces (REPower plan's objectives)	Maximisation of local RES deployment, coupled with smart sector integration (e.g. power to gas systems)	Maximisation of European large-scale RES deployment, supplemented with energy

		imports and generation from low carbon technologies
Power generation technologies	Decentralised technologies (e.g., PV plant, batteries, etc.) and smart charging. Minimal share of nuclear energy in power generation	Large scale centralised technologies (e.g., large-scale wind farms and storage systems). Higher share of nuclear energy in power generation
Heat generation technologies	Electric heat pumps and district heating	Hybrid heating technology
Transport technologies	Higher share of electric vehicles, supplemented with bio-fuels and e-liquids for heavy transport (e.g., aviation and maritime transport)	Higher diversification of energy carriers in transport sector, including electricity, hydrogen and biofuels
Carbon Capture and Storage (CCS) technology	Minimal CCS utilization	Higher CCS utilization

To facilitate the comprehension of TYNDP's insights, ENTSOE developed interactive tools such as online platforms allowing users to access a wide range of data and to visualize findings by means of interactive maps, tables, and charts (System Needs Platform [84]). Moreover, all TYNDP documents are characterized by effective infographics, aimed at conveying complex concepts to a wider range of audiences. For instance, Figure 16 extracted from the High-level report [16], [82] condenses the main findings of the TYNDP2022 study into a single image using a set of reference indicators for key areas of study: GW of cross-border capacity, TWh/y of avoided energy curtailment, TWh/y of decrease in gas consumption for power generation, Mton/y of avoided CO2 emissions, and G€ of decrease in generation costs.



In 2030

- 64 GW of capacity increases after 2025 on over 50 borders
- 17 TWh of curtailed energy saved each year
- Dependence on gas for power generation decreases by 9 TWh/year
- 14 Mton of CO_2 emissions avoided each year
- Generation costs decrease by 5 billion euro per year
- Existing transmission projects do not cover all system needs, a 15 GW investment gap remains

In 2040

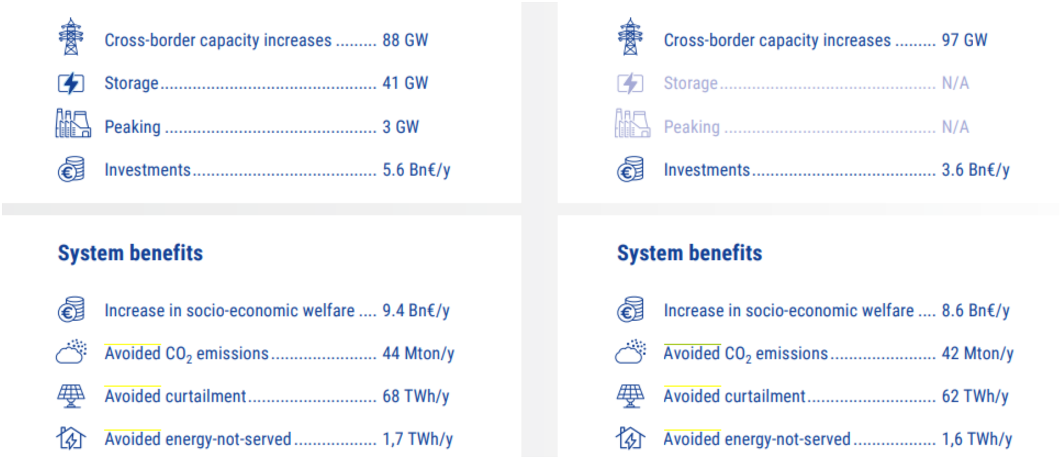
- 88 GW of capacity increases after 2025 on over 65 borders, 41 GW of storage in 19 countries and 3 GW of CO_2-free peaking units in 4 countries
- 42 TWh of curtailed energy saved each year
- Dependence on gas for power generation decreases by 75 TWh/year. That's equivalent to 14 % of the EU gas-based electricity generation in 2021.
- 31 Mton of CO_2 emissions avoided each year
- Generation costs decrease by 9 billion euro per year
- Increased security of electricity supply, with 1,6 TWh of avoided energy-not-served
- There are opportunities for new solutions to address the needs throughout Europe

Figure 16: Key findings of the TYNDP 2022 study (Source: High-Level report, TYNDP 2022)

These indicators can be classified into two main categories:

- System needs, encompassing both the additional capacity [GW] (cross-border transmission lines, peaking system, storage system) and investments [Bn€/y].
- System benefits include avoided carbon emissions [Mton/y], avoided RES curtailment [TWh/y], avoided energy-not-served [TWh/y], and an increase in socio-economic welfare [Bn€/y].

These indicators allow for comparative analysis among different solutions such as when evaluating the impacts and benefits resulting from the installation of storage systems and peaking units in addition to the increased capacity of cross-border lines. To facilitate the comprehension, the differences between the two alternative solutions are illustrated into an infographic (Figure 17) which summarizes the impacts both in economic terms (investment cost) and in technical terms (additional capacity required for cross-border lines and the additional capacity of the peaking and storage installations). Below the impact section, the beneficial effects are outlined both in economic terms (increase in socio-economic welfare) and in environmental terms (greater amount of avoided carbon emissions), as well as in energy terms (reduced RES curtailment and energy-not-served).



Cross-border capacity increases .... 88 GW
Storage .... 41 GW
Peaking .... 3 GW
Investments .... 5.6 Bn€/y

System benefits

Increase in socio-economic welfare .... 9.4 Bn€/y
Avoided CO_2 emissions .... 44 Mton/y
Avoided curtailment .... 68 TWh/y
Avoided energy-not-served .... 1,7 TWh/y

Cross-border capacity increases .... 97 GW
Storage .... N/A
Peaking .... N/A
Investments .... 3.6 Bn€/y

System benefits

Increase in socio-economic welfare .... 8.6 Bn€/y
Avoided CO_2 emissions .... 42 Mton/y
Avoided curtailment .... 62 TWh/y
Avoided energy-not-served .... 1,6 TWh/y

Figure 17: Infographics showing the main differences among two alternative solutions (Source: Opportunities for a more efficient European power system in 2030 and 2040, TYNDP 2022)

Although the TYNDP study provides reliable and detailed results on various aspects related to the impacts of energy transition on the European power network, it does not consider the effects related to the reduction of air pollution, despite these being another important factor for assessing the benefits of decarbonization on a European scale. Indeed, as outlined in the Electrify Italy report ([16]), it is estimated that every year 7.3 million deaths are attributable to air pollution, and that 91% of the world's population live in areas where air pollution exceeds the recommended limits set by the World Health Organization (WHO). Therefore, one of the aims of this work is to estimate the avoided air pollution emission from power generation according to NT, DE and GA scenarios. Additionally, the contribution of European countries to the overall European air pollutant emissions is analysed over the diverse time-horizons (2030, 2040 and 2050) and further comparative analyses are performed. Although already presented in the results of the TYNDP 2022, carbon emissions are quantified by means of two approaches for the estimation of equivalent CO2 emissions, namely the Activity-Based approach (AB) and the Life-Cycle approach (LCA). Furthermore, a specific section of this study is devoted to evaluating the impacts of the growth of intermittent renewable generation in the European power generation mix. The focus is on the unpredictable variability (i.e., ramps) in power generation due to penetration of intermitted RES, causing instability issues in the power network. To conduct such an assessment, an hourly generation profile is necessary, which is not available in the TYNDP2022 datasets. Additionally, employing the total generation for each country provided in the TYNDP 2022 is inadequate for a detailed assessment of ramp intensity. Consequently, to examine the influence of the growing intermittent generation in electricity system security, it becomes imperative to derive disaggregated hourly generation profiles for individual generation nodes. Therefore, method has been developed to derive disaggregated hourly generation profiles for individual nodes from the TYNDP annual generation by country.

4.1.1 Procedure for Building Hourly Generation Profiles by Node

Generation profiles disaggregated by hour and node are obtained starting from the annual and country-level data collected from TYNDP 2022, combined with PyPSA "Python for Power System Analysis" [83]. PyPSA provides high voltage AC lines (>220kV), covering 33 countries in the European region, as well as hourly generation profiles categorized by technology type disaggregated by node.

The input data necessary to build the generation profiles are summarised below:

ENTSOE-TYNDP data

- 3 scenarios: National Trends (NT), Distributed Energy (DE), Global Ambition (GA)
- 3 time-horizons per each scenario: 2025, 2030, 2040 for NT and 2030, 2040, 2050 both for DE and GA
- 9 combinations of scenario and time-horizon: NT2025, NT2030, NT2040, DE2030, DE2040, DE2050, GA2030, GA2040, GA2050
- Temporal resolution: annual resolution for generation [GWh] and hourly generation for load [MW]
- Spatial resolution: generation and load per country
- Annual Generation: disaggregated per country and per energy carrier (bioenergy', 'coal', 'gas', 'hydro', 'nuclear', 'oil', 'geothermal', 'solar', 'wind')
- Hourly Load: disaggregated per country
- Spatial coverage: all ENTSOE's members (47 countries: 'AL', 'AT', 'BA', 'BE', 'BG', 'CH', 'CY', 'CZ', 'DE', 'DK', 'DZ', 'EE', 'EG', 'ES', 'FI', 'FR', 'GB', 'GR', 'HR', 'HU', 'IE', 'IL', 'IS', 'IT', 'LT', 'LU', 'LV', 'LY', 'MA', 'MD', 'ME', 'MK', 'MT', 'NL', 'NO', 'NS', 'PL', 'PS', 'PT', 'RO', 'RS', 'SE', 'SI', 'SK', 'TN', 'TR', 'UA')

PyPsa data

- Spatial resolution: it is possible to choose among various level of clustered network: 1024 bus, 512 bus, 256 bus, 128 bus, 37 bus.
- Temporal resolution: hourly generation (MW) by node and by type of technology, hourly load by node (MW)
- Generation technology: 11 generation technologies (Biofuels, Coal & Lignite, Gas, Hydro, Nuclear, Oil, Other Non RES, Other RES, Solar, Wind Offshore, Wind Onshore)

- Spatial coverage: 33 countries in the European area (AL', 'AT', 'BA', 'BE', 'BG', 'CH', 'CZ', 'DE', 'DK', 'EE', 'ES', 'FI', 'FR', 'GB', 'GR', 'HR', 'HU', 'IE', 'IT', 'LT', 'LU', 'LV', 'ME', 'MK', 'NL', 'NO', 'PL', 'PT', 'RO', 'RS', 'SE', 'SI', 'SK')

For the purpose of this study, it is sufficient to use an intermediate spatial resolution: the simplified network composed by 256 nodes has been selected (Figure 18).

Figure 18: Simplified European network composed by 256 nodes (Source: PyPsa)

Calculation of spatial share and time shares to split annual generation by country

Since in PyPSA the generation is disaggregated by type of technology (11 technologies), whereas ENTSOE-TYNDP generation is disaggregated based on the type of energy carrier (9 carriers), it is necessary to intervene to align the PyPSA generation with the TYNDP generation. The procedure is as follows:

- STEP 1: grouping ENTSOE and PyPsa technologies into common energy carriers (9): wind, solar, nuclear, oil, gas, coal, hydro, biomass, other RES.
- STEP 2: estimation of the hourly PyPSA generation. Pypsa provides the hourly p_max_pu for intermittent generation from wind, solar and run-of-river hydro which is used to obtain

their hourly profile by multiplying it with the nominal power disaggregated by node available in the PyPsa's database as shown in the examples below:

$$P_{w,h,i} = p_{max_{pu_{w,h}}} \cdot p_{nom\,\max,w,i} \quad [MW]$$

$$P_{s,h,i} = p_{max_{pu_{s,h}}} \cdot p_{nom,\max s,i} \quad [MW]$$

Since the hourly profile of p_max_pu is not available for all non-intermittent generation (e.g. gas, oil, coal, etc.) and it is set equal to 1 by default by PyPsa, therefore an approximation is employed to obtain the temporal shares: the Average Loading Factor (Figure 19) provided by ENTSOE in RoCoF report [85] is used instead to 1 in the product with the nominal power of the single node:

$$P_{g,h,i} = cost = LF_g \cdot p_{nom,g,i} \quad [MW]$$

Once completed the procedure, the hourly profile of power generation by node and by commodity is available for the next steps:

- Output 1 of the Python code: pypsa_generation_256_nodes.csv

- STEP 3: estimation of the temporal shares to allocate over time the annual TYNDP generation with an hourly time resolution. The hourly share is obtained for each node by diving the power generation at a given hour over the annual generation for the intermittent renewables:

$$s_{w,h,i} = \frac{P_{w,h,i}}{\sum_{h=1}^{8760} P_{w,h,i}} \quad [-]$$

$$s_{s,h,i} = \frac{P_{s,h,i}}{\sum_{h=1}^{8760} P_{s,h,i}} \quad [-]$$

$$s_{r,h,i} = \frac{P_{r,h,i}}{\sum_{h=1}^{8760} P_{r,h,i}} \quad [-]$$

Where:

  - $P_{s,h,i}$ is the solar power generation at the hour h in the node i
  - $P_{w,h,i}$ is the wind power generation at the hour h in the node i
  - $P_{r,h,i}$ is the hydro (ror) power generation at the hour h in the node i
  - $\sum_{h=1}^{8760} P_{s,h,i}$, $\sum_{h=1}^{8760} P_{w,h,i}$ and $\sum_{h=1}^{8760} P_{r,h,i}$ are the annual solar, wind and hydro (ror) generations ($H = 8760$) in the node i

The hourly share of the other commodities (e.g., gas, oil, coal) is approximated as shown in the example below:

$$s_{g,h,i} = cost = \frac{P_{g,h,i}}{8760} \quad [-]$$

The final result of this step is:

- Output 2 of the python code: Generation_time_shares.csv (TYNDP Load is already available with hourly resolution)

- STEP 4: estimation of the spatial shares to allocate the TYNDP data (country-scale spatial resolution) to the PyPsa nodes (node-scale spatial resolution). The generation spatial share by commodity *j* and by node is calculated by dividing the annual generation of commodity *j* in node *i* with the annual generation of commodity *j* in the country *k* the node belongs to.

$$\frac{\sum_{h=1}^{8760} P_{j,h,i}}{\sum_{h=1}^{8760} \sum_{i \in k} P_{j,h,i}} = \frac{P_{j,i_y}}{\sum_{i \in k} P_{j,i_y}}$$

Where:

- P_{j,i_y} represents the sum of the hourly generation over a year in node *i* by commodity *j*
- $\sum_{i \in k} P_{j,i_y}$ represents the yearly generation by commodity *j* of the country *k* which includes the node *i*

The same approach is adopted to calculate the load spatial share for allocating the TYNDP load disaggregated by country to the 256 PyPsa nodes.

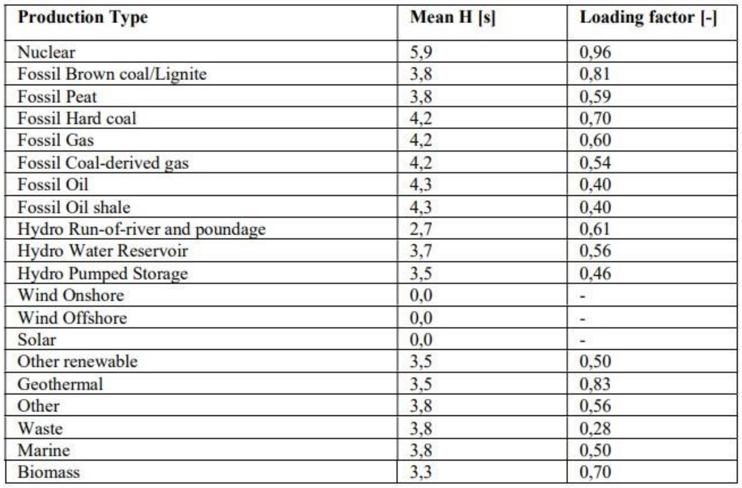
$$\frac{\sum_{h=1}^{8760} L_{h,i}}{\sum_{h=1}^{8760} \sum_{i \in k} L_{h,i}} = \frac{L_{i_y}}{\sum_{i \in k} L_{i_y}}$$

Where:

- L_{i_y} represents the sum of the hourly load over a year in node *i*
- $\sum_{i \in k} L_{i_y}$ represents the yearly load of the country *k* which includes the node *i*

After completed the step 4, the spatial shares of both generation and load are ready to be used to split into nodes the country-scale TYNDP data

  - Output 3 of python code: Generation_spatial_shares.csv
  - Output 4 of python code: Load_spatial shares.csv



Production Type	Mean H [s]	Loading factor [-]
Nuclear	5,9	0,96
Fossil Brown coal/Lignite	3,8	0,81
Fossil Peat	3,8	0,59
Fossil Hard coal	4,2	0,70
Fossil Gas	4,2	0,60
Fossil Coal-derived gas	4,2	0,54
Fossil Oil	4,3	0,40
Fossil Oil shale	4,3	0,40
Hydro Run-of-river and poundage	2,7	0,61
Hydro Water Reservoir	3,7	0,56
Hydro Pumped Storage	3,5	0,46
Wind Onshore	0,0	-
Wind Offshore	0,0	-
Solar	0,0	-
Other renewable	3,5	0,50
Geothermal	3,5	0,83
Other	3,8	0,56
Waste	3,8	0,28
Marine	3,8	0,50
Biomass	3,3	0,70

Figure 19: Average Loading Factor and Inertia Level by commodity (Source: ROCOF report by ENTSOE)

Splitting annual generation over 256 nodes and 8760 hours and hourly load over 256 nodes

- STEP 5: allocate the TYNDP generation by country and by year to 256 nodes (selected simplified PyPsa network) and over time (8760 hours):
  - Output 5 of python code: hourly_nodes_generation.csv (one csv file for each of the 9 scenarios: NT2025, NT2030, NT2040, DE2030, DE2040, DE2050, GA2030, GA2040, GA2050)

- STEP 6: allocate the hourly ENTSOE load to 256 nodes:
  - Output 6 of python code: hourly_nodes_load.csv (one csv file for each of the 9 scenarios: NT2025, NT2030, NT2040, DE2030, DE2040, DE2050, GA2030, GA2040, GA2050)

Data adjustment before power flow simulation

Since a simplified PyPSA networks composed by 256 nodes is adopted, in power flow calculations outliers are commonly observed at reference nodes, therefore it is necessary data adjustment (STEP 7) before performing the power flow simulation through PyPsa. The adjustment procedure [86] involves the following intermediary steps:

- STEP 7a: the power flow is tested over several hours to identify nodes exhibiting abnormal values in the results;
- STEP 7b: the input values of these nodes are incrementally adjusted;
- STEP 7c: for each adjustment the effect on the surrounding nodes' power flow results is observed.

Through multiple iterations, the extensive network is segmented into relatively independent areas. In conjunction with line parameters, a balance between supply and demand is achieved within each distinct region.

- Output 7 of python code: adjusted generation .csv

Running Power flow simulation through PyPSa

Once configurated input data (generation and load disaggregated by node and by hours) and once completed the adjustment procedure, the power flow simulation (STEP 8) is performed. The outputs of the power flow simulation are listed below:

- PyPsa's output 1: load by node, by hour
- PyPsa's output 2: generation by carrier, by node, by hour
- PyPsa's output 3: congestions in lines

The hourly profile of load by node and of generation by node and energy source are used to perform further analyses discussed in following section (sections 4.1.2, 4.1.3, and 4.1.4) on the impacts and the benefits brought by the increase in power generation from intermittent renewable sources at the European scale.

4.1.2 Effects of increasing intermittent renewable generation in the power system security

In order to achieve a reduction in emissions of -55% compared to 1990 by 2030 and to reach European carbon neutrality by 2050, as defined in the European FIT55 plan [17], a significant increase in the share of renewable energy within the European energy mix is imperative. This transition poses challenges for the electricity generation sector, particularly regarding the integration of photovoltaic (PV) and wind power, due to their non-programmable and intermittent nature which hinder the stability of the power network and the overall security of the power system. Power system security is a general concept, and various definitions are available in literature. For instance, ENTSOE, incorporates the concept of security within the broader concept of the reliability of the electrical system [87]. Reliability, which represents the system's ability to supply electricity in required quantities while maintaining acceptable standards of supply quality, includes two fundamental aspects: system adequacy and system security. The system adequacy refers to the ability of the grid to meet electricity demand under standard operating conditions, while the system security relates to maintaining system reliability under abnormal, sudden, and unexpected circumstances. Non-predictable and intermittent renewable generation can cause sudden grid imbalances that require prompt corrective actions to ensure system reliability. These generation-side imbalances can indeed cause disturbances that alter the standard frequency and voltage parameters of the power grid; moreover, unexpected and intense peaks in renewable generation can lead to extreme over-generation (power system security issue): in this case, decreasing the production of programmable power plants is not sufficient to balance the network, therefore it is necessary to intervene by storing excess energy through storage systems. In some cases, storing systems cannot cover all the exceeding electricity and curtailment of renewable generation (RES curtailment) is the only solution.

As the intermittent renewable generation is expected to sharply increase in all European countries to meet the decarbonization targets of FIT55 plan [17], the issue of electricity security is going to assume even more relevance in the next years. For this reason, the impacts of intermittent renewable penetration in power system security have been further investigated in this study. The TYNDP 2022 [34] scenarios (i.e., National Trends, Distributed Energy and Global Ambition) and time-horizons (i.e., 2025, 2030, 2040 and 2050) are used as reference for generation and load. To perform the study, the hourly generation and load profiles are required. Since the available TYNDP data are provided with annual resolution and by country, the procedure described in section 4.1.1 has been adopted to obtain load and generation (per type of energy carrier) disaggregated by hour and by node. The selected indicator to investigate the effects of increasing intermittent renewable generation in NT, DE, and GA scenarios, is the Hourly Residual Load, intended as the amount of load covered by intermittent renewable

(RES_{int}) over time. It can be used to monitor and measure the intensity of variations in power generation (i.e., ramps) due to RES's intermittence, over time (i.e., hourly resolution). The Hourly Residual Load is obtained by the difference between the total load and the intermittent renewable at a given hour.

Since the generation and load hourly profiles have been allocated to the 256 PyPsa nodes, it is possible to assess the Hourly Residual Load per each node.

$$RL\ (t) = \ L\ (t) - \ P_{int}(t) \quad [MW]$$

Since the TYNDP's generation data do not distinguish between types of hydroelectric power plants (e.g., conventional hydroelectric plants, run-of-river plants, pumped storage plants) it is not possible to precisely define the amount of intermittent generation provided by the run-of-river hydroelectric plants (ror). Therefore, considering that the ror contribution is less significant compared to the conventional hydro generation, as well as compared to wind (w) and photovoltaic (s) generation, hourly intermittent generation is estimated as the sum of the wind (including onshore and offshore) and photovoltaic generation:

$$P_{int}(t) = \ P_s(t) + \ P_w(t) \quad [MW]$$

The residual load changes over time and is therefore computed by subtracting the total load with the intermittent power generation at a given time. It corresponds to the amount of remaining load that must be covered by dispatchable generation units (e.g., conventional thermal plants and nuclear plants).

The hourly residual load can be used to detect whether ramps in intermittent generation leads to issues on the power system security: for instance, when the hourly residual load is lower than technical minimum of conventional plants, prompts intervention (e.g., storage of exceeding electricity and RES curtailment in extreme cases) are necessary, affecting the reliability of the network and electricity supply.

An additional insightful metric for evaluating power grid stability issues resulting from intermittent generation is the hourly fluctuation of the residual load. This fluctuation is determined by comparing the absolute load of the h-th hour with that of the previous hour. Greater fluctuations are indicative of a higher likelihood of induced disturbances in the power system.

$$\Delta_{RL,h} = \ RL_h - \ RL_{h-1} \quad [MW]$$

Where:

- RL_h is the Residual Load in hour h [MW]

- RL_{h-1} is the Residual Load in hour $h-1$ [MW]

Since the absolute value of this variation alone does not provide a comprehensive impact assessment, the hourly fluctuation of the residual load is normalized by dividing it by the load in the h-th hour:

$$\Delta_{RL,h_n} = \frac{\Delta_{RL,h}}{L_h} \quad [-]$$

The normalized indicator is more effective for capturing the extent of hourly fluctuation relatively to the load in the node; in this way, it is more evident whether the disturbances will be balanced with minimal effort or if they can cause major disturbances in node stability requiring further interventions. to distinguish between minor disturbances and major disturbances a threshold value equal to 10% of the load is considered accordingly with ENEA's methodology [54] adopted to evaluate the adequacy of Italian power grid. This methodology entails counting the hours over the year in which the limit of 10% of the hourly load is exceeded and deriving the percentage of annual hours exceeding the threshold.

A similar approach was adopted, extending the assessment to 33 countries and refining the spatial resolution from the country-scale to the node-scale. Moreover, a wider range of thresholds were included (10%, 20%, and 30% of the hourly load) to compare the extent of intermittent RES impacts in power system security among the nine TYNDP 2022 scenarios. The mathematical definition of hours exceeding the threshold is the following:

$$h_l = \sum_{i}^{N} \mathbb{I}\left(\Delta_{RL,h_n} > l\right) \quad [-]$$

$$h_{l,n} = \frac{h_l}{8760} \quad [-]$$

$$h_{l\%} = h_{l,n} \cdot 100 \quad [\%]$$

Where:

- l is the threshold defined to assess the hourly variation of residual load compared to the hourly load ($l = 10\%, 20\%, 30\%$)
- N is the number of hours in a year, corresponding to 8760.
- $\mathbb{I}$ is the indicator function, returning 1 if its argument is true, otherwise returning 0.
- h_l is the number of hours in a year that satisfy the condition defined by the indicator function.
- $h_{l,n}$ is the number of hours in a year that satisfy the condition normalized by the total number of hours in a year.

- $h_{l\%}$ is the percentage of annual hours exceeding the threshold l

4.1.2.1 Node-scale Assessment of intermittent RES generation impacts

Due to the extensive number of data considered in the analysis (256 nodes and 9 scenarios), the top 50 $h_{l\%}$ values were filtered and plotted on a bar chart, aiding in the interpretation of results across all nodes and scenarios and facilitating the detection of nodes experiencing the greatest impact from renewable generation intermittency and the identification of scenarios where the threshold is most frequently surpassed. Three bar charts showing the output obtained by using different thresholds, namely 10%, 20% and 30% of the hourly load, are illustrated in Figure 20, Figure 21, and Figure 22 respectively.

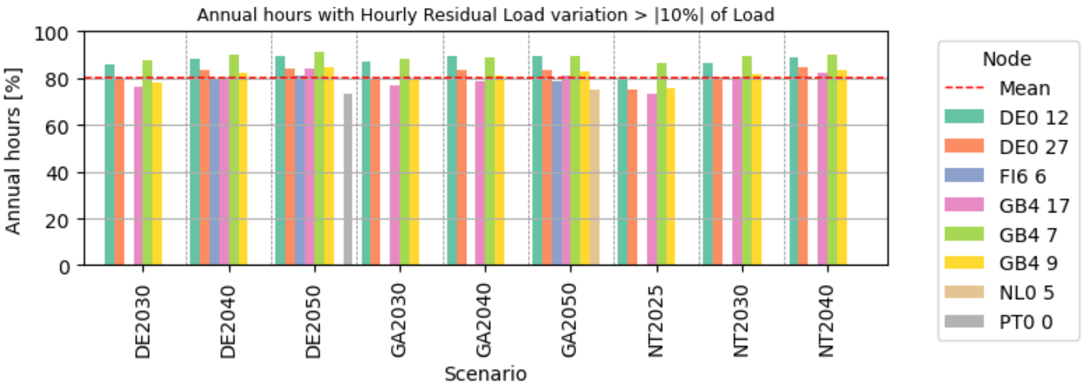


Figure 20: Nodes with the highest share of hours exceeding the threshold 10% of Hourly Load

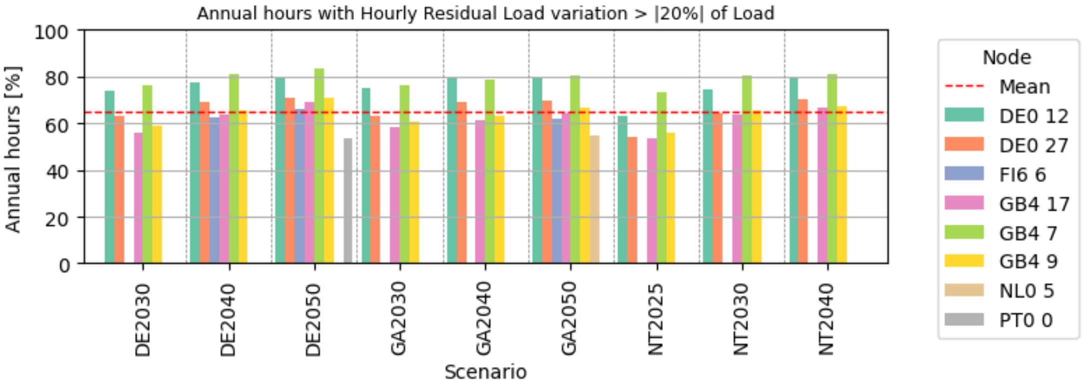


Figure 21: Nodes with the highest share of hours exceeding the threshold 20% of Hourly Load

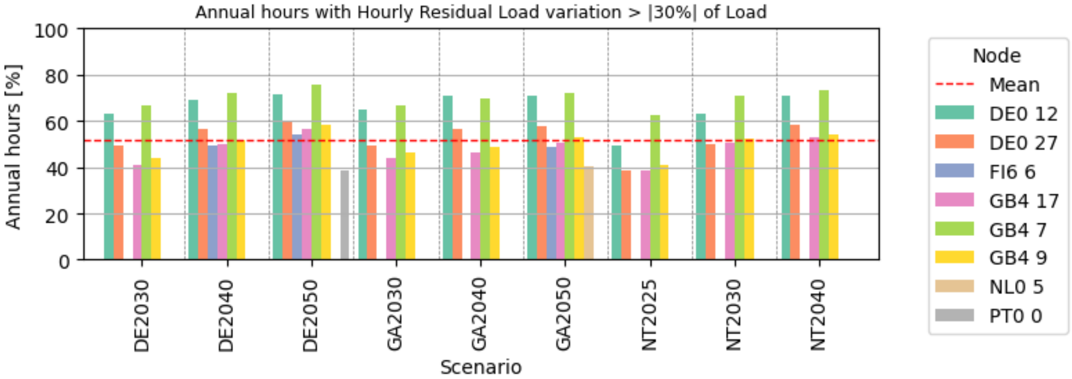


Figure 22: Nodes with the highest share of hours exceeding the threshold 30% of Hourly Load

Upon examining the outcomes of the analysis conducted with a 10% threshold (Figure 20), it becomes evident that scenarios DE2050 and GA2050 exhibit a greater number of nodes included in the top fifty $h_{l\%}$ values. This finding is justified by the projected reliance on intermittent renewable sources (specifically, solar and wind) in both DE2050 and GA2050 scenarios, which is expected to intensify both the magnitude and the frequency of threshold exceedance. These observations are further supported by charts referring to 20% threshold in Figure 21 and to 30% threshold in Figure 22.

It is evident that, as the threshold value is increased, the proportion of annual hours exhibiting exceedance decreases and the mean value represented by the dashed red line across all the three bar charts outlines this evidence: in the first graph (threshold = 10%) the mean percentage of exceedance hours approximates 81%, declining to 65% in the second graph (threshold = 20%), and further to 52% in the last graph (threshold = 30%). Furthermore, by examining the nodes illustrated in the graphs, it is possible to identify those most susceptible to surpassing the threshold. Notably, nodes GB4 and DE0 demonstrate recurrent threshold exceedance across all nine scenarios, while nodes NL0, PT0, and FI6 just in specific scenarios: for instance, FI6 node appears in scenarios DE2040, DE2050, and GA2050, node PT0 emerges solely in scenario DE2050, and node NL0 exclusively in scenario GA2050.

In addition, to gain deeper insights on the impacts of different generation mix configurations across various scenarios, a further study has been focused on Germany (nodes DE) and the United Kingdom (nodes GB), as DE nodes and GB nodes exhibit the highest percentage of hours exceeding the limit. The configuration of generation mix of these countries are then compared with France (FR), the second-largest electricity producer in Europe (IEA [88], 2022), which shows a notable disparity in the percentage of hours exceeding the limit between the NT scenarios and the GA and DE scenarios.

Figure 23 illustrates the annual generation mix of Germany by energy carrier type across all nine scenarios. This configuration results quite similar to that of the United Kingdom (Figure 24). A significant distinction between them is the wind share in the power generation mix; this is the key insight which justifies the reason why Germany and United Kingdom have so frequent exceedances over the year compared to France. Conversely, France's power generation deeply relies on nuclear energy, accounting for almost 60% of total electricity generation in the NT2025 scenario. Nevertheless, as policies encourage the adoption of solar and photovoltaic energy, consequently reducing the proportion of dispatchable generation provided by nuclear power, there is a discernible decline in nuclear power generation across all scenarios post-2025. This observation justifies the notable increase in the percentage of hours exceeding the limit depicted in Figure 26. Consequently, while such policies allow to diminish the reliance on fossil fuel consumption, favouring countries still dependent on fossil source imported abroad, while reducing CO2 and air pollutant emissions (see section 4.1.3), on the other hand, intermittent renewable generation poses serious challenges for the security of the future European power network, also disfavouring countries like France, which are already energy-independent and produce low-carbon electricity by means of advanced nuclear plants.

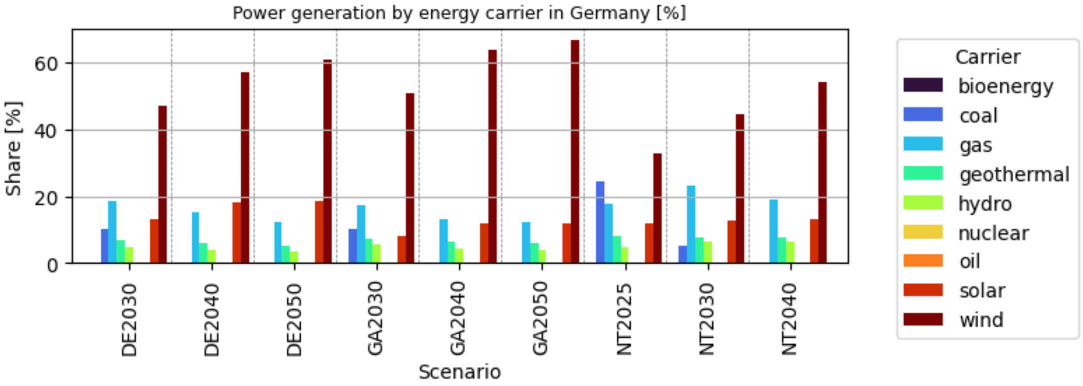


Figure 23: Configuration of power generation by energy carrier in Germany

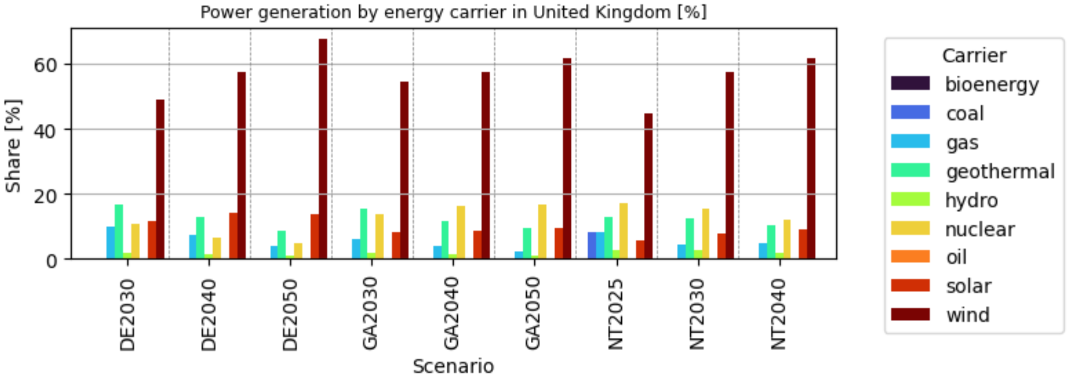


Figure 24: Configuration of power generation by energy carrier in United Kingdom

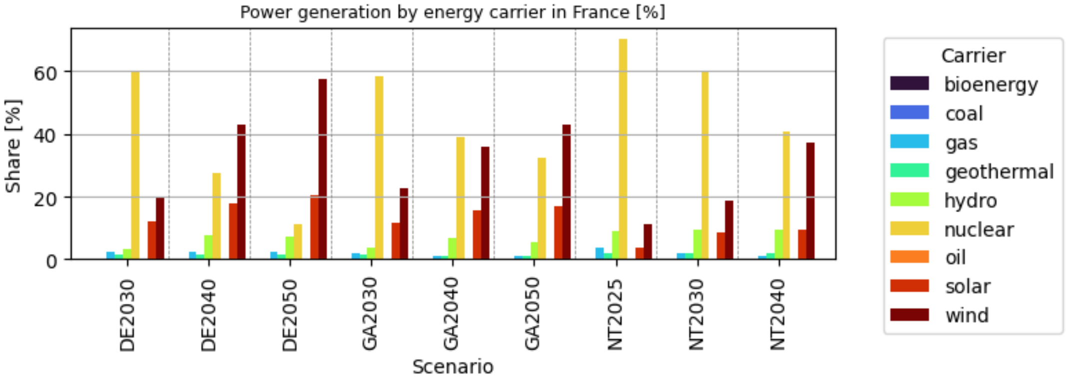


Figure 25: Configuration of power generation by energy carrier in France

These findings underscore that the heightened integration of intermittent renewables into the generation mix amplifies the incidence of nodes experiencing frequent, pronounced hourly fluctuations in residual load (e.g., FI6 in scenario DE2040). Nonetheless, this granular node-level analysis does not allow for general conclusions; hence, the analysis was extended to the country level.

4.1.2.2 Country-scale Assessment of intermittent RES generation impacts

To extend the impact assessment to the country-scale, the average of $h_{l\%}$ is computed by considering all nodes per country. In this comparative analysis among countries and scenarios, only the 10% threshold is considered more significative when dealing with average values. Figure 26 presents the outcome of the analysis on annual hours exceeding the 10% threshold at the country-scale, encompassing 33 European countries.

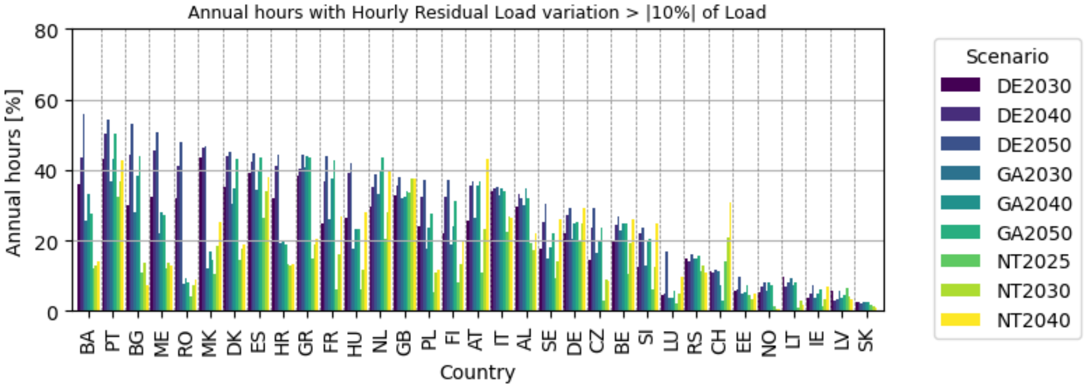


Figure 26: Average of annual hours exceeding the 10% threshold by country and by scenario

As shown in Figure 26 the countries with highest percentage of hours exceeding the 10% threshold are the following: Bosnia and Herzegovina, Portugal, Bulgaria, Montenegro, Romania, North Macedonia, and Denmark (BA, PT, BG, ME, RO, MK, DK). A further analysis on these countries revealed that all of them belong to the category of countries with the lowest number of node (highlighted in bold in Table 10), as a result of using the average value per country.

Table 10: Number of nodes by country

Number of nodes by country	**Country code**
>25 nodes	FR,DE
11-25 nodes	IT,GB,ES,PL,SE
5-10 nodes	NO,NL,FI,BE,CZ,AT
<5 nodes	**RO**,CH,GR,**PT**,RS,**BG**,HU,SK,IE,**DK**,LV,**ME**,**MK**,LU,LT,HR,EE,**BA**,SI,AL

As outlined by the following mathematical expression, the average score plotted in the bar chart is inversely proportional to the number of nodes belonging to the country, justifying why countries with less nodes show higher values in Figure 26:

$$\bar{h}_{l\%,k} = \frac{\sum_i hl\%,i}{N_k}$$

Where:

- $\bar{h}_{l\%,k}$ is the average of exceeding hours percentage for country k
- $hl\%,i$ is the percentage of exceeding hours for node i
- N_k is the total number of nodes belonging to country k

Despite it represent the average of annual hours in which the hourly residual load over the load exceeds the 10% threshold, this metric allows to evaluate simultaneously and compare all the scenarios in a single chart, unlike in the previously analysis (node-scale). By observing the colours and height of bars it is possible to better understand which scenario presents, overall, more exceeding hours over the year. Therefore, the country-scale $\bar{h}_{l\%,k}$ makes evident what was challenging to grasp in the node-scale analysis: the highest peaks of exceeding frequency correspond to the DE and GA scenarios, evidencing the impact of intermittent generation increase in the national power system.

4.1.3 Assessment of air pollutants emissions by scenario and by country

To estimate the quantity of air pollution by pollutant type for each ENTSOE scenario, the EMEP/EEA methodology [89] has been adopted. Pollutant emissions are determined by the product of electricity generation per type of fuel (provided by ENTSOE for all scenarios) and fuel-specific emission factors provided by EMEP/EEA. The assessment is conducted on country scale ad with annual temporal resolution with the goal to estimate the air pollutants emitted by each country in each ENSTOE scenario. The objective of the study does not require to trace the hourly profile and the generation spatial distribution (i.e., nodes) derived from PyPSA, therefore the assessment can be extended to all the ENTSOE countries, not limited only to the 33 countries included in PyPSA.

According to the EMEP/EEA's methodology, the amount of pollutant emissions produced by electricity generation from non-combustible renewables such as wind, hydro, and solar, is assumed negligible. The EMEP/EEA proposes two approaches to quantify air pollutants emissions: Tier 1, which utilizes fuel-specific emission factors, and Tier 2, which instead employs technology-specific emission factors.

According to Tier 1, the emissions of y-th pollutant (EM_y) are calculated by the product between the j-th fuel consumption (C_j) and the fuel-specific emission factor ($EF_{j,y}$):

$$EM_y = C_j \cdot EF_{j,y}$$

Where:

- C_j is the consumption of fuel j
- $EF_{j,y}$ is the emission factor of pollutant y for fuel j

Tier 2 approach, unlike Tier 1, requires not only the fuel consumption but also the specific technology g employed to generate electricity such as dry bottom boiler, wet bottom boiler, fluid bed boiler, gas turbine, and stationary engine. Therefore, the emission of i-th pollutant is obtained by multiplying the fuel consumption (disaggregated by fuel and technology) with the fuel-specific and technology-specific emission factor.

$$EM_y = \sum_g C_{j,g} \cdot EF_{g,y}$$

Where:

- $C_{j,g}$ is the consumption of fuel j by using the specific technology g
- $EF_{g,y}$ is the emission factor of pollutant y for the specific technology g

Default emission factors (g/GJ) are provided by EMEP/EEA as reference values for the main fuels (Tier 1 emission factors in Table 11) and technologies (Tier 2 emission factors in Table 12) employed for electricity generation (non-combustible energy source such as wind, solar and nuclear are excluded.

The EMEP/EEA's Guidebook 2023 includes specific guidelines for the assessment of pollutant emissions in energy industries [90]. The section 'Public electricity and heat production' of the EMEP/EEA 2023 Guidebook provides further details and instructions on estimating pollutant emissions from the power sector. This document outlines the main pollutants emitted by power plants:

- Sulphur oxides, SOx, directly related to the sulphur content of the combusted fuel: the sulphur content of refined natural gas is negligible whereas certain qualities of oil, called 'sour' oil, are characterised by higher sulphur content (> 0.5%). Typically, SOx emissions refer to sulphur dioxide (SO2) but also small amount of sulphur trioxide (SO3) may be emitted.
- Nitrogen oxides, NOx, is more present in the combustion of solid and liquid fuels rather than gaseous fuels.
- Non-methane volatile organic compounds (NMVOC) emission results from incomplete combustion
- Carbon monoxide (CO) emission occurs under sub-stoichiometric combustion condition as an intermediate product of fossil combustion. Compared to CO2 emission, CO emissions are less relevant.
- Particulate matter (PM) emissions results from combustion of solid fuels; in terms of emission per unit of energy, smaller plants emit more than large power plants (>50 MW). Fuels with high ash content such as coal, have higher potential of PM emission. Two main categories of PM can be distinguished: primary PM and secondary PM. The first is the fraction of solid residue (ash) which remains suspended in exhaust gases beyond the abatement equipment and passes to the atmosphere; the secondary PM is formed by chemical and physical processes occurring after the discharge in atmosphere. The EMEP/EEA guidebook includes only the primary PM. To measure the emission factors of fuels, PM10 and PM2.5 are the most widely used indicators.

Table 11: Default emission factors by type of fuel - Tier 1 approach (Source: EMEP/EEA, 2019)

Unit [g/GJ]	**AIR POLLUTANTS**					
Fuel	**CO**	**NMVOC**	**NOx**	**PM10**	**PM2.5**	**SOx**
Biogas	156.0	10.0	198.0			10.8
Biomass	90.0	7.3	81.0	155.0	133.0	10.8

Brown Coal	8.7	1.4	247.0	7.9	3.2	1,680.0
Light oil	16.2	0.8	65.0	3.2	0.8	46.5
Hard Coal	8.7	1.0	209.0	7.7	3.4	820.0
Heavy Fuel Oil	15.1	2.3	142.0	25.2	19.3	495.0
Natural gas	39.3	2.6	89.0	0.9	0.9	0.3

Since the available data on electricity generation is disaggregated by type of fuel, not by type of technology, Tier 1 approach has been adopted. Figure 27 summarises the configuration of power generation by carrier for each ENSTOE scenario.

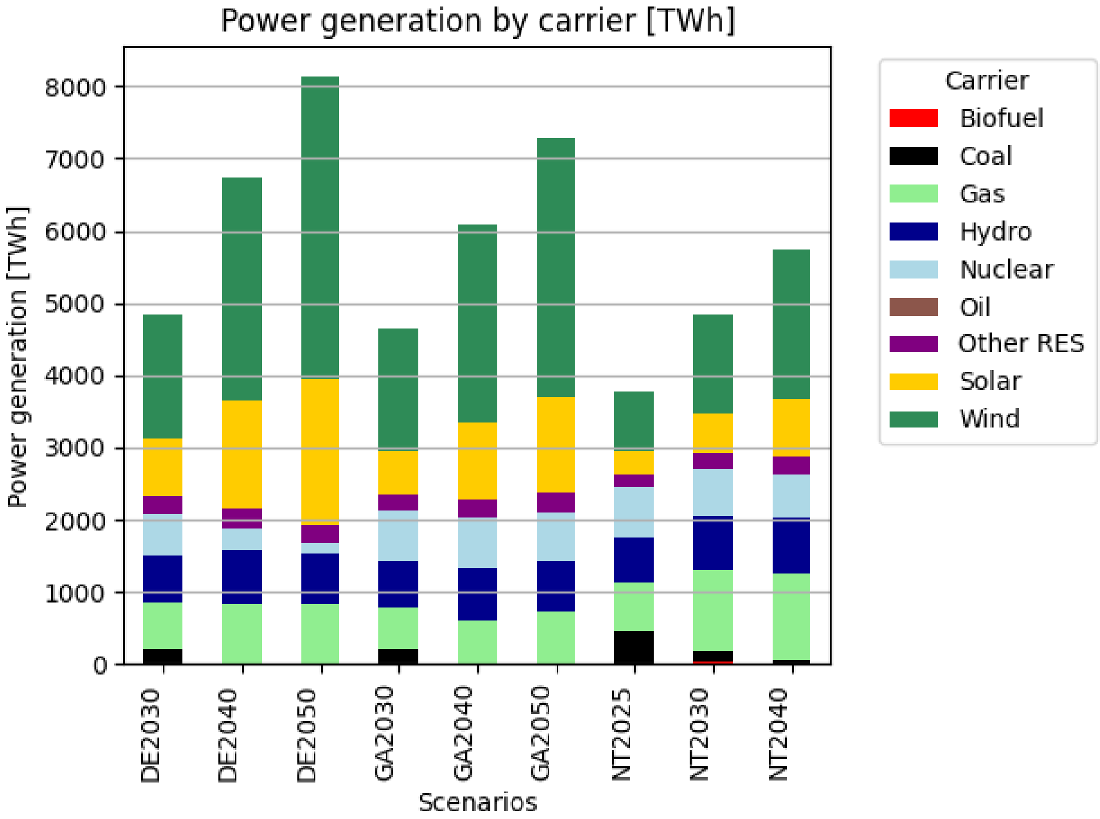


Figure 27: Power generation by carrier of ENSTOE's scenarios (Source: Elaborated data from TYNDP 2022)

The graph in Figure 27 outlines in all scenarios the progressive reduction of power generation from coal and a sharp increase in solar and wind generation. While the contributions from oil and biofuel show minimal variation, nuclear generation differs significantly across scenarios.

In NT and GA scenarios, nuclear generation remains relatively constant, whereas it is expected to decrease significantly in DE scenarios. Natural gas and hydro power generation are expected to remain relatively constant in absolute terms, but the rise in solar and wind generation are projected to account for the majority of total electricity generation.

To evaluate the effect in terms of pollutant emissions of different energy mix configurations, the EMEP/EEA Tier 1 methodology has been adopted. The first step consists of estimating the amount of fuel consumed (C_j) to produce a certain amount of electricity (G_j). The following expression represents the mathematical definition of fuel consumption by type of fuel:

$$C_j = \frac{G_j}{\eta_j} \cdot f \quad [GJ]$$

Where:

- G_j is the electricity produced by using the fuel j [GWh]
- η_j is the efficiency of electricity generation from fuel j [-]
- $f = 3.6 \cdot 10^3$ is the conversion factor from GWh to GJ (Table 12)

Table 12: Default average efficiency of power station by type of fuel (Source: EMEP/EEA, 2019)

Fuel	**Default efficiency value η_j**
Coal	0.33
Natural gas	0.49
Heavy Fuel Oil	0.40
Disel	0.35
Biomass	0.80

As the generation data are provided by country, it is possible to estimate the pollutant emissions of power generation in each ENSTOE country. The formulation results equal to:

$$EM_{y,k} = C_{j,k} \cdot EF_{j,y}$$

Where:

- $EM_{y,k}$ is the total annual emission of pollutant y for power generation in country k
- $C_{j,k}$ is the annual consumption of fuel j for power generation in country k

The second step consists of mapping the fuel classification used by ENTSOE against the EMEP/EEA's fuel categories in Table 13. From the ENTSOE's 2022 Statistical Factsheet [91] is derived the quote of generation by type of coal and gas, whereas for oil are used the proportions of heavy and light oil provided by EMEP/EEA. For the fuel category Other RES is not possible to assign a quote by type of combustible sources (waste and biomass) since ENTSOE scenarios lack the information of power generation per type of Other RES. The output of mapping process is summarised in Table 13:

Table 13: Mapping of ENTSOE's fuel type against EMEP/EEA's fuel categories

ENTSOE classification	**EMEP/EEA classification**
Gas	100% Natural Gas
Coal	55% Brown Coal 45% Hard Coal
Oil	66% Heavy Fuel Oil 34% Light Fuel Oil (= Gas oil)
Other RES (geothermal, wave and tide, biomass, waste)	Not applicable
Nuclear	Not applicable
Solar	Not applicable
Wind Offshore	Not applicable
Wind Onshore	Not applicable

The total emissions of major air pollutants, including 'CO', 'NMVOC', 'NOx', 'PM10', 'PM2.5', and 'SOx', have been calculated by aggregating the estimated pollutant emissions from all the 47 countries within the ENTSOE area. The results indicate that the reduction in coal usage leads to a significant decrease in both NOx and SOx emissions (Figure 28), resulting in better air quality and mitigating the consequences of high concentration of these pollutants in the atmosphere such as the formation of acid rain, acidification of soil and water damaging vegetation and ecosystems. Moreover, although it is not included in the greenhouses gases (GHGs), NOx contributes to the cycle of ozone depletion in stratosphere. NOx can also contribute to the formation of particular matter (PM), with drawbacks human health, increasing the risk of serious respiratory diseases and premature deaths [16].

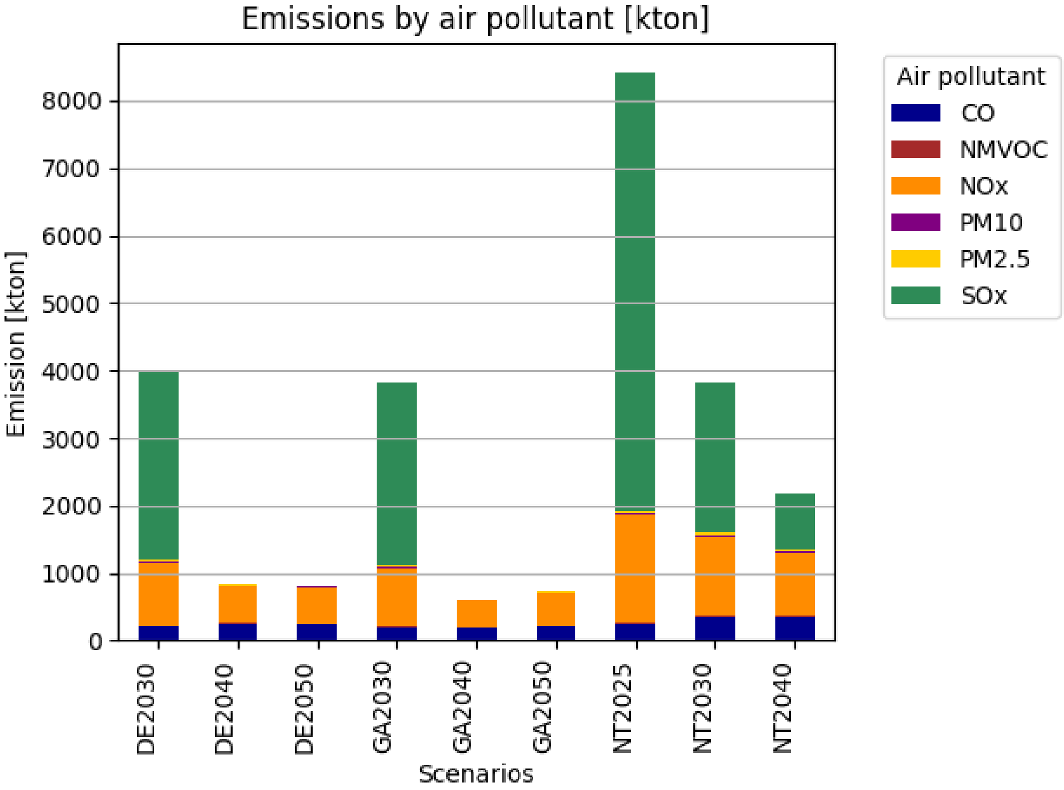


Figure 28: Total emissions by type of air pollutant emitted from electricity generation in ENTSOE area

As the comprehensive emissions chart does not adequately reveal variations in CO, NMVOC, PM10, and PM2.5 emissions, the percentage change in emissions relative to the NT2025 reference scenario is illustrated in the following bar charts in Figure 29:

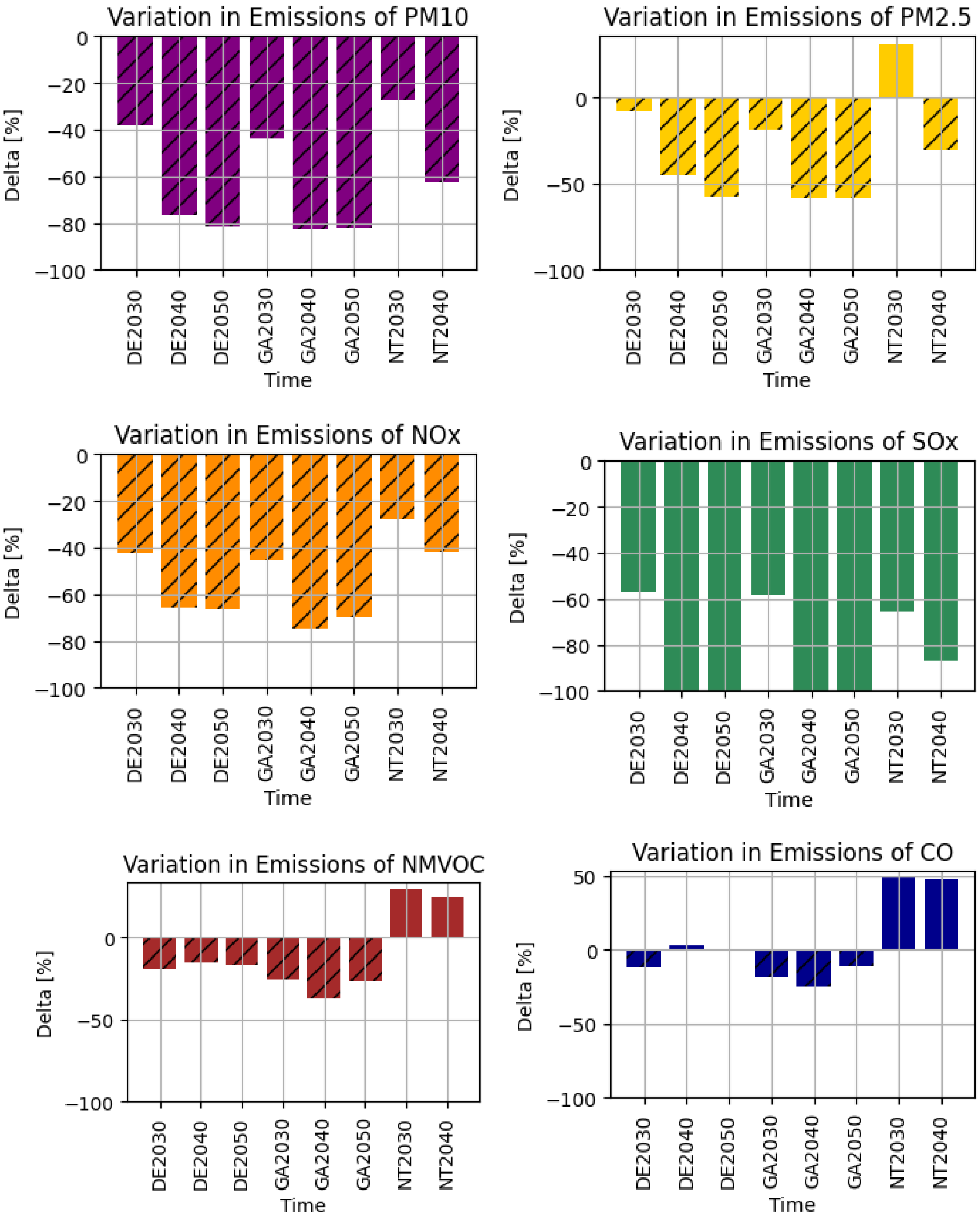


Figure 29: Percentage Change (%) in emissions with respect to the reference scenario's emissions (NT2025 scenario)

As regards particulate matter (PM), PM10 shows more pronounced reductions compared to PM2.5. By analysing the variations among the three scenarios for 2030, GA exhibits the most substantial decrease in PM10 (over -40% compared to NT2025), followed closely by DE, which approaches the -40% threshold. Despite less significant reductions compared to PM10, GA also demonstrates pronounced decreases in PM2.5. Conversely, NT2030 shows an increase in PM2.5 emissions due to the growth in natural gas consumption for electricity generation, resulting from lower penetration of intermittent renewable sources, such as solar and wind. In terms of NMVOC and CO emission, DE and GA exhibit significant contractions with respect to the reference scenario (NT2025), although their contribution in the overall air pollutant emissions is more modest compared to NOx and SOx. Conversely, scenarios NT2030 and NT2040 reveal an increasing trend in emissions of these pollutants. The variations in SOx, already evident in the overall overview illustrated in Figure 28, indicate that both scenarios DE and GA would lead to zero SOx emission by 2040.

To better understand the contribution of each country to the overall air pollutant emissions, a detailed analysis on the pollutant emissions by country was conducted. Three benchmark pollutants, resulting the most critical pollutants in the ENTSOE total emissions (Figure 28), were selected to perform the analysis: PM10, NOx and SOx.

The comparative analysis between countries highlighted the major contributors to pollutant emissions (e.g., Germany and Poland), but the absolute values did not capture the country-specific characteristic such as GDP, population, electricity demand, and generation. Therefore, the analysis has been extended by considering the emissions of PM10, NOx and SOx in relation with all of these aspects. Among them, generation resulted the most effective to outline the enhancement of the power system in terms of reduced pollutant emissions and to compare the scenarios. Therefore, pollutant emissions (ton) disaggregated by country and by scenario are illustrated in Figure 30,

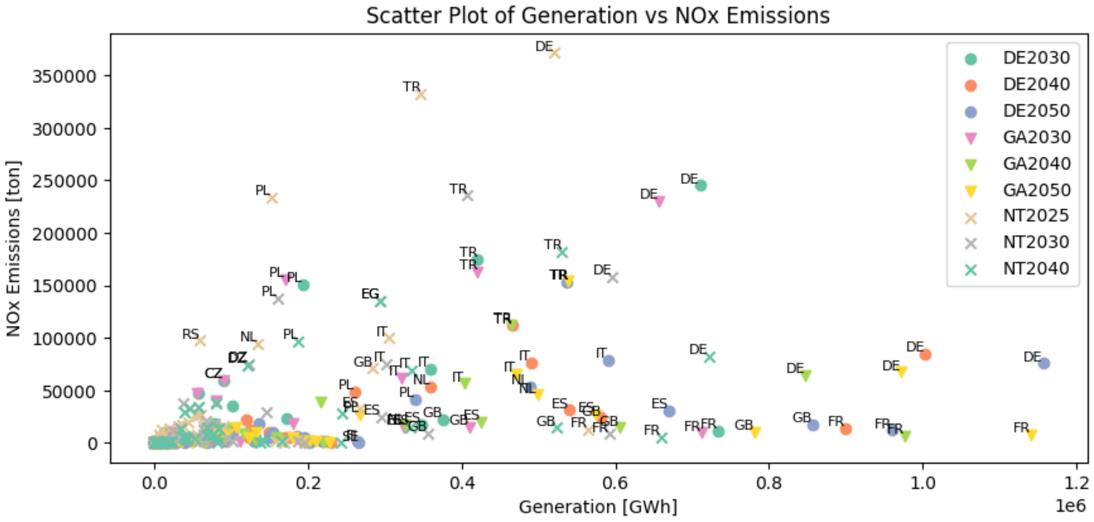


Figure 31, and Figure 32, in relation with the overall electricity generation by country and by scenario (GWh).

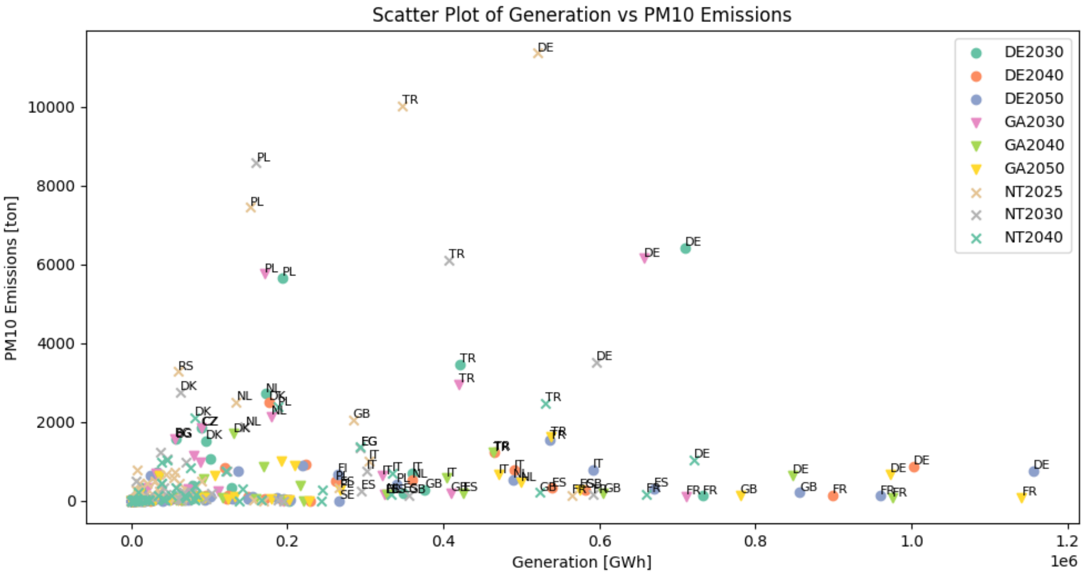


Figure 30: Scatter plot of Generation (GWh) and PM10 emissions (ton) by country and by scenario

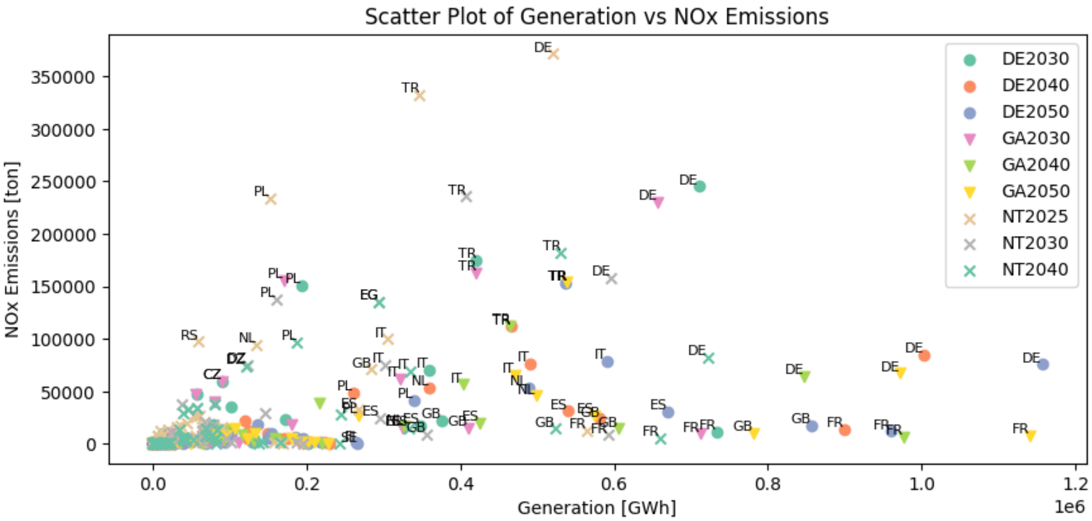


Figure 31: Scatter plot of Generation (GWh) and NOx emissions (ton) by country and by scenario

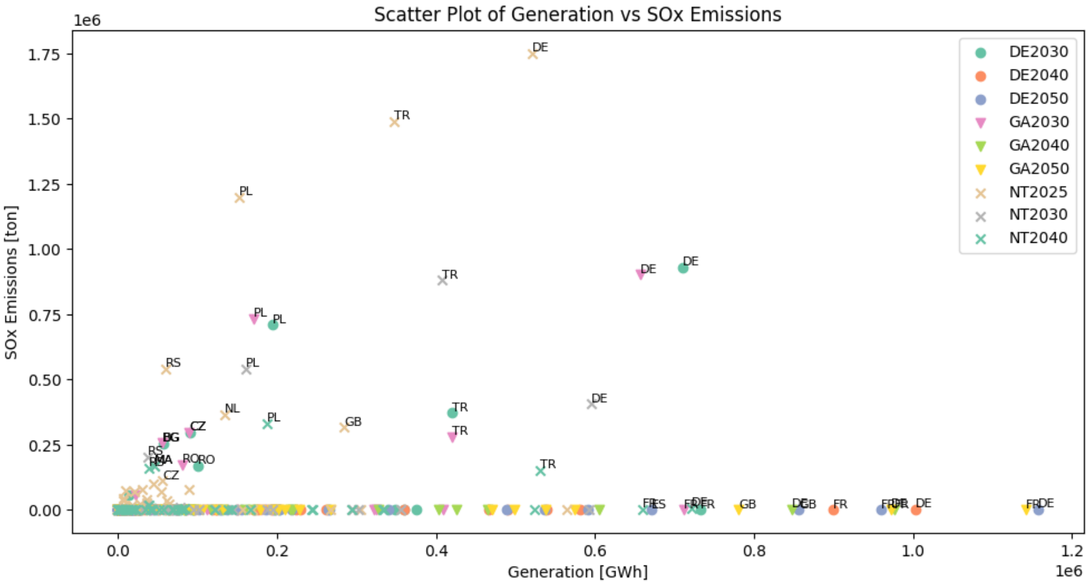


Figure 32: Scatter plot of Generation (GWh) and SOx emissions (ton) by country and by scenario

By analysing the highest values on the vertical axis in all three charts, Germany consistently emerges as the leading emitter of both PM10, NOx, and SOx in the short-term scenario NT2025. This dominance can be attributed to Germany's power generation mix: according to IEA 2022 statistics [88] combustion sources cover approximately 56% of the total electricity generation in Germany (32.8% coal, 15.6% gas, 0.8% oil, and 7.1% biofuels). Furthermore, Germany ranks among the top ten countries globally for electricity production (IEA, 2021) and holds the first position among European countries. Consequently, to produce such quantities of electric energy with a mix mainly composed of combustible sources, it is evident that the pollutant emissions result the highest among the ENTSOE countries. Turkey and Poland take the second and third positions, respectively: Turkey is characterized by an electricity generation mix consisting of approximately 60% from combustible energy sources (34.7% coal, 23% natural gas, and 2.2% biofuels, IEA 2022 [88]) and ranks third in electricity generation among European countries (IEA, 2021 [88]), while Poland, on the other hand, owes its high emissions to the heavy reliance on coal, characterized by the highest pollutant emission factors among fossil fuels and accounting for more than 70% of the generation mix.

It is important to note that, due to lack of data, the adopted methodology (EMEP/EEA Tier 1 [90]) does not include the avoided emissions by the abatement systems, hence the results overestimate the quantities actually emitted by the country. However, this methodology allows to capture the efficiency of electricity generation systems in terms of emitted pollutants and generated electricity: the lower the share of combustible energy sources, the lower the emissions of pollutants for the same amount of generated electricity (greater efficiency in terms of pollutant emissions).

Furthermore, the choice of data visualization through the scatter plot chart was precisely designed to outline variations in air pollutant emissions considering the quantity of generated electricity: It is observed that Germany, despite significantly increasing electricity production, manages to deeply reduce PM10, NOx, and SOx emissions. The negative trend of air pollutant emissions is already evident between 2025 and 2040 in the NT scenario; actually, NT2030 has lower emission levels compared to GA2030 and DE2030. However, it should be noted that the GA and DE scenarios consider a higher electricity generation compared to the NT scenario. As regards NOx emissions, NT2040 and DE2040 have almost equivalent emissions, but since the DE scenario assumes a greater amount of electricity produced, it demonstrates a better configuration of the electricity generation mix in terms of NOx emissions compared to NT scenario; GA2040, characterized by a higher generation share compared to NT2040 but lower than DE2040, shows emission levels lower than both NT2040 and DE2040. Regarding PM10 emissions, since 2040 both DE and GA scenarios show lower emission levels than NT2040. Similarly, by 2040, SOx emissions for DE2040 and GA2040 are lower than NT2040, indeed, they are negligible. By 2050, Germany will remain the leading electricity producer in Europe, followed closely by France, but its emission levels are expected to deeply decrease and to align with those of other European countries. In France, the second-largest electricity producer in Europe, nuclear energy accounts for the majority share of electricity generation (in 2022 accounted for 62% of the total generation, IEA, 2022 [88]), allowing to produce electricity without fuel combustion, and therefore, to maintain lower emission levels. For this reason, despite a significant increase in electricity production (e.g., electricity generation in GA2050 doubles compared to NT2025), France's air pollutant emissions remain low.

Hence, it can be affirmed that Germany, thanks to the transition strategies delineated in the GA and DE scenarios, is expected to witness the most substantial enhancement in terms of reduction in air pollutant emissions, resulting in relevant benefits (e.g., reduced cost of abatement system, improvement of public health and reduction of premature deaths due to air pollution, etc.) for the country. Similarly, Turkey and Poland, still profit from decarbonization policies since they demonstrate a decrease in PM10, SOx, and NOx emissions levels in both the DE and GA scenarios compared to NT. However, Turkey and Poland show marginal improvement in terms of pollutant emission reduction; indeed, unlike Germany, they decrease their emission levels but electricity generation is just slightly higher than the reference scenario NT2025.

4.1.4 Life-Cycle Approach and Activity-Based Approach to estimate CO2 emissions

To analyse the trend of CO2 emissions produced by power generation in the ENTSOE area, a method similar to that presented in the air pollution assessment (section 4.1.3) has been adopted. The general formulation employed for calculating carbon emissions is the following:

$$EM_{CO_{2_{eq}}} = C_j \cdot EF_{j,CO_{2_{eq}}}$$

Where:

- $EM_{CO_{2_{eq}}}$ is the total emission of $CO_{2_{eq}}$ for power generation [g]
- $EF_{j,CO_{2_{eq}}}$ is the emission factor in terms of $CO_{2_{eq}}$associated to fuel j [g/GJ]
- C_j is the consumption of fuel j for power generation [GJ]

The actual amount of consumed fuel is obtained by the ratio between the amount of electricity generated by the fuel j (G_j) and the average value of power plant's efficiency by type of fuel η_j provided by EMEP/EEA (see section 4.1.3) as shown below:

$$C_j = \frac{G_j}{\eta_j} \cdot f$$

Where f is the conversion factor to convert electricity generation from GWh to GJ and the efficiency values by type of fuel η_j are listed in Table 12. For power generation plants operating without fuel combustion (i.e., wind, solar, geothermal, hydro, nuclear) an efficiency value of 1 is assigned ($\eta_j = 1$). Then, the emission value is derived by multiplying the energy consumption by the corresponding emission factor. The complete formula of carbon emission results equal to:

$$EM_{CO_{2_{eq}}} = \frac{G_j}{\eta_j} \cdot f \ \cdot EF_{j,CO_{2_{eq}}}$$

Among the various emission factors available in the literature, the equivalent CO2 emission factors provided in the "Greenhouse gas emission factors for local emission inventories" (2024) by the Covenant of Mayors (CoM, [92]) have been adopted. Two different approaches to estimate equivalent CO2 emissions are distinguished: the Activity-Based Approach (AB) and the Life-Cycle (LC) Approach. The emission factor of the first approach is obtained by considering just the stationary energy combustion and the global warming potentials (GWPs) of fuels provided by the International Panel on Climate Change (IPCC). The second approach, instead, includes not only the emission from the stationary combustion but also the emission produced by the supply chain associated with the specific fuel (e.g., natural gas extraction). To estimate the CO2 emissions in 2025, 2030, 2040, and 2050 for all ENTSOE scenarios, each energy commodity was previously associated with the corresponding average CO2 emission factor, derived from the CoM's emission factors. In Table 14 are reported the emission factors by energy commodity and for both AB and LC approaches used to obtain the carbon emission assessment produced by power generation.

Table 14: CO2 emission factors by type of carrier and calculation approach (Source: Elaborated data from CoM 2024 dataset)

Carrier	Indicator	tCO2-eq/MWh)
gas	Activity-Based Approach	0.2203
oil	Activity-Based Approach	0.2680
coal	Activity-Based Approach	0.3525
bioenergy	Activity-Based Approach	0.3057
geothermal	Activity-Based Approach	-
wind	Activity-Based Approach	-
hydro	Activity-Based Approach	-
solar	Activity-Based Approach	-
nuclear	Activity-Based Approach	-
gas	Life-Cycle Approach	0.3037
oil	Life-Cycle Approach	0.3400
coal	Life-Cycle Approach	0.3963
bioenergy	Life-Cycle Approach	0.0781
geothermal	Life-Cycle Approach	0.0830
wind	Life-Cycle Approach	0.0360
hydro	Life-Cycle Approach	0.0040
solar	Life-Cycle Approach	0.0630
nuclear	Life-Cycle Approach	-

The Activity Based emission factor (EF) measured in terms of CO2-eq encompasses not only CO2 emissions, but also CH4 and N2O emissions resulting from fuel combustion. The updated EF values provided by CoM are sourced from the IPCC Emission Factor Database, specifically the 'Energy Industries' section (IPCC 2006), and the Sixth Assessment Report (IPCC, 2021). As illustrated in Table 14, Life-Cycle (LC) emission factors are higher than Activity Based (AB) ones: indeed, the LC methodology incorporates an additional emission factor associated to the energy commodity’s upstream processes such as raw material extraction, transportation, and processing. As for the AB's emission factors, also LC's emission factors are updated with the IPCC's Sixth Assessment Report (2021).

By considering the temporal and spatial resolution of generation by energy carrier derived with the methodology discussed in section 4.1.1, the CO2_eq emission can be calculated by single node and with hourly resolution. Therefore, the general equation for carbon emission calculation becomes:

$$EM_{CO_{2_{eq,h,i}}} = C_{j_{h,i}} \cdot EF_{j,CO_{2_{eq}}}$$

Where:

- $C_{j_{h,i}}$ represents the hourly consumption of fuel j at the hour h for the generation node i
- $EM_{CO_{2eq,h,i}}$ is the hourly carbon emission at the hour h from the generation node i

The overall carbon emission over a year can be obtained by aggregating all the hourly emissions (H=8760 hours) of the 256 nodes composing the network:

$$EM_{CO_{2eq}} = \sum_{h}^{H} \sum_{i}^{I} C_{j_{h,i}} \cdot EF_{j,CO_{2eq}}$$

The output of the carbon emission assessment obtained by means of both the Activity-Based approach and Life-Cycle approach are summarised in the Table 15:

Table 15: Total CO2eq emission (Gton) calculated with Life-Cycle Approach and Activity-Based Approach (Elaboration from Annual Generation by country provided by ENTSOE, TYNDP 2022)

Scenario	Life-Cycle Approach	Activity-Based Approach
	[Mton CO2eq]	[Mton CO2eq]
DE2030	767.77	504.57
DE2040	744.46	377.50
DE2050	809.90	371.23
GA2030	714.27	473.19
GA2040	567.39	277.17
GA2050	686.29	328.51
NT2025	1043.34	799.36
NT2030	997.96	688.89
NT2040	958.47	602.65

The findings indicate that the Life-Cycle results the most conservative among the two approaches, since it takes into account also non-combustible renewable sources like solar, wind, and hydroelectric (Table 14). Focusing 2030 results the DE and GA scenarios exhibit higher total emissions from electricity generation compared to the NT scenario. Even though it seems to be in contrast with expected decarbonisation targets, this is a result of the sharp increase in power generation as a consequence of the higher electricity demand in DE2030 and

GA2030 scenarios. Higher power generation leads to intensified fuel consumption and, consequently, to higher level of carbon emissions.

However, despite the increased electricity generation expected in GA2040 and DE2040, the disparity in emissions between DE and GA scenarios and NT scenario diminishes significantly: GA2040's emissions are even lower than emissions registered in NT2040 scenario thanks to the relevant share of nuclear in the power generation mix. Indeed, unlike non-combustible renewable sources which are accounted among the Life-Cycle emission factors, nuclear is excluded, consequently, total emissions in the GA scenarios are notably lower than in the other two scenarios.

These insights reveal that while the LC approach is more conservative and accounts for upstream processes of the energy sources used for electricity production, it tends to disadvantage the DE scenarios (DE2030, DE2040 and DE2050) while favouring the GA scenarios (GA2030, GA3040 and GA2050). In fact, DE scenarios are characterized by higher penetration of intermittent renewable sources in the power generation mix compared to GA scenarios. As all intermittent RES such as wind and solar are factored into the LC emission factors, they contribute to raise the overall level of carbon emissions. Conversely, the GA scenarios are characterized by a high quote of nuclear generation not included in the LC emission rates, therefore not accounted into the carbon emissions. Ultimately, the LC approach cannot be considered as a fair assessment tool for comparative analysis among these scenarios.

An alternative to the LC approach is the Activity-Based method, which only considers emissions from combustible sources and assigns a zero-emission not only to nuclear but also to all the non-combustible renewable sources (e.g., hydro, solar, wind, geothermal).

4.1.4.1 Comparative analysis between country's carbon emissions and national power generation

In line with the analysis conducted on air pollutant emissions, the assessment of carbon emission contributions by country has been performed. Since the hourly emission trend is not necessary to perform this analysis, the input data are collected by the TYNDP 2022 study [93], which provides the annual generation by country, encompassing a more countries (47 countries) compared to the hourly generation profiles (33 countries). The outcomes are summarized through scatter plots for each approach type (Life-Cycle in Figure 33 and Activity-Based in Figure 34). It is immediately evident that the values obtained with the LC approach are higher than those derived from the AB approach, as a consequence of the diverse emission factors employed in the two approaches.

As observed in the air pollutant analysis (section 4.1.3), Germany holds the top position. The reason is that Germany is the first country in electricity production among European countries, therefore it proportionally consumes larger amount of fuel for power generation and consequently it produces more carbon emissions. Nonetheless, aligning with FIT55 objectives, Germany’s carbon emission decrease over the time-horizons despite the higher power generation necessary to meet the heightened electric demand due to the electrification of final uses such as transport and residential sectors. Turkey emerges as the second-largest CO2 equivalent emitter, despite its generation being lower than Germany's, suggesting that its power generation mix remains more dependent on fossil fuels. Conversely, France maintains low emissions over all the time-horizons while augmenting electricity generation, thanks to the nuclear generation allowing to increase electricity production without increasing the country’s carbon emissions.

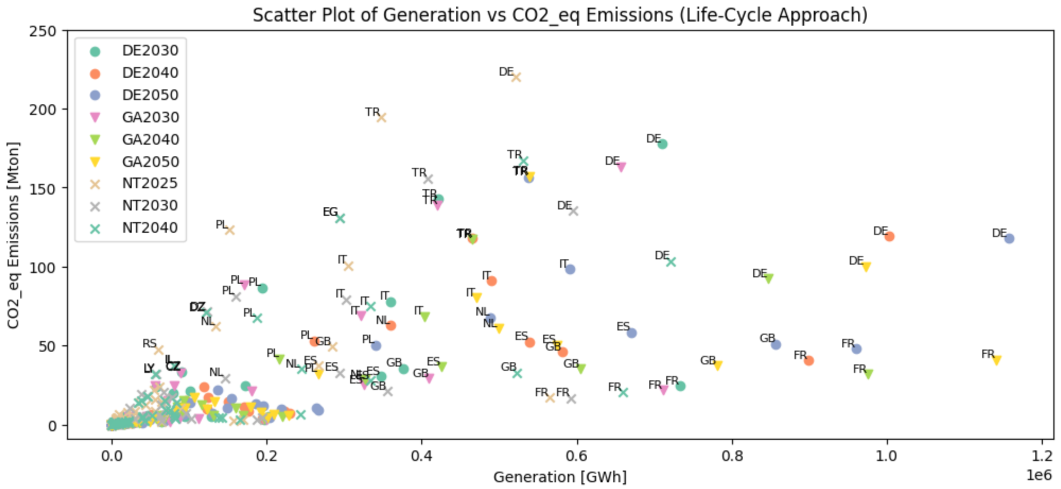


Figure 33: Life-Cycle Approach: scatter plot of electricity generation [GWh] and CO2 emission (Mton CO2_eq)

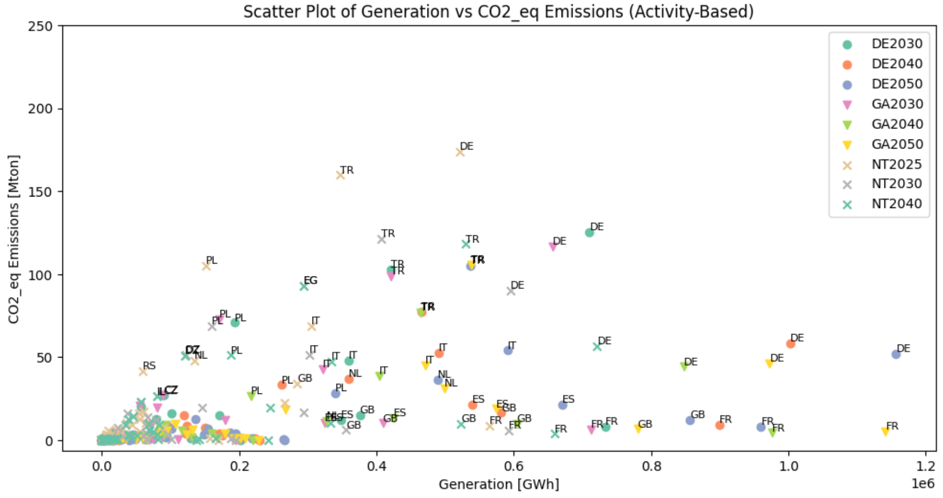


Figure 34: Activity-Based approach: scatter plot of electricity generation [GWh] and CO2 emission (Mton CO2_eq)

To better understand the temporal distribution of emissions throughout the year, an analysis of hourly emissions was conducted based on the hourly generation profile obtained using the method presented in section 4.1.1. Since the profile was derived from the combination of TYNDP's annual generation by country with the simplified European network (composed by 256 nodes), hourly emissions calculation can be extended to the 33 countries included in PyPsa. The estimation of the hourly carbon emissions revealed that DE is the scenario showing the most intense peaks of carbon emissions over all the time-horizons (2030,2040 and 2050), reaching the maximum values in DE2030.

All scenarios show two periods with higher concentration of intense peaks of carbon emissions between July and September and between December and February; this trend is affected by the increase in electricity demand from the building sector during summer and winter for cooling and heating. DE and GA scenarios assume policies more oriented toward stronger electrification of final uses, leading to an overall increase in power needs and consequently in higher carbon emissions from power sector.

As a consequence of global warming, it is expected a further increase in electricity demand for buildings' cooling, especially in summer. The electrification of building sector, coupled with the growth of temperature in summer, leads to more pronounced carbon emission peaks in winter and summer for DE and GA scenarios compared to NT scenario.

By comparing DE and GA scenarios, summer peak results more pronounced in DE scenarios because they involve higher penetration of photovoltaics and wind in the generation mix compared to GA; therefore, as Life-Cycle approach accounts carbon emissions from solar power generation which significantly increases in summer, DE scenarios record sharper seasonal variations than GA scenarios.

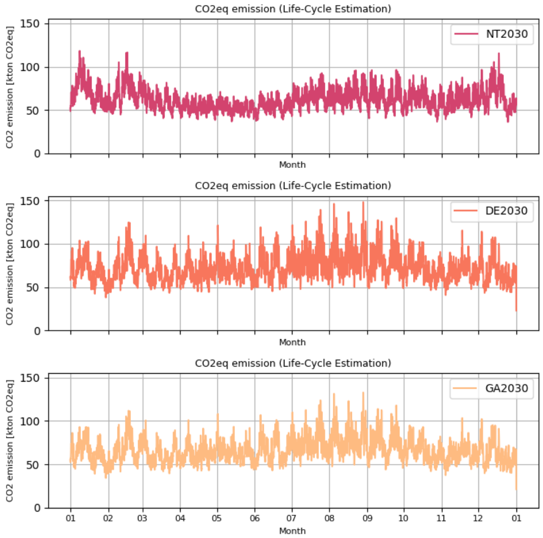


Figure 35: *Hourly CO2 emission in 2030 (LC Approach)*

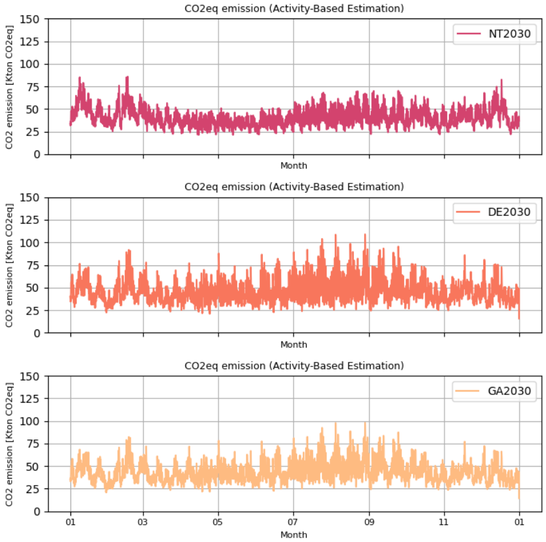


Figure 36: *Hourly CO2 emission in 2030 (AB Approach)*

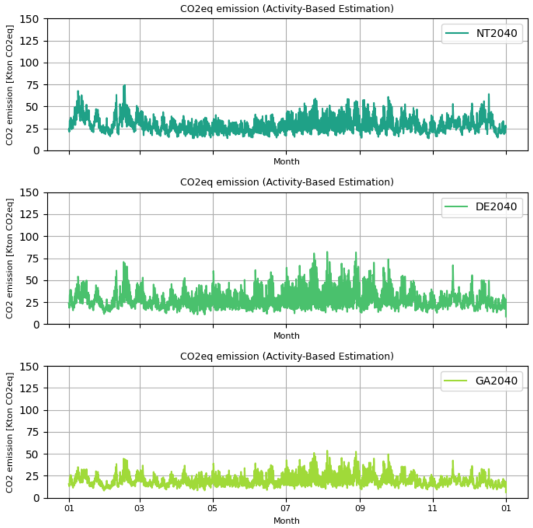


Figure 37: *Hourly CO2 emission in 2040 (LC Approach)*

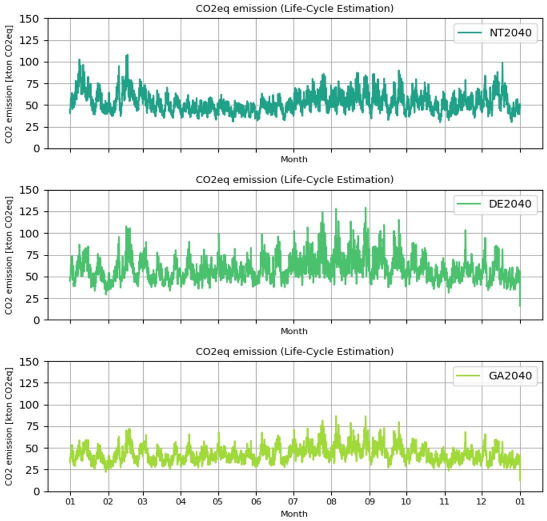


Figure 38: *Hourly CO2 emission in 2040 (AB Approach)*

As shown in Figure 35 and Figure 38, the emission trends calculated using Activity-Based approach are lower than carbon emissions obtained by using the Life-Cycle approach (Figure 35 and Figure 37). Moreover, Activity-Based output show smoothed seasonal peaks in winter and summer compared to LC method. Indeed, conversely to the Life-Cycle method, the Activity-Based approach excludes the contribution from non-combustible energy sources (e.g., solar, wind, hydro, geothermal, nuclear), resulting in significantly lower emissions and minor seasonal discrepancies in summer due to solar and wind power generation.

Another element which affects the discrepancy in carbon emissions between scenarios is the amount of assumed electricity demand: the higher the electricity demand, the higher power generation needed and consequently higher carbon emissions. DE scenarios assume higher power generation (Figure 27) compared to GA and NT scenarios, consequently higher carbon emissions are recorded.

4.2 Metric-based monitoring of the energy transition trend at the country level

In alignment with the goals of the European Green Deal, all the EU-27 countries, committed to align their policies towards a more sustainable system while concurrently reconfiguring their energy mix to reduce the share of fossil fuels and promote an increase in renewable sources. Such a transition poses significant challenges involving multiple dimensions, not only environmental and energy-related but also economic and social. To evaluate effective and targeted strategies in this context, it is essential to consistently monitor the progress of the transition with a multidimensional approach.

4.2.1 The "energy trilemma" within the energy transition

Given the scale and magnitude of the transition impacts, implying socio-economic, environmental, and energy challenges, models and metric-based frameworks are crucial for supporting policymaking. Additionally, the European Commission's commitment to reach carbon neutrality by 2050 (FIT55) places even greater emphasis on this matter. For this reason, numerous studies have been focused on this topic with the aim of assisting policymakers in planning effective strategies and establishing short and medium-term targets.

At the global level, the Energy Transition Welfare Index included in the World Energy Transitions Outlook [67] of the International Renewable Energy Agency (IRENA), encompasses five sub-domains (economics, society, environment, distribution, and accessibility) to measure the effects of the energy transition with a socio-economic perspective. As regards the country level, the annual World Economic Forum (WEF) report [68] assesses the transition performances of 120 countries by means of the Energy Transition Index (ETI). Similarly, the Transition Performance Index (TPI) [69], used by the European Commission to rank EU-countries, is obtained by the combination of scores referring to both economic, social, environmental and governance factors. Other international organizations, such as the World Bank [94] (WB) and the International Energy Agency (IEA) [95] monitor energy system performances through a set of indices and indicators tailored to quantitatively assess specific aspects of energy transition process. IEA's metric-based approach relies on key indicators that provide insights into multi-dimensional trends at both national level (Clean Energy Transition Indicators [96]) and global level (Global Energy Transitions Stocktake [97]). Similarly, the World Bank Group developed the Regulatory Indicators for Sustainable Energy (RISE) [98] to measure the policy performances across 140 countries by taking into account three pillars assessment: Energy Access, Energy Efficiency, and Renewable Energy. As underscored by the European Climate Foundation (ECF) and the ongoing Net Zero 2050 initiatives [25], beside tracking energy transition performance, climate performance indicators play a crucial role in monitoring progress towards carbon neutrality. The Climate Change Performance Index

(CCPI) report [99] is specifically intended to assess the effectiveness of policies aimed at mitigating the impacts of climate change. It offers a comparative analysis of the climate performance of 59 countries, providing valuable insights into their efforts towards achieving carbon neutrality.

Furthermore, another common perspective adopted to assess performance at the country level involves three main dimensions: energy security, energy sustainability and energy equity. These dimensions are centra to evaluating the “energy trilemma”, a concept coined in 2010 by the World Energy Council (WEC) with the Energy Trilemma Index (ETI) [78]. The annual ETI’s report offers a comparative ranking of 127 countries: the overall ETI’s score depends on three sub-scores: the energy security score reflects the capacity of the country to ensure reliable energy supply to meet the national demand, even in case of system shocks and any supply disruptions; the environmental sustainability score evaluates whether the transition process is performed in a sustainable manner, preserving natural resources and mitigating climate change impacts; the energy equity score measures the capacity of a country to provide affordable and fairly priced energy access. There are contrasting opinions on the reliability of the ETI methodology: some consider it a highly useful tool for assessing the progress of the energy transition worldwide [100], while others, such as Šprajc et al. [80], who analysed the method using several tests (including the Pearson Correlation test, Kaiser-Meyer-Olkin Measure of Sampling Adequacy, Bartlett's Test of Sphericity, and Cronbach's Alpha test), argue that the ETI’s method requires further improvements [101] to enhance its reliability and applicability to support policy decision-making. Following the concept of the energy trilemma introduced by WEC, ENEA (Italian National Agency for New Technologies, Energy and Sustainable Economic Development) has developed a metric-based framework for calculating the ISPRED (Security, Prices, and Decarbonization Index). The ISPRED index is integrated into a broader study reported quarterly in the "Analisi Trimestrale del Sistema Energetico Italiano" report [54], intended for systematically assessing the progress of energy transition in Italy, offering updated insights into the trends and impacts of the transition by means of a multi-dimensional perspective encompassing energy security, economic and environmental factors.

4.2.2 The ENEA's Metric-Driven Method for Monitoring the Italian Energy Transition

Since the energy transition is a multifaceted and intricate process influenced by numerous variables, ENEA seeks to provide through the Quarterly Analysis Reports a reliable and systematic assessment of Italy's progress towards energy transition encompassing the Energy Trilemma’s dimensions. As achieving a balanced energy transition necessitates high performances across all the three dimensions included in the trilemma (security of energy supply, decarbonization of energy mix, and affordability of energy commodities) it is essential to continuously monitor their trends. The goal is to enhance understanding and communication of valuable insights into energy transition and to favourite engagement of both public and private stakeholders.

ENEA translates the original concept of the energy trilemma, formulated by the World Energy Council (WEC), into three dimensions (Security, Prices, Decarbonization) which constitute the composite index ISPRED:

1. S - Security Dimension encompasses the ability of the energy system to consistently meet national energy demand, even in the face of events that threaten the energy flows or cause disruptions in energy supply. It includes metrics on the security of supply of electricity, natural gas and oil.
2. PRE - Price Dimension monitors the temporal evolution of energy prices in Italy compared to other European countries. Price metrics include both electricity, oil products and gas prices for both businesses and households.
3. D - Decarbonization Dimension refers to the gradual reduction of national carbon emissions, aligned with the EU roadmap for achieving climate neutrality by 2050 [17], encompassing the carbon emissions (ETS and no-ETS) as well as the increase in renewable power generation.

The composite index is obtained by performing additive aggregation between Security, Price and Decarbonization with equal weight allocation. Each of the three dimensions comprising the ISPRED is further subdivided into sub-domains. According to the adopted formalisation approach (discussed in section 3) ISPRED is classified as 5th level aggregate index, obtained through aggregation of 4th level aggregate indices, namely Energy Security index, Decarbonization index and Price index. An explicative representation of ISPRED structure and level of aggregation is reported in Table 16:

Table 16: Structure of the ENEA's ISPRED (Source: ENEA)

Security of energy system	
Sub-Domain: OIL SYSTEM	Metrics
Resilience of crude oil system	Weighted crude oil dependency
	Diversification of crude supply
Resilience of oil products system	Coverage of Gasoline Demand with national production
	Coverage of Diesel Demand with national production
Adequacy of refinery system	Refinery profit margins
	Refinery Utilization Rate
Sub-Domain: GAS SYSTEM	Metrics
Resilience of gas system	Weighted Gas Dependency
	Geopolitical Stability Of Suppliers

	Diversification Of Gas Supply
Adequacy of gas system	Demand/Supply Variability
Adequacy of gas market	PSV-TTF Spread
	Liquidity Level of PSV
Sub-Domain: ELECTRICITY SYSTEM	Metrics
Adequacy of electricity system	Minimum Margin of Capacity Reserve
Flexibility of electricity system	Uplift
	Hourly Variation of Residual Demand
Adequacy of electricity market	Spark Spread
Energy price	
Sub-Domain: ELECTRICITY COMMODITY	Metrics
Households electricity price	Price Band IB: 20 MWh < Consumption < 500 MWh
	Price Band IC: 500 MWh < Consumption < 2,000 MWh
	Price Band ID: 2,000 MWh < Consumption < 20,000 MWh
	Price Band IE: 20,000 MWh < Consumption < 70,000 MWh
Sub-Domain: OIL COMMODITY	Metrics
Oil products price	Diesel price
Sub-Domain: GAS COMMODITY	Metrics
Households gas prices	Price Band: 1,000 GJ < Consumption < 10,000 GJ
	Price Band: 10,000 GJ < Consumption < 100,000 GJ
	Price Band: 100,000 GJ < Consumption < 1,000,000 GJ
	Price Band: 1,000,000 GJ < Consumption < 4,000,000 GJ
Decarbonization of energy system	
Sub-Domain: CO2	Metrics
Carbon emissions	ETS Sectors Carbon Emissions
	Non-ETS Sectors Carbon Emissions
	Total Carbon Emissions
Sub-Domain: RES	Metrics
RES penetration	RES in Total Final Consumption

In the context of the research activity conducted in collaboration with ENEA, the study has been focused the energy security dimension. Specifically, the metrics review activity comprises all the three macro-categories encompassed by the energy security domain, namely the electricity, gas, and oil system security.

4.2.3 Security domain: Metrics to assess the Electricity System Security

Electricity security can be evaluated with different perspectives (e.g., internal and external fronts) referring to diverse type of threats (e.g., risk of renewable generation curtailment due to over-generation, or risk of failure in transmission and distribution infrastructure, disruption of one or more supply corridors, etc.). Furthermore, the assessment can be focalised specifically on the physical system (i.e., power system infrastructure) or can be extended to the electricity market system. However, as evidenced by the variety of definitions available in literature, a unique and general definition for electricity system security does not exist. For instance, according to the European Transmission System Operators (TSOs) Association (ENTSOE), security is considered as one of the metrics contributing to the overall reliability of the power system.

Electricity security definition used by ENSTOE [87] refers to the capability of the system to ensure uninterrupted availability of electricity in presence of disturbances such as unexpected failures or short circuits, promptly recovering a state of equilibrium (system stability) and delivering electricity to customers without any interruptions. A similar concept of power system security is used by the Italian TSO, TERNA. In addition to the security definition, TERNA and IEA consider the resilience of the system, namely the ability of the system to withstand major disturbances, including short-term shocks and long-term changes [102], and to regain a state of standard operating conditions within limited and temporary interventions. IEA, also introduces the climate resilience of electricity system, intended as the ability to anticipate, mitigate and recover from adverse climate impacts on the power system [103]. Furthermore, IEA distinguished an additional attribute, the robustness of the system which reflects its capability to avoid extreme adverse impacts with preventive measures, not necessarily to mitigate them by means of protection actions (i.e., resilience).

While security attribute reflects the capability of the system to ensure system stability in presence of unexpected disturbances, on the other hand, both TERNA, ENTSOE and IEA agree with the definition of system adequacy as the ability of the system to maintain the stability of the system and meet the total demand under steady-state conditions.

A more general concept encompassing both security and adequacy is the system reliability, adopted both by ENSTOE, IEA and TERNA, referring to the system's capacity to supply electricity according to specific standards and quantities, in all conditions, even in presence of disturbances. Additionally, ENEA extends the assessment of system adequacy not only to the physical system but also to the electricity market with the Electricity Market Adequacy measured by the Spark Spread and Uplift metrics (Table 17).

The list of key definitions on the security of the electricity system provided by IEA [102] outlines another crucial attribute contributing to the overall power system reliability: the flexibility of the electricity system. This attribute reflects the capability of the system to consistently manage supply and demand over time and to recover from disturbances on very short time scales (a few seconds or less). Power system flexibility is also defined by IEA [104] as the capability to consistently and cost-effectively manage the variability and uncertainty of both demand and supply over time.

Quality is a further attribute employed by TERNA to distinguish the ability of the system to guarantee the continuity of power system service, and it is generally used to indicate the interruptions in electricity supply to final users (quality of distribution service), as well as frequency and voltage within certain technical limit ranges. Moreover, TERNA introduce the efficiency attribute, to summarise the overall performance of the power system in terms of adequacy (ensuring stability in normal conditions), security (withstanding sudden disturbances and maintain stability in abnormal conditions) and quality (ensuring electricity supply to end users while maintaining voltage and frequency levels within admitted thresholds).

As regards the ENEA's definition of electricity system security, it encompasses three key aspects: outlined in Table 17: System Adequacy, System Flexibility, and Market Adequacy.

Table 17: Formalisation of metrics included in the ENEA's ISPRED to evaluate the security of Italian power system and electricity market

Domain Of Energy Trilemma	**Electricity Security Sub-Domains**	**Indicator**	**Mathematical Expression**
Security	Power System Adequacy	Minimum Margin of Capacity Reserve [%]	$\frac{C_{th} - 0{,}15 \cdot C_{th} + P_{ex} - (nD + R_m)}{nD + R_m}$
	Power System Flexibility	Variation of Residual Demand over the total Net Demand [%]	$\frac{rD_i - rD_{i-1}}{nD_i} \cdot 100 \geq 10\%$
		Uplift charge [c€/kWh]	Data from TERNA [105]
	Adequacy Of Electricity Market	Spark Spread [€/MWh] in MGP Market	$P_{MGP} - \frac{P_{PSV}}{\eta}$

The adequacy of the system is defined by ENEA as the capacity of the system to ensure sufficient production and storage, as well as adequate demand control and transport capacity, to meet the expected demand with a consistent adequacy margin. At the global scale, the majority of electricity generation is produced by thermal power plants, especially coal (36% of the total electricity production in 2021[88]), followed by natural gas (23%) and hydro (15%). In OECD Europe, the power generation mix is more diversified: 20% is covered by natural gas, 18% by nuclear, 16% by coal and 15% from wind and hydro generation (2022 IEA data [88]). Conversely, Italian power generation depends mainly on natural gas (48% of the total), followed by 10% from hydro, 10% from solar PV and 10% from coal; nuclear generation is null, and wind covers almost 7% of the total power generation (2022 IEA data [88]). Italy is a net importer country of electricity; indeed, the local generation covers almost 87% of the national demand, the remaining quote is covered by imports from neighbouring countries (e.g., France). Despite the quote of generation from natural gas is still high, the share of generation from "programmable" power plants such as coal and hydro plants with reservoir or pumping storage, is progressively decreasing while the penetration of intermittent generation from solar and wind is increasing. Moreover, according to the FIT55 goals [17], Italy and all EU-27 member countries have to further reduce their carbon emissions, therefore, since the power sector is one of the main sources of CO2 emissions due to the fossil combustion, the share of power generation from renewables is expected to increase even more. Programmable power plants allow, within technical limits, to regulate the power generation to meet the demand, ensuring minimum reserve margins. Conversely, intermittent renewable source, consisting of run-of-river hydro plants, photovoltaic (PV) plants, and wind farms, are not programmable: their generation depends on external weather factors. Therefore, they contribute to system adequacy but in a non-programmable manner and it is challenging to make precise predictions (ex-ante) about their contribution in the overall generation. Therefore, due to unpredictable nature of solar and wind, their power generation can significantly fluctuate due to weather conditions and time of day. This unpredictability poses challenges for grid operators in balancing electricity supply and demand in real time. Additionally, intermittent sources often experience rapid and intense changes in output, known as "ramps", which can strain grid stability and require rapid adjustments by means of conventional power generation or energy storage systems. For this reason, it is essential to ensure a quote of "programmable" generation capacity, which can be used to address sharp unbalances between demand and generation caused by intermittent generation of wind and solar sources. TERNA, the Italian Transmission System Operator (TSO), every year presents a list of production plants essential for the security of the Italian power system, according to Article 63, paragraph 63.1, of Annex A to ARERA Resolution N. 111/06 [106].

To include the crucial aspect of system adequacy in the assessment of the electricity system security within the Italian energy transition, ENEA uses the Minimum Margin of Capacity Reserve:

$$MCR_i = \frac{C_{th} - f \cdot C_{th} + P_{ex,i} - (nD_i + R_m)}{nD_i + R_m} * 100 \qquad [\%]$$

Where:

- C_{th} is the installed thermal capacity [MW]
- P_{ex} is the net electricity (i.e., difference between imports and exports) exchanged with foreign countries per hour [MWh/h]
- $f = 0.15$ is the coefficient of capacity unavailability [-] [107]
- nD_i is the hourly net electricity demand (excluding self-consumption) [MWh/h]
- R_m is the national minimum reserve capacity updated by TERNA [107] [MW]

The second attribute included in the ISPRED's electricity security framework, is the system flexibility, intended as the system's ability to adjust electricity demand or generation in response to sudden fluctuations. The inherent intermittency of Non-Programmable renewables hinders the normal conditions of operation of the power system and therefore the system stability and quality. Since the fluctuations due to intermittent renewable generation is expected to increase as a result of energy transition policies, the ability of the system to manage effectively these variations in generation and demand (i.e., flexibility) gains even more relevance. One of the possible solutions in case of variations in generation from intermittent renewable sources, is to accordingly adjust the generation from the Programmable generation plants (e.g., thermal plants and hydro plants with pumping storage or reservoir) to avoid over-generation or scarcity of generation and maintain the balance of the system. In case of over-generation from Non-Programmable sources (e.g., wind, solar, run-of-river hydro), it is necessary to promptly reduce generation from other plants but there is the minimum technical threshold which limits the range of admitted reduction of Programmable plants generation. If the admitted reduction is not sufficient to balance the over-generation, the only solutions are either exporting excess electricity or the curtailment of intermittent generation (RES curtailment). Since it is expected a further penetration of intermittent generation in the national power system, sharp and sudden fluctuations in generation will be more frequent. Recognizing the relevance of this factor for evaluating the flexibility of the power system, the frequency of critical residual demand variation ($\Delta_{\mathrm{rD_i}}$) was included in the ENEA's ISPRED framework. It was calculated by considering the percentage of annual hours (n/8760) in which the hourly variation of residual demand $rD_i - rD_{i-1}$ over the hourly net electricity demand nD_i exceeded the 10% threshold.

$$\Delta_{\mathrm{rD_i}} = \frac{rD_i - rD_{i-1}}{nD_i} \cdot 100 = \frac{(nD_i - IG_i) - (nD_{i-1} - IG_{i-1})}{nD_i} \cdot 100 \qquad [\%]$$

$$h_{rD} = \sum_{i}^{8760} \frac{h_i}{8760} \qquad with\ \Delta_{\mathrm{rD_i}} \geq 10\% \qquad [\%]$$

Where:

- rD_i and rD_{i-1} are the hourly residual demands in the i hour and $i-1$ hour [MWh/h]
- nD_{i-1} is the net electricity demand (excluding self-consumption) in the $i-1$ hour [MWh/h]
- IG_i is the intermittent renewable generation (i.e., solar, wind, run-of-river hydro) in the i hour [MWh/h]
- IG_{i-1} is the intermittent renewable generation (i.e., solar, wind, run-of-river hydro) in the $i-1$ hour [MWh/h]
- h_{rD} is the percentage of hours of the with $\Delta_{\mathrm{rD_i}} \geq 10\%$ [%]

In the last version of ISPRED (2024) this indicator is replaced by the Uplift [c€/kWh] (comma 44.1, b), periodically published by TERNA, and which represents the unit charge to cover the expenses related to managing the electricity system, including measure to handle congestions, over-generation or over-load situations. By analysing the uplift trend, it is possible to outline the ability of the system to respond to fluctuations in generation and demand in a cost-effectively way, in line with the IEA's definition of power system flexibility [102].

Since the adequacy of electricity market can deeply affect the adequacy of the physical electricity system and vice versa, ENEA extends the analysis of the electricity system adequacy also to the electricity market. The electricity market adequacy can be defined as the balance between two aspects: 1) the ability of the electricity market to ensure adequate compensation to all generators, including conventional thermal plants, and 2) as the ability of the electricity system to supply electricity at an affordable price to end-users. Since the Italian energy mix is shifting towards renewable sources, the Italian electricity markets, operating as free and competitive markets, are experiencing significant variations too: for instance, if in the past the major contribution of thermal plants generation was in the Day-Ahead Market (MGP), currently, the increase of renewable generation is leading to a progressive reduction of thermal contribution in the MGP. Since the function of thermal plants are essential to ensure stability to the system and manage abnormal conditions, it becomes necessary to verify whether these plants receive sufficient remuneration. This aspect is monitored by ENEA through the Spark Spread (€/MWh), also called Dirty Spark Spread [108] and the Clean Spark Spread (€/MWh). The first metric is included in the ISPRED's calculation and refers to the difference between the market price of electricity referring to the MGP price (i.e., PUN in the Italian MGP market) and the cost of natural gas required to produce that electricity. It is typically used to assess the profitability of natural gas-fired power plants. The second metric is used as auxiliary metrics in the quarterly report, and it extends the Spark Spread's concept by considering also the carbon emissions costs: indeed, it is calculated by the difference between the PUN and both the cost of natural gas and the cost of emission allowances (i.e., European Union Allowances, EUAs). Another indicator used by TERNA in the monthly report [108] is the Dirty Dark Spread (€/MWh) representing the profit margin for a carbon-fired power plant; however, this metric is less relevant to track the evolution of electricity market adequacy since the carbon plants are expected to be phased out by 2025 according to the FIT55's goals [17].

$$DSS_{MPG} = P_{MGP} - \frac{P_{PSV}}{\eta} \qquad \left[\frac{€}{MWh}\right]$$

Where:

- DSS_{MPG} is the Dirty Spark Spread calculated by the difference between MGP electricity price (i.e., Prezzo Unico Nazionale, PUN) and the cost of natural gas (i.e., Virtual Trading Point of natural gas in Italy, PSV)
- η is the efficiency of thermal plant [-]

However, as Clean Spark Spread includes the costs of carbon emissions allowances, it provides a more accurate assessment of the profitability of natural gas-fired power plants compared to the Dirty Spark Spread. For this reason, in the periodical reports by GME (Gestore dei Mercati Energetici) and by TERNA (the Italian TSO), the Clean Spark Spread is more used than the Dirty Spark Spread to track the electricity market adequacy. Therefore, in order to align the ISPRED with the evolving dynamics of energy markets, and especially in order to provide a more accurate representation of the profitability of natural gas-fired power plants, ISPRED should be revised by replacing the Dirty Spark Spread with the Clean Spark Spread. Moreover, as proposed in the Di Renzo's study [109], the evaluation of the Clean Spark Spread could be extended also to the other Italian electricity markets, rather than considering only the Day-Ahead Market (MGP): Intraday Market (MI), Ancillary Services Market (MSD ex-ante), and Balancing Market (MB).

$$CSS_{MGP} = DSS_{MGP} - P_{EUA} \qquad \left[\frac{€}{MWh}\right]$$

$$CSS_{MI} = P_{MI} - \frac{P_{PSV}}{\eta} - P_{EUA} \qquad \left[\frac{€}{MWh}\right]$$

$$CSS_{MSD} = P_{MSD} - \frac{P_{PSV}}{\eta} - P_{EUA} \qquad \left[\frac{€}{MWh}\right]$$

$$CSS_{MB} = P_{MB} - \frac{P_{PSV}}{\eta} - P_{EUA} \qquad \left[\frac{€}{MWh}\right]$$

Where:

- CSS_{MPG} is the Clean Spark Spread calculated by the difference between the Dirty Spark Spread and the cost of carbon emission allowances (i.e., European Allowances).

- CSS_{MI} is the Dirty Spark Spread calculated by the difference between MI electricity price (P_{MI}) and the cost of natural gas (i.e., Virtual Trading Point of natural gas in Italy, PSV)
- CSS_{MSD} is the Dirty Spark Spread calculated by the difference between MSD electricity price (P_{MSD}) and the cost of natural gas (i.e., Virtual Trading Point of natural gas in Italy, PSV)
- CSS_{MB} is the Dirty Spark Spread calculated by the difference between MB electricity price (P_{MB}) and the cost of natural gas (i.e., Virtual Trading Point of natural gas in Italy, PSV).

Another crucial aspect for assessing the electrical system's security, lacking in the current version of the ENEA quarterly analysis, is system stability. As mentioned earlier, stability refers to the ability of the electrical system to maintain equilibrium under normal operating conditions or in the event of disturbances. While the indicators of system flexibility included in the ENEA's methodology are focused on the system's capacity to cost-effectively adapt to fluctuations in generation and demand (Uplift) and the frequency of critical residual load variations caused by intermittent generation sources (h_{rD}), stability measures both the intensity of disturbances and the speed at which the system returns to equilibrium. Parameters such as frequency, voltage regulation, and inertia level are crucial in evaluating system stability. In Europe, the nominal value of system frequency is 50 Hz, but it can vary due to disturbances. Similarly, the electric system voltage can be affected by disturbances, but these variations must be kept within certain acceptable operating boundaries since prolonged violation of these limits can lead to further deterioration of the system operating conditions. Unlike conventional power plants, equipped with synchronous generators operating in synchrony with the grid frequency (in Europe equal to 50 HZ), wind and solar generators do not contribute to voltage regulation, on the contrary, due to their inherent variability and unpredictability, their intermittent generation con lead to fluctuations in voltage levels, straining voltage control system. Since it is expected a significant increase in intermittent renewable generation, voltage regulation will result more challenging in the future.

Another essential parameter to measure the power system stability is the Inertia level, representing the ability to maintain a stable frequency even in presence of significant fluctuations in generation and demand. In other words, it represents the inherent resistance of the electricity system to changes in rotational speed caused by disturbances, balancing the system prior to interventions from the frequency regulation systems (i.e., primary, secondary and tertiary regulation systems). Both renewable and conventional generators contribute to inertia, even though renewable generators are typically characterized by lower inertia. Due to their technical characteristics, inertia contribution from intermittent power generators (i.e., wind and solar) is null. Solar generators lack rotating masses, therefore it cannot provide inertia to the system by nature, whereas wind generators, despite equipped with rotating masses, are not direct coupled to the system as they operate with power converters to interface generation and demand, neutralizing the balancing effect following the transfer of any disturbances to the rotating masses. The mathematical formulation of the total system inertia is the following:

$$H_{sys}(t) = \sum_{i=1}^{n} \frac{H_i(t) \cdot w_i(t)}{LF_i}$$

Where:

- $H_i(t)$ is the constant of inertia at a given time t
- LF_i is the average Loading Factor of the i-th generator (i.e., the ratio between the average power and the nominal power of the i-th generator)
- $w_i(t)$ is the ratio between the nominal power of the i-th generator at a given time ($S_i(t)$) over the total nominal power at a given time $S_{tot}(t)$:

$$w_i(t) = \frac{S_i(t)}{S_{tot}(t)}$$

Two parameters are commonly used to evaluate the level of inertia of the system: Rate of Change of Frequency (ROCOF), and Maximum Frequency Deviation (MFD). These metrics allow to track the response of the system in presence of disturbances. The capability and the rapidity of the system to repristinate the state of equilibrium, depend on the magnitude of the disturbance and on the system inertia.

ENTSOE's [85] describes two methodologies to measure inertia (PMU and SCADA) but they need input data which are not publicly available. ENTSOE also presents another approach to estimate the total system inertia by using the hourly generation mix and basic assumptions about inertia constants and loading factors per production type. In Table 18 is reported the complete list of average inertia constants and loading factors by type of generation technology, calculated by ENSOE for the Continental European power system.

Table 18: Typical inertia constants by type of fuel (Source: ENTSOE [85]*)*

Fuel	**Average inertia [s]**	**Loading factor [-]**
Nuclear	5.9	0.96
Fossil Oil	4.3	0.4
Fossil Oil shale	4.3	0.4
Fossil Coal-derived gas	4.2	0.54
Fossil Gas	4.2	0.6
Fossil Hard coal	4.2	0.7
Fossil Brown coal/Lignite	3.8	0.81
Fossil Peat	3.8	0.59

Marine	3.8	0.5
Other	3.8	0.56
Waste	3.8	0.28
Hydro Water Reservoir	3.7	0.56
Geothermal	3.5	0.83
Hydro Pumped Storage	3.5	0.46
Other renewable	3.5	0.5
Biomass	3.3	0.7
Hydro Run-of-river and poundage	2.7	0.61
Solar	0	NaN
Wind Offshore	0	NaN
Wind Onshore	0	NaN

These inertia constants offer an approximation of the real inertia of each generator, allowing the estimation of the level of inertia of the power system. By employing the inertia constants calculated by ENTSOE for the Continental Europe power system, the system inertia level can be estimated as follows:

$$H_{sys}(t) = \sum_{i=1}^{n} \frac{\overline{H}_i \cdot w_i(t)}{LF_i}$$

Where:

- $H_i(t)$ is assumed constant over time and equal to $\overline{H}_i$ (shown in Table 18)

Inertia Constants vary according to the typology of generators: in general, conventional plants provide more inertia than renewable power plants. The output of the formulation is a conservative estimation since it neglects other contributions such as the additional inertia provided by loads and by installed synchronous compensator, as well as it does not consider the innovative technologies (integrated storage systems) to compensate the inertia deficit of renewable generators.

By extending the conventional definition, it is possible to distinguish “installed inertia” from the “dispatched inertia” as discussed in [110]:

- "installed inertia"(H_{sys}), corresponding to the conventional inertia definition, refers to the nominal power of all potentially dispatchable generators and its value depends on the assumed constant of inertia and loading factor per type of generator;
- "dispatched inertia" (H_{sys_d}), referring to the actual generation, therefore only inertia contributions from generation online at a given hour are considered. The actual

generation includes the outcomes of the electricity markets (MGP, MI, MSD ex-ante, and MB).

In other words, the installed inertia is related to the consistency of installed generators which potentially can contribute to the inertia level, whereas the dispatched inertia depends on the generation units that are effectively connected to the system at a given moment based on the outcomes of the electricity markets.
By focusing on the dispatched inertia definition $H_{sys_d}(t)$, and replacing the nominal power $S_i(t)$ with the actual dispatched generation $G_i(t)$ (obtained by the outcomes of the electricity markets) the formula results equal to:

$$H_{sys_d}(t) \to \sum_{i=1}^{n} \frac{\overline{H}_i \cdot G_i(t)}{G_{tot}(t)}$$

Where:

- $H_i(t)$ is assumed constant over time and equal to $\overline{H}_i$ (shown inTable 18)
- $G_i(t)$ is the actual generation of i-th generator at time t
- $G_{tot}(t)$ is the total actual generation at time t

Since the current approach of electricity security assessment does not include any parameters on system flexibility because of the lack of specific information allowing the precise calculation of the system's level of inertia, the proposed estimation of dispatched inertia can be a valid alternative to fill this gap and to visualize the effect of decreased inertia level caused by the increasing RES penetration. The aim of this metric is therefore to outline the trend of decreasing system inertia by using publicly available data (the average inertia constants in Table 18 and the hourly actual generation by type of generation provided in ENSTOE Transparency Platform) and by adopting a simple approach, easy to replicate and to communicate.

To compute the level of inertia in the Italian electrical system, a Python code was developed, incorporating the following steps:

1. downloading the excel files containing the hourly actual generation [MW] by generator type in Italy (available period: 2020-2023) from the ENTSOE's Transparency Platform ("Actual Generation per Production Type");
2. data cleaning and creation of a unified generation dataframe including hourly generation from 2020 to 2023;
3. calculation of weights for each generator by dividing the i-th generation with the total generation at time t.
4. multiplication of each weight by the average inertia constant of the i-th generator type;

5. calculation of the total inertia level at time t obtained by summing the contributions of all active generators at time t.
6. plot of the historical trend of the level of inertia of the Italian power system (Figure 39).

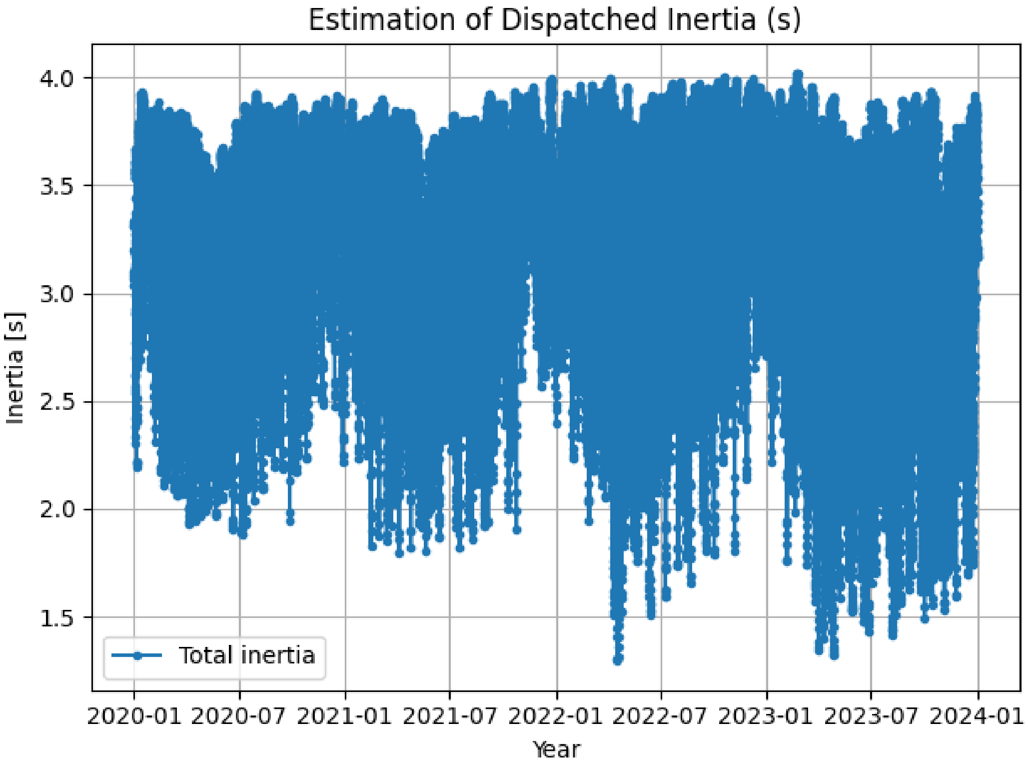


Figure 39: Trend of the Level of Dispatched Inertia of the Italian power system (Python-code output)

As shown in Figure 39 the trend of dispatched inertia levels tends to reach lower values as the penetration of intermittent sources increases. The dispatched inertia outlines the effect of renewable generation which saturate the electricity markets during high wind and solar production since they have low marginal cost of production compared to conventional power plants.

This result does not aim to precisely measure the evolution of inertia levels but rather to provide graphical evidence of the impact of renewable penetration on the stability of the electricity system. This estimation could be refined with additional technical information provided by the national TSO (TERNA) or substituted with direct measurements of inertia that are currently not publicly available.

To summarise the main findings obtained by the review activity concerning the existing electricity security definitions and metrics utilized by ENEA, Table 19 is presented below, including the main categories included in the evaluation of the electricity system security, their definition, the selected metrics, the causes and the threats for the power system resulting from the increase in intermittent generation.

Table 19: Conceptual revision and formalisation of electricity security definitions currently used in the ISPRED calculation

Electricity Security Category	Source	Definition	Metric	Threats and Impacts of energy transition	Cause
System adequacy	System Adequacy by TERNA	The capacity of the system to ensure sufficient production and storage, including demand control, to meet the expected demand with a consistent adequacy margin	Minimum Margin of Capacity Reserve [%]	Reduction of the adequacy margin during peak load periods, particularly during low intermittent generation hours from renewable sources	Unpredictability of Intermittent Renewable Generation
System flexibility	System Flexibility by IEA (2018)	The capability to cost-effectively adjust demand and supply in response to sudden fluctuations	Uplift charge [c€/MWh]	Increasing intermittent generation raises the frequency of fluctuations and the need of balancing interventions which increase Uplift cost.	
			Frequency of exceeding the Limit for Residual Demand Hourly Variation [%]	The unpredictability of intermittent generation raises the risk of over-generation necessitating RES curtailment when the required supply reduction goes beyond the minimum technical level of generation of thermal plants	
System stability	System Stability by IEA (2021), ENTSOE, TERNA	The ability of the electrical system to maintain a state of equilibrium under normal and	Level of Inertia [s]	Intermittent RES are inherently characterized by lower inertia compared to conventional plants	Technical characteristics of intermittent generation plants

		abnormal operating conditions.	Voltage [V] & Frequency [Hz]	Fluctuations in intermittent generation can lead to voltage and frequency variations	
				Unlike conventional plants, intermittent generators typically do not allow voltage and frequency control, hence their penetration could limit the capacity of the power system to regulate voltage and frequency.	
Market Adequacy	Market Adequacy by ENEA	The ability to ensure adequate remuneration for all generators (including conventional plants) in the electricity markets	Clean Spark Spread [€/MWh] in all markets (MGP, MI, MSD ex-ant and MB)	RES can saturate the electricity market during the periods with high renewable generation. Additionally, RES have priority access to dispatch, impacting the revenues and the utilization rate of conventional plants which risk to struggle to cover their operating costs.	Low marginal cost of production and priority dispatch

4.2.4 Security domain: Metrics to assess the Gas and Oil System Security

As the Italian energy system still rely on fossil resources, in particular natural gas, crude oil and oil products, the assessment of national energy security must include the security metrics referring to gas and oil systems. Indeed, particularly those energy systems heavily reliant on fossil fuels but whose local production is not sufficient to meet national demand, are characterized by high level of dependence on foreign countries. In these cases, diversifying the supply system becomes imperative. Italy, despite gas accounts for 39.5% [88] and oil for 34.3% of the total primary energy supply (TPES), has insufficient indigenous resources to cover the national demand (domestic gas production covers only 4.5% of total gas supply and domestic crude oil production covers only 7.6% of total crude oil demand). To meet the gas and crude oil demands, Italian energy mix depends on other countries supplying gas and oil commodities mainly by sea (i.e., vessels) and by pipelines, underscoring the need for supply system diversification. Apart from diversification of suppliers, another relevant aspect to take into consideration while evaluating a secure and reliable supply system, is the geopolitical stability of suppliers. Indeed, typically oil and natural gas sources are located in unstable areas, subjected to frequent conflicts which may affect the stability and security of production and supply. As evidenced by the economic and energy crises following the Russia-Ukraine war, low diversification of suppliers coupled with low geopolitical stability of suppliers leads to critical situations such as experienced by EU-27 area.

The revising process encompassed 12 security metrics (6 for the oil-system security and 6 for the gas-system security) currently included in the ISPRED's framework. Adjustments and novel metrics have been developed to better investigate these crucial aspects, all encompassed in the category of System Resilience: energy dependency, energy supply diversification and geopolitical stability of suppliers. Five metrics, highlighted in Table 20, are devoted to track resilience of oil and gas systems.

Table 20: Reviewed metrics of natural gas and oil systems security included in the ISPRED's framework

Security of energy system	
Sub-Domain: OIL SYSTEM	Metrics
Resilience of crude oil system	Weighted Crude Oil Dependency
	Diversification of Crude Supply
Resilience of oil products system	Coverage of Gasoline Demand with national production
	Coverage of Diesel Demand with national production
Adequacy of refinery system	Refinery Profit Margins
	Refinery Utilization Rate
Sub-Domain: GAS SYSTEM	Metrics
Resilience of gas system	Weighted Gas Dependency
	Geopolitical Stability Of Suppliers
	Diversification Of Gas Supply
Adequacy of gas system	Demand/Supply Variability
Adequacy of gas market	PSV-TTF Spread
	Liquidity Level of PSV

The highlighted metrics refer to the resilience of oil and gas systems. System Resilience, System Adequacy and Market Adequacy of oil and gas systems, reflect the security definitions presented in the Electricity Security section.

4.2.4.1 System Resilience of oil and gas systems

The REPower plan (2022) [18] developed by the European Commission to face the energy crisis due to geopolitical tensions with Russia, following the Russia-Ukraine war, prioritized diversification of the energy supply system, both in terms of suppliers (e.g., reducing the quote of imported Russian natural gas and crude oil), both in terms of energy commodities (e.g., increasing electricity production from wind and solar, promoting the electrification of final uses, delaying the phase-out of coal power plants). Among the solutions proposed in REPower plan, replacing fossil resources with renewable one allows, on one hand to decrease the carbon emissions, on the other, to reduce the quote of fossil demand in TPES and to enhance the exploitation of indigenous resources (e.g., wind and solar).

Dependency index

The expected increase in RES generation, even though poses challenges to maintaining the electricity system stability, it will bring benefits to the energy supply system by decreasing the quote of imported crude oil and natural gas from foreign countries, enhancing the energy self-sufficiency of the country.

Oil and gas dependency indexes help to outline this benefit and to track the decrease in national energy dependency. The current ENEA's methodology adopts the Gross Inland Consumption (GIC), provided by EUROSTAT (Table 21), and encompassing Local Production, Net Imports, Recovered & recycled products, change in storage, and International maritime bunkers but excluding international aviation. This choice does not affect the calculation of natural gas energy dependency, as natural gas is not used for International maritime bunkers and international aviation. On the other hand, accounting or excluding maritime and aviation international bunkers affects the overall calculation of oil dependency index.

Table 21: Energy balance definitions provided by EUROSTAT

+	Primary production	**PPRD**
+	Recovered & recycled products	**RCV_RCY**
+	Imports	**IMP**
-	Exports	**EXP**
+	Change in stock	**STK_CHG**
=	**Gross available energy**	**GAE**
-	International maritime bunkers	**INTMARB**
=	**Gross inland consumption**	**GIC**
-	International aviation	**INTAVI**
=	**Total energy supply**	**NRGSUP**

Oil dependency is calculated by the ratio between the net import of oil over the total oil consumption (gross inland consumption of oil), multiplied (weighted dependency) by the share of oil consumption over the total energy consumption (total gross inland consumption); the same calculation approach is adopted to calculate the weighted gas dependency index.

$$D_o = \frac{IMP_o - EXP_o}{GIC_o} \cdot \frac{GIC_o}{GIC_{tot}} = \frac{IMP_o - EXP_o}{GIC_{tot}} \qquad [-]$$

$$D_g = \frac{IMP_g - EXP_g}{GIC_g} \cdot \frac{GIC_g}{GIC_{tot}} = \frac{IMP_g - EXP_g}{GIC_{tot}} \qquad [-]$$

Two possible alternatives have been evaluated to calculate the oil and gas dependency indexes:

1. Replacing the GIC with $NGRSUP$ (Table 21), corresponding to the Total Energy Supply ($TPES$) which excludes both international aviation and international maritime bunkers:

$$D_o = \frac{IMP_o - EXP_o}{TPES_o} \cdot \frac{TPES_o}{TPES_{tot}} \ [-] \qquad D_g = \frac{IMP_g - EXP_g}{TPES_g} \cdot \frac{TPES_g}{TPES_{tot}} \ [-]$$

2. Replacing the GIC with GAE (Table 21), corresponding to the Gross Available Energy, includes both international aviation and international maritime bunkers:

$$D_o = \frac{IMP_o - EXP_o}{GAE_o} \cdot \frac{GAE_o}{GAE_{tot}} \ [-] \qquad D_g = \frac{IMP_g - EXP_g}{GAE_g} \cdot \frac{GAE_g}{GAE_{tot}} \ [-]$$

Although the presence or absence of maritime and aviation bunkers in the calculation of natural gas consumption is irrelevant as it is not used as fuel for aviation and naval purposes, for the sake of analogy between dependency indexes and to enable a comparison between them, the proposed metrics are extended to natural gas.

In the first case, by replacing GIC with $TPES$, the value of the dependency index will be higher than the original one, as the denominator is lower (GAE $>$ GIC $>$ TPES). On the other hand, by replacing GIC with GAE, the overall index results lower than the original one as the denominator is higher (GAE $>$ GIC $>$ TPES). Ultimately, to calculate the dependency index for gas and oil systems, it is proposed to adopt the most conservative calculation method, using TPES instead of GIC.

Diversification index

In ENEA's current assessments, the supply diversification for gas and oil is calculated using the Herfindahl-Hirschman Index (HHI). The HHI was introduced as a market concentration index, obtained by summing the squares of individual market shares within a market comprised of N companies.

$$HHI = \sum_{i}^{N} s_i^2$$

By extending the HHI's concept to the energy supply system, the market shares are replaced with individual contribution (s_k) of energy suppliers and the HHI can be formulated as follows:

$$HHI = \sum_{k}^{N} s_k^2$$

As the HHI index is designed to assess market concentration, it ranges from 0 (perfect competition) to 1 (monopoly). By analogy, 0 represents perfect diversification (numerous suppliers), while 1 indicates the absence of diversification (a single supplier) in the supply chain. However, it's important to note that the HHI is not inherently a diversification index, but rather a measure of concentration. Additionally, due to its simplistic nature (sum of squares), it may not effectively capture fluctuations in the supply. Therefore, to fill this gap, an alternative solution is proposed: Shannon-Wiener metric, employed in statistics to measure the diversity of a population, and calculated as follows:

$$S = -\sum_{i}^{N} p_i \cdot ln(p_i) \quad [-]$$

Where p_i is the proportion of each i-th species in the entire population N. the higher the value of index S, the higher the diversity of species in the sample under study. A value equal to zero indicates a population composed just by single species i. By extending the concept of diversity of species to the supply system context, the diversity of species becomes the diversity of suppliers (i.e., countries) of a certain commodity c. In this case, the proportion of each species p_i corresponds to the quote of import by a specific supplier country over the total import:

$$p_i \rightarrow P_k^c = \frac{I_k^c}{\sum_k^N I_k^c}$$

$$P_k^c = \frac{I_k^c}{I_{tot}^c} \quad [-]$$

Where:

- I_k^c represents the net import (i.e., import-export) of commodity c from country k
- I_{tot}^c represents the total net import (i.e., import-export) of commodity c from all the supply countries

By implementing this modification, the new formulation for calculating the indicator of supply system diversification for a certain commodity c becomes as follows:

$$S^c = -\sum_k^N P_k^c \cdot ln(P_k^c) \quad [-]$$

In this form, the metric takes into account the shares of imported commodity from each country k and returns a value between 0 and 1, where 0 indicates no diversification, corresponding to 1 single supplier. The advantage is that this method can be applied to assess the diversification of both natural gas and oil supply system (including crude and refined products).

To obtain the final index it is necessary to perform a normalization of the indicator. The normalization is performed by dividing the value with the maximum value of the indicator $S_{P_{max}}^c$, corresponding to the perfect diversification case: equal distribution of import shares among all suppliers (N).

$$H_s^c = \frac{S^c}{S_{max}^c} \quad [-]$$

The mathematical formulation of the perfect diversification corresponds to:

$$S_{max}^c = -ln\left(\frac{1}{N}\right) \quad [-]$$

Another advantage of this index is its applicability to various context. For instance, it can be extended to investigate the diversification of energy mix in terms of energy commodities. In this case the proportion of each species p_i corresponds to the share of each commodity c over the total energy mix ($TPES$):

$$p_i \rightarrow Z^c = \frac{TPES^c}{TPES} \quad [-]$$

After normalization of the indicator with the perfect diversification case (i.e., equal shares among all energy commodities contributing to the coverage of the national primary energy supply), the index of diversification of the national energy mix results equal to:

$$H_{TPES} = \frac{-\sum_c^M Z^c \cdot ln(Z^c)}{-\ln\left(\frac{1}{M}\right)} \qquad [-]$$

Where:

- M represents the total number of energy commodities contributing to the national primary energy mix (TPES)
- $-\ln\left(\frac{1}{M}\right)$ serves as normalization factor and corresponds to the maximum value of energy mix diversification (assuming perfect diversification of energy mix, hence equal commodities share in the primary energy mix)

Italy is a net importer of crude oil and natural gas resources; therefore, the assessment of diversification of the supply system results more relevant than export system for the evaluation of national energy security. However, the diversification index can be employed also to evaluate the diversification of export system.

Although export diversification is less critical from an energy security perspective, it can be a useful tool for monitoring the evolution of the Italian energy exports, particularly concerning petroleum products contributing to the 85% of the Italian energy export (EUROSTAT, 2022). Indeed, although the scarce production of local crude oil, the Italian refining system produces high quality oil products, especially automotive fuels such as gasoline and diesel fuel, which are then exported to many European countries. However, according to the European policies oriented to decarbonization of energy mix, the demand of petroleum products from European countries is expected to decrease significantly. By monitoring the diversification, it is possible to verify the response of Italian export system: whether it will orientate the market to non-European countries or it will decrease progressively the export activity accordingly with the reduction of European demand.

Therefore, the diversification assessment can be extended to track the evolution of export diversification and, as regards Italy, to monitor the trend of diversification of refined products export over the energy transition process.

The complete list of proposed metrics is presented in Table 22 outlining the description, the mathematical formulation and the unit of measurements.

Table 22: Proposed metrics to evaluate the diversification of energy supply system

Name	**Definition**	**Formula**	**u.m.**
Share of imported commodity c from country (supplier) k	Share of commodity c imported from country (k) over the total import	$P_k^c = \frac{I_k^c}{\sum_k I_k^c}$	-
Share of exported commodity c to country (importer) k	Share of commodity c exported to country (k) over the total export	$Y_k^c = \frac{E_k^c}{\sum_k E_k^c}$	-
Share of commodity c in the national energy mix	Share of commodity c over the total primary energy mix	$Z^c = \frac{TPES^c}{TPES}$	-
Shannon-Wiener indicator of the supply system of commodity c	Indicator of diversification of suppliers of commodity c	$S^c = -\sum_k P_k^c * ln\left(P_k^c\right)$	-
Shannon-Wiener indicator of the export system of the commodity c	Indicator of diversification of importers of commodity c	$S_y^c = -\sum_k Y_K^c * ln(Y_K^c)$	-
Shannon-Wiener indicator of the national energy mix	Indicator of diversification of national energy mix	$S_{TPES} = -\sum_k Z^c * ln(Z^c)$	
Diversification index of supply system of the commodity c	Normalized Shannon-Wiener indicator	${H_S}^c = \frac{S^c}{S_{max}^c} = \frac{S^c}{-\ln(1/K)}$	-
Diversification index of national energy mix	Normalized Shannon-Wiener indicator	$H_{TPES} = \frac{S_{TPES}}{-\ln(1/M)}$	

The data sources of input data necessary to calculate these metrics are the reported below:

- MiSE (Italian Ministry of Economy) provides the ‘Bollettino Petrolifero’, including datasets on monthly crude import by country of origin and quality of crude (crude identification code, API gravity and content of sulphur), monthly import of refined product by country of origin and monthly crude and refined product export by country of destination. These datasets are available in excel format which allows the implementation of automatic download by means of we-crawler.
- SNAM provides daily dataset on natural gas balance, including import and export, in excel format.
- EUROSTAT provides annual energy balance, in excel format, providing information on TPES composition.

To validate the proposed diversification index, a comparative analysis between the index of diversification (Shannon-Wiener) and the index of concentration HHI (Herfindahl-Hirschman Index) has been performed, by introducing five cases with hypothetic import shares of a generic commodity c from a set of suppliers. The aim of the analysis is to verify whether the Shannon-Wiener index allows to measure more precisely than HHI diversification of supply systems and to capture slight variations among the proposed scenarios. The assumed import shares are summarised in Table 23. To perform the comparative analysis, the complement of HHI (0 for monopoly and 1 for perfect competition) was adopted and in Table 24 are reported the outputs of the study.

Table 23: Scenarios configurations included in the comparative analysis between diversification index (H_s) and concentration index (HHI)

Import shares [%] by supplier	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
	$P^c_{k\,1}$	$P^c_{k\,2}$	$P^c_{k\,3}$	$P^c_{k\,4}$	$P^c_{k\,5}$
SUPPLIER 1	0.0%	5.4%	0.4%	5.7%	6.3%
SUPPLIER 2	3.5%	8.8%	13.2%	8.8%	6.3%
SUPPLIER 3	0.0%	5.4%	1.9%	5.4%	6.3%
SUPPLIER 4	0.3%	5.7%	0.1%	5.6%	6.3%
SUPPLIER 5	4.9%	10.2%	3.3%	10.2%	6.3%
SUPPLIER 6	7.3%	12.6%	1.8%	12.5%	6.3%
SUPPLIER 7	84.0%	51.9%	50.2%	17.3%	50.0%
SUPPLIER 8			14.1%	17.3%	6.3%
SUPPLIER 9			15.0%	17.3%	6.3%
N° SUPPLIERS	5	7	9	9	9

Table 24: Results of comparative analysis between Shannon-Wiener Index and HHI

Index	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
${H_s}^c$	0.346	0.784	0.669	0.955	0.789
$1 - HHI^{\,c}$	0.285	0.687	0.687	0.867	0.719

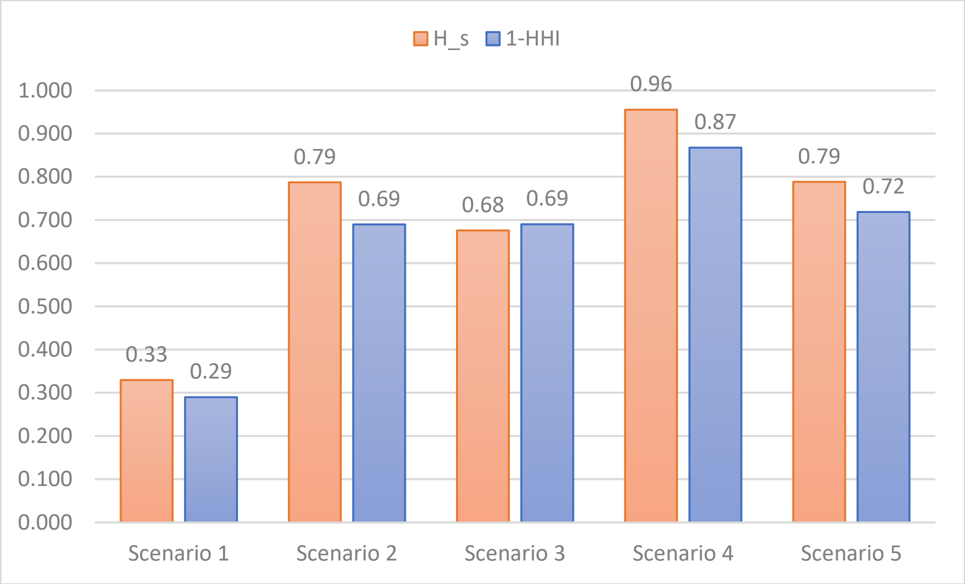


Figure 40: Results of the sensitivity of diversification index (H_s) and concentration index (HHI)

As evidenced by the graph in Figure 40, the findings obtained by H_s and HHI correspond for the extreme cases: both diversification and concentration indexes indicate the Scenario 1 as the worst case, as it is characterized by less suppliers (only 5) than the other cases and by an uneven distribution of import shares (84% of the total import is covered by a single supplier). As regard the best configuration, both indexes identify the Scenario 4, as it combines high number of suppliers (9) with a quite uniform distribution (the maximum share of each supplier does not exceed 17.3% of the total).

Conversely, by focusing on the intermediate cases, it is possible to notice that the concentration index (HHI) assigns the same value to both Scenario 2 and Scenario 3, therefore it fails to trace small variations in the supply distributions. This limitation is due to its function, namely tracking the level of concentration, therefore it allows to highlight whether or not there are unbalances between import shares. On the other hand, the diversification index of Shannon-Wiener is capable of identifying differences between Scenario 2 and Scenario 3. Diversification index of Scenario 2 results higher than Scenario 3: indeed, despite Scenario 3 has one more supplier than Scenario 2, four suppliers out of eight are characterized by low import shares (≤3%). This means that the remaining part of the import is distributed among the other four countries, therefore not an optimal distribution. Scenario 2, on the other hand, presents all import shares ≥5%, therefore the import shares are more balanced among the seven suppliers, resulting better diversified than Scenario 3.

In conclusion, the comparative analysis evidenced that the diversification index is more precise than concentration index in evaluating minor differences between various supply system configuration.

Therefore, to enhance the current index of diversification of oil and gas supply system, it is proposed to replace the concentration index HHI with the Shannon-Wiener index (H_s).

Stability index of supplier countries

Another crucial aspect to be considering when evaluating resilience of supply system, is the geopolitical stability of suppliers. This factor is included in the ENEA's methodology by means of the OECD country risk classification [111]. According to this classification, 0 corresponds to low-risk country and 7 corresponds to high-risk country. However, the use of this index presents some disadvantages summarised below:

1. Since 2013, no risk value has been assigned to high-income OECD countries.
2. Since 2013, no risk value has been assigned to high-income European countries (including Italy).
3. The risk index is published every two years, so an estimate must be made for intermediate years.
4. The limited range (from 0 to 7) does not provide enough granularity to accurately capture the nuances of risk among countries.
5. They are provided in pdf format which makes more challenging data collection compared to datasets in excel format.

As an alternative to the OECD risk index, a composite index derived by the World Bank's World Governance Indicators (WGIs) is proposed. Index, the WGIs presents several advantages:

1. They cover over 200 countries (including OECD countries and high-income European countries).
2. They are available for each year from 1996 to 2022.
3. The ranking scores range from 0 to 100, allowing to capture the diverse degree of geopolitical stability among countries.
4. It takes into account an extensive set of six indicators (i.e., Voice and Accountability, Political Stability and Absence of Violence/Terrorism, Government Effectiveness, Regulatory Quality, Rule of Law, Control of Corruption) characterising the geopolitical situation of the countries.
5. They are provided in excel format, facilitating the automatic collection system by means of web crawlers.

The WGIs are annually updated by the World Bank and they provide a comprehensive governance ranking covering over 200 countries and including six aspects characterising the overall governance performance. The index scores range from approximately -2.5 (weak) to 2.5 (strong) performance, therefore, to better understand the nuances of performance among countries, the percentile rank among all countries, ranging from 0 (lowest) to 100 (highest) rank, are used to build the proposed index of stability. The six WGI indicators composing the developed index of geopolitical stability are listed below:

1. Voice and Accountability (VA): measures the perception of the extent to which citizens are able to participate in the selection of their government, as well as freedom of expression, freedom of association, and freedom of the media.

2. Political Stability and Absence of Violence/Terrorism (PV): measures the perception of the likelihood of political instability and/or politically motivated violence, including terrorism.
3. Government Effectiveness (GE): measures the perception of the quality of public services, the quality of the civil service and its degree of independence from political pressures, the quality of policy formulation and implementation, and the credibility of government commitments.
4. Regulatory Quality (RQ): measures the perception of the government's ability to formulate and implement valid policies and regulations.
5. Rule of Law (RL): measures the perception of confidence in laws and the enforcement of such laws, as well as the likelihood of crime and violence.
6. Control of Corruption (CC): captures the perception of the extent to which public power is subjected to forms of corruption, as well as the extent to which the state is captured by elites and private interests.

The proposed index of stability (WGI) is obtained by the average of the six WGIs. As the ranking score is used as input, the obtained WGI ranges from 0, corresponding to low geopolitical stability (high risk), to 100, which instead reflects high geopolitical stability (low risk):

$$WGI = \frac{VA + PV + GE + RQ + RL + CC}{6} \qquad [-]$$

Combination of supply system diversification with stability index

By combining the diversification index (Shannon-Wiener) together with the geopolitical stability index (WGI), a novel aggregated index is obtained, which considers both variations in the degree of supply diversification and variations in the geopolitical stability of supplier countries.

Before proceeding with combination of H_s with WGI, it is necessary to rescaling the WGI index to the same scale of Shannon-Wiener (0-1 range) and verify the orientation of the metrics:

- $H_s = 0$ means low supply diversification
- $H_s = 1$ means high supply diversification
- $WGI = 0$ means low geopolitical stability (high risk)
- $WGI = 100$ means high geopolitical stability (low risk)

Since both metrics present a positive orientation, therefore they contribute to a higher overall score of diversification, it is not necessary to calculate the complement of this indicators to calculate the index of diversification and stability of suppliers.

$$I_{WGI} = \frac{WGI}{100} \qquad [-]$$

By coupling the diversification index with the geopolitical stability of the supplier countries, the novel index $HR_s{}^c$ is obtained. This index is aimed at measuring simultaneously the degree of diversification of a supply system for a given commodity c and the geopolitical stability of suppliers.

$$HR_s{}^c = -\sum_k^N \left[\frac{S^c}{S^c_{\max}} * I_{WGI,k}\right]$$

The proposed index can be calculated for assessing the supply system of any energy commodity (e.g., natural gas, crude oil, etc.). A sensitivity analysis was conducted to verify the response of the new developed index to variations in diversification of suppliers and in geopolitical stability of suppliers. Three different supply distribution scenarios (i.e., Scenario 1, Scenario 2, Scenario 3) and two hypothetical geopolitical scenarios (I_{WGI_1} scenario and I_{WGI_2} scenario) are assumed. The values of import shares and country stability assumed in the comparative analysis are summarised in Table 25:

Table 25: Input data for comparative analysis

	Supply diversification scenarios			Geopolitical stability scenarios	
	Scenario 1	Scenario 2	Scenario 3	Scenario A (2022)	Scenario B (2017)
Suppliers	$P^c_{k\,1}$	$P^c_{k\,2}$	$P^c_{k\,3}$	I^A_{WGI}	I^B_{WGI}
Austria	0.0%	5.4%	0.6%	0.87	0.92
France	3.5%	8.8%	13.2%	0.80	0.81
Germany	0.0%	5.4%	1.8%	0.88	0.89
Libya	0.3%	5.7%	0.1%	0.04	0.04
Quatar	4.9%	10.2%	3.3%	0.70	0.62
United Kingdom	7.3%	12.6%	1.8%	0.85	0.88
Russia	84.0%	52.0%	50.1%	0.17	0.26
Nigeria			14%	0.17	0.17
China			15%	0.41	0.42
N° suppliers	5	7	9		

The first three cases used in the previous comparative analysis are used as supply distribution scenarios: the first case represents the worst distribution combination, as it has less suppliers and the majority of imported commodity is supplied by Russia; the second scenario reflects instead the better combination among the three scenarios (as previously discussed); the third scenario represents an intermediate situation. As regards the geopolitical stability scenarios, the first (Scenario A) is obtained by the 2022 WGIs, whereas the second (Scenario B) reflects the geopolitical situation of countries in 2017. The output of the comparative analysis proved that, by nature, the simple diversification index cannot capture the effects of variations in geopolitical risk of suppliers in the supply system ($H_{S_A}^c = H_{S_B}^c$) but just in the distribution of import shares. On the other hand, the proposed index (HR_S) results an effective metric to trace both the fluctuations in import shares among suppliers and in the geopolitical stability of suppliers.

The results of the comparative analysis, summarized in Table 26 and illustrated in Figure 41, outline that the overall scores referring to the geopolitical situation in 2022 results lower than the ones calculated by using the WGIs recorded in 2017. Although the distribution shares are the same, the geopolitical stability of many suppliers experienced a decrease in 2022 (Scenario A). Russia, one of the main suppliers in both the Diversification Scenarios (Table 25), recorded a decrease in geopolitical stability, caused by the impacts of the Russia-Ukraine war. This proves that the proposed index of diversification integrated with the geopolitical stability of suppliers is capable of effectively capturing both variations in import distribution and also fluctuations in geopolitical stability of suppliers, offering a more comprehensive overview of the overall performance of the supply system. To show the applicability of the index hypothetical shares of a generic commodity are assumed, however, this methodology can be applied to any commodity and by using both historical data and future estimation. For instance, it can be employed in future scenarios analysis to evaluate the effects of different supply configurations, assuming variations in geopolitical stability of suppliers, in the overall supply system's score.

Table 26: Results of comparative analysis

Index	Scenario 1	Scenario 2	Scenario 3
$H_{S_A}^c = H_{S_B}^c$	0.318	0.784	0.669
$HR_{S_A}^c$	0.199	0.462	0.305
$HR_{S_B}^c$	0.202	0.477	0.319

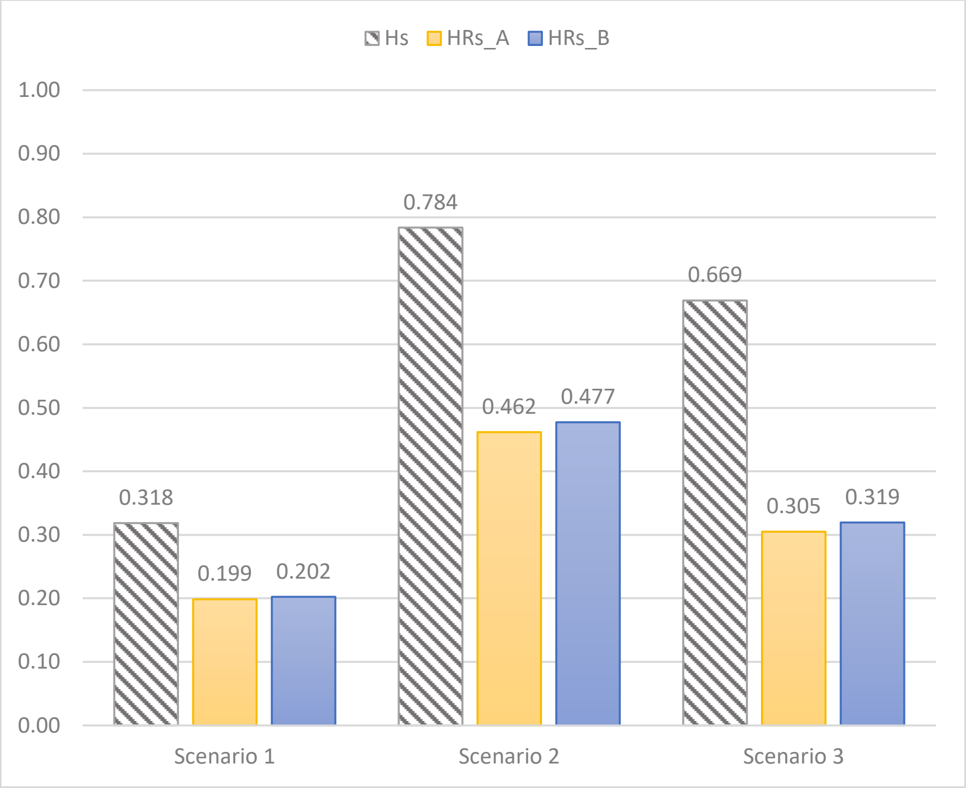


Figure 41: Results of comparative analysis between Hs and the index HRs of diversification and stability of suppliers

4.2.5 Decarbonization domain

As shown in Table 16, the framework of metrics for evaluating the decarbonization performance of the Italian energy system includes CO2 emissions and the penetration of renewables in the energy mix. The score is obtained from the difference between the recorded data and the theoretical data for achieving the objectives in the PNIEC 2023 [112] in line with the European decarbonization objectives (FIT55 [17]). These two pieces of information are crucial for tracking the evolutionary trend of Italy towards decarbonization. However, although electrification is an essential element for fully evaluating Italian decarbonization policies, the current ENEA's decarbonization assessment lacks a detailed study of the evolutionary trend of electrification in Italy by sector.

4.2.5.1 The Green Electrification Rate

Electrify Italy [16] stresses the importance of electrification in the decarbonization process. It focuses on the electrification potential of each sector contributing to the energy consumption in Italy. Among the key findings of the study, it is demonstrated that electrification can significantly contribute to reduce carbon emissions: it is estimated up to -68% in total CO2 emissions compared to 2015 by 2050, thanks to the electrification of the residential, industrial, and transport sectors. Additionally, the study shows that electrification can bring environmental benefits, particularly in terms of air quality, by significantly reducing atmospheric pollutant such as PM10 emissions and NOx emissions, respectively -76% and -69% compared to 2015 by 2050. Furthermore, the reduction in air pollution would contributes to the improvement of public healthcare. As a result, from an economic perspective, electrification would contribute to reducing healthcare costs and to favouring the energy affordability for Italian families, by reducing energy expenses by up to 17% by 2050.

As regards the expected electrification rates for each sector, the electrification possibilities are greater for the residential and transport sectors, for which there is a greater margin of electrification compared to industrial and services sectors. In fact, about 90% of final energy consumption in the transport sector is covered by oil products (IEA 2021, [88]), while in the residential sector, over half of the energy consumption is covered by natural gas. Conversely, the electrification potential of the industrial and services sectors is limited both because of the high quote of electricity in their final consumption which restricts the margin of further electrification, and due to technical issues making electrification more challenging (e.g., modifying the operation cycle of large industrial plants).

As evidenced by the analysis of final consumption composition by sector in Italy, the services sector reveals the highest share of electricity, accounting for 48% of the total energy consumption ((IEA, [88]), followed by natural gas (44%) and oil products (4%). In the industrial sector the electrical contribution to the total consumption reaches 38% (IEA, [88]), whereas natural gas covers 42% of total energy consumption, followed by oil (7%) and coal (3%). According to the Electrify Italy study, by 2050 the residential sector can achieve up to 53% of electrical share in final consumption, the transport sector up to 41%, and the industrial sector up to 42%.

To better understand the evolutionary trend of electrification in Italy, it is important to track its progress by considering the electrification rates by sector (i.e., residential, industry, transport, and services). Referring to the annual data provided by EUROSTAT [113] in the Energy Balance (Table 27), a Python code was developed to collect from the Italian annual energy balances, available from 1990 to 2022, necessary information to calculate the national Electrification Rate ($R_{e,tot}$): the final energy consumption and the electricity consumption by sector, the total national final energy consumption (FC_{tot}) and electricity consumption ($FC_{e,tot}$).

$$R_{e,tot} = \frac{FC_{e,tot}}{FC_{tot}}$$

Similarly, the formulations of Electrification rates for each sectors result equal to:

$$R_{e,res} = \frac{FC_{e,res}}{FC_{res}} \qquad R_{e,tra} = \frac{FC_{e,tra}}{FC_{tra}} \qquad R_{e,ind} = \frac{FC_{e,ind}}{FC_{ind}} \qquad R_{e,oth} = \frac{FC_{e,oth}}{FC_{oth}}$$

Where:

- $R_{e,res}$ refers to the residential sector;
- $R_{e,tra}$ refers to the transport sector;
- $R_{e,ind}$ refers to the industrial sector;
- $R_{e,oth}$ refers to other sectors (i.e., commercial and public services, agriculture and forestry, fishing and other in Table 27)

Table 27: Input data to calculate the trend of electrification rate in Italy (Source: Energy Balance by EUROSTAT [113]*)*

		TOTAL	E7000
ktoe 2022		Total	Electricity
Final energy consumption	FC_E	110,840.7	24,676.5
+ Industry sector	FC_IND_E	24,753.8	9,599.1
+ Transport sector	FC_TRA_E	36,345.8	774.6
+ Other sectors	FC_OTH_E	49,741.1	14,302.8
+ Commercial & public services	FC_OTH_CP_E	16,478.0	8,165.7
+ Households	FC_OTH_HH_E	29,976.7	5,558.0
+ Agriculture & forestry	FC_OTH_AF_E	2,918.2	549.2
+ Fishing	FC_OTH_FISH_E	189.8	19.8
+ Not elsewhere specified (other)	FC_OTH_NSP_E	178.4	10.1

The trends in electrification rate shown in Figure 42 demonstrate that industry and services sectors already have high quote of electricity in their final consumption, characterized by a constant increase since 1990. Residential sector, and in particular transport sector, on the other hand, registered slight improvement of electricity quote, therefore it is essential to raise their electrification in order to increase the overall electrification of national final energy consumptions.

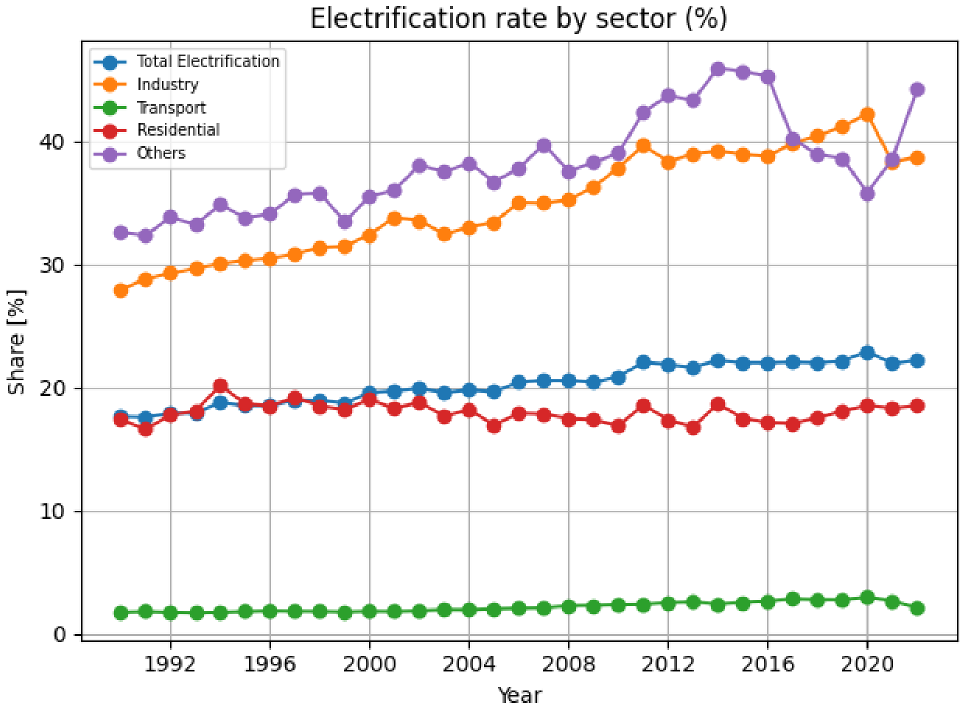


Figure 42: Trend of Electrification Rate by sector (Source: Elaborated data from EUROSTAT database [114]*)*

It is widely recognized that electrification plays a pivotal role in the decarbonization process. However, achieving the decarbonization objective urges not solely electrification of final energy uses but also the enhancement in low-carbon electricity generation, by increase the quote of power production from non-combustible energy sources.

Penetration of renewable energy sources (RES) in the energy mis is often stressed as a pillar of European Green Deal; however, to meet the decarbonization targets defined in the European FIT55 plan (aiming for carbon neutrality across Europe by 2050 [17]), firstly, it is necessary to prioritize non-combustible energy sources. Among the renewables, solar, wind, geothermal, and hydroelectric energy, meet this requirement, since they do not involve combustion to produce energy, unlike other RES, such as biofuel and waste, which contribute to the overall carbon emissions. Although it is not included in the renewables category, also nuclear energy provides emission-free electricity generation. For this reason, IEA in the Net Zero Roadmap distinguishes between the RES generation and the low-carbon sources generation, including non-combustible RES and nuclear generation. Moreover, IEA added among the World Energy Transition Indicators the share of low-carbon source in power generation (IEA, Energy Statistics Data Browser [115]).

Recognizing the paramount importance of achieving carbon neutrality, a novel indicator has been introduced to combine the penetration of non-combustible renewables (excluding energy derived from biofuels, waste, etc.) in the electricity generation system together with the national electricity consumption: the Green Electrification Rate.

$$R_{e_{green}} = \frac{G_{e_{nc}}}{FC_{e,tot}} = \frac{G_{e,ncRES} + G_{e,nuc}}{FC_{e,tot}} \qquad [\%]$$

Where:

- $R_{e_{green}}$ is the Green Electrification Rate;
- $G_{e_{nc}}$ corresponds to the total electricity generation from non-combustible sources;
- $G_{e,ncRES}$ reflects the electricity generation from non-combustible renewables such as hydro, solar wind and geothermal;
- $G_{e,nuc}$ corresponds to the electricity generation from nuclear;
- $FC_{e,tot}$ represents the national final consumption of electricity.

To calculate this indicator, it is possible to gather the required input data from the IEA's Monthly Electricity Statistics [116]which provides updated electricity data for all the OECD countries. The fine temporal resolution (monthly) allows to capture the fluctuations in Green Electrification Rate (Figure 43). The dataset covers a wide range of information such as electricity generation by source (GWh), distribution losses, import and export, but it lacks data on electricity consumption by sector, therefore this information is collected from the EUROSTAT Energy Balance [113] .

The calculation of the indicator has been performed through python code: as shown in the Figure 43, the Green Electrification Rate can vary significantly over a single year. This is due to the inherent variability of wind and solar production according to the seasons (e.g. more solar production in summer), which also affects the hourly fluctuations over the day. However, the quarterly (Figure 44) and the annual (Figure 45) results allow to observe an overall increase in the Green Electrification Rate.

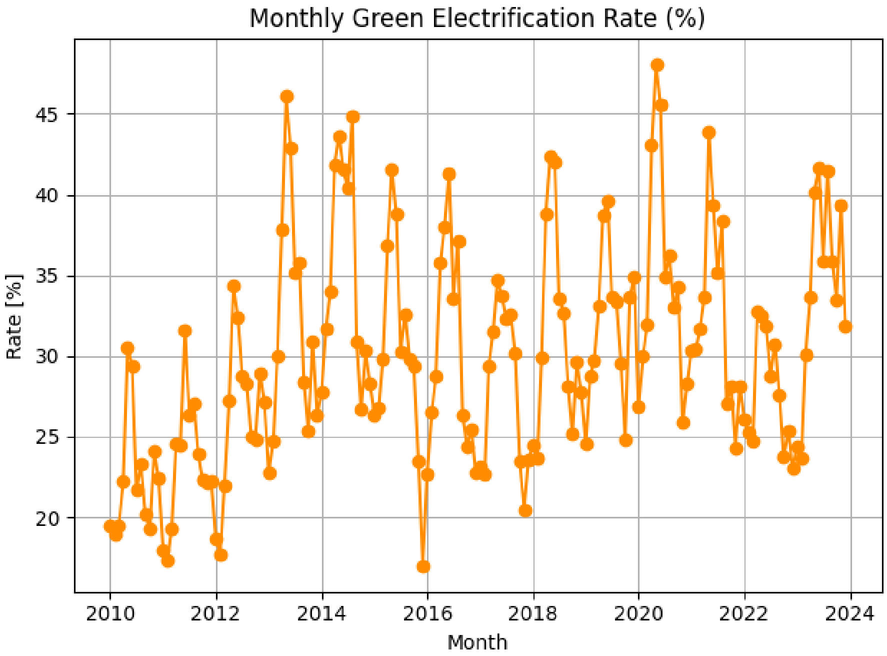


Figure 43: Monthly trend of Green Electrification Rate in Italy (Source: Elaborated data from IEA's Electricity Statistics)

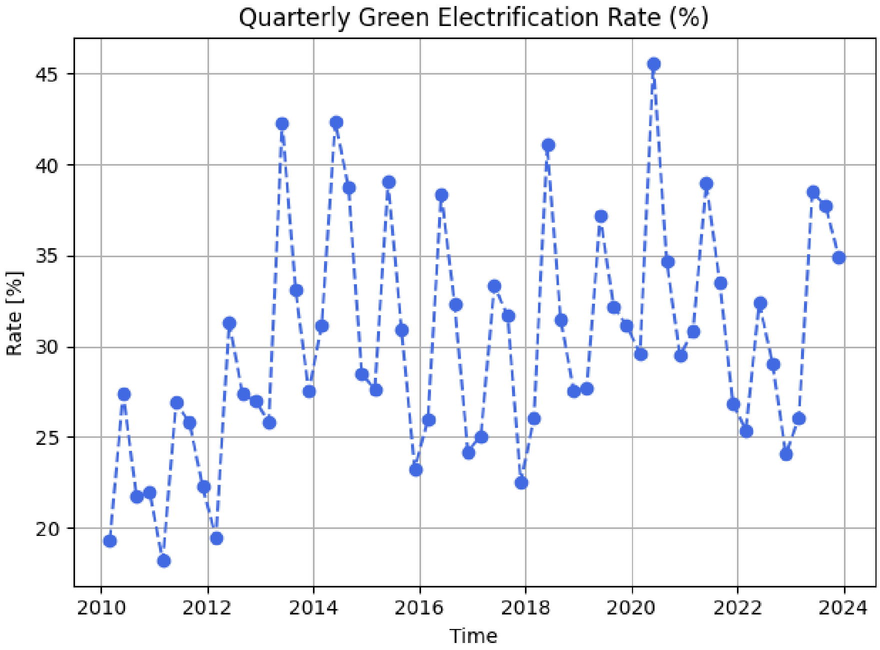


Figure 44: Quarterly trend of Green Electrification Rate in Italy (Source: Elaborated data from IEA's Electricity Statistics)

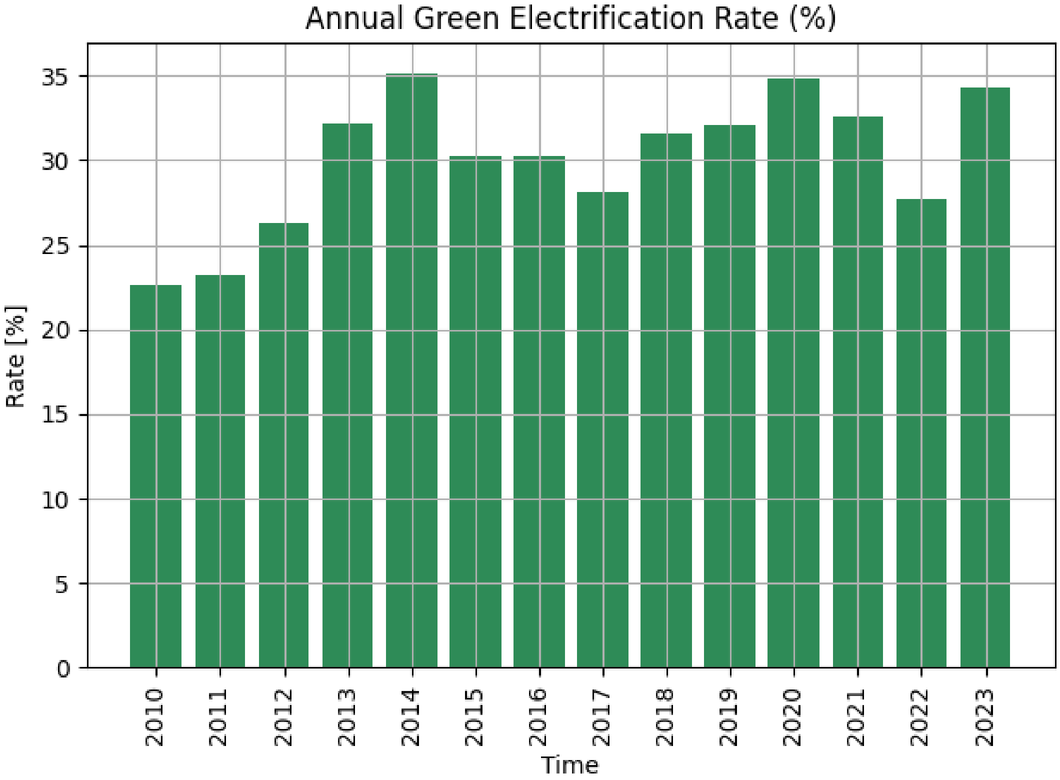


Figure 45: Annual trend of Green Electrification Rate in Italy (Source: Elaborated data from IEA's Electricity Statistics)

The peak recorded in 2014 (35.2% in Figure 45), a historical record of renewable penetration in Italy, was nearly reached in 2020 (34.8%). However, it's important to note that the 2020 was significantly influenced by the Covid-19 pandemic and the following lockdowns, which led to a general contraction in final consumption, including electricity consumption. Since the Green Electrification Rate has the electricity consumption in its denominator, the consumption decrease brings an increase in the $R_{e_{green}}$ score.

After a decreasing trend between 2021 and 2022, a positive trend was recorded: indeed in 2023, unlike 2020, Green Electrification Rate achieved 34.3% under normal conditions of consumption and production activity.

To consider the contribution of electricity in the total energy consumption, Green Electrification Rate can be adjusted by using a weighting factor calculated as the ratio between the electricity consumption and the final energy consumption of the country:

$$w_e = \frac{FC_e}{FC_{tot}} \qquad [-]$$

The final energy consumption is collected from the EUROSTAT's Energy Balance [113], whose the last available data is up to 2022, therefore the 2023 data is gathered from ENEA's estimation. Despite the IEA's Electricity Statistics, the EUROSTAT's energy balances have annual resolution.

To calculate the numerator of the weighting factor, two alternative data can be employed:

- Monthly data from IEA Monthly Electricity Statistics [GWh]
- Annual data from EUROSTAT [ktoe] (final consumption of electricity used also to calculate the national Electrification Rate)

To maintain consistency in data sourcing, EUROSTAT data is employed for both the numerator and denominator of the weighting factor. As the EUROSTAT data is up to 2022, the 2023 data of electricity consumption is derived from the aggregation of Monthly Electricity Statistics of IEA. To convert from ktoe to GWh a conversion factor is employed (11.63 GWh/ktoe). The Figure 46 outlines the evolution of electricity share in total energy consumption from 1990 up to 2023: it is evident that the electricity share experienced a net increase, reaching the maximum value in 2020. As already mentioned, the 2020 was characterized by the abnormal conditions caused by the impacts of the Covid-19 pandemic. Although the electricity share decreased between 2020 and 2023, the overall trend demonstrates the effectiveness of electrification measures in Italy.

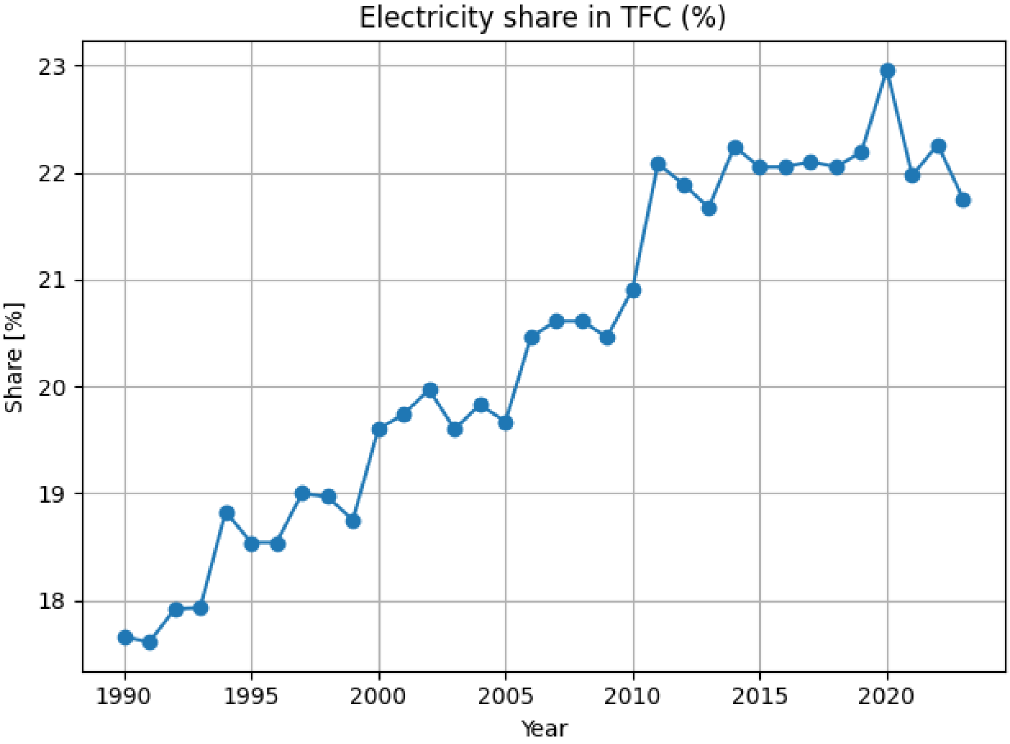


Figure 46: Trend of Electricity share in Total Final Consumption (Source: Elaborated data from EUROSTAT)

To take into consideration the actual weight of green electrification in the national final consumption, the Green Electrification Rate can be modified as follows:

$$R^*_{e_{green}} = R_{e_{green}} \cdot w_e \quad [\%]$$

Where:

- $R^*_{e_{green}}$ represents the normalized Green Electrification rate [%]
- w_e is the weighting factor corresponding to the electricity share in final energy consumption [-]

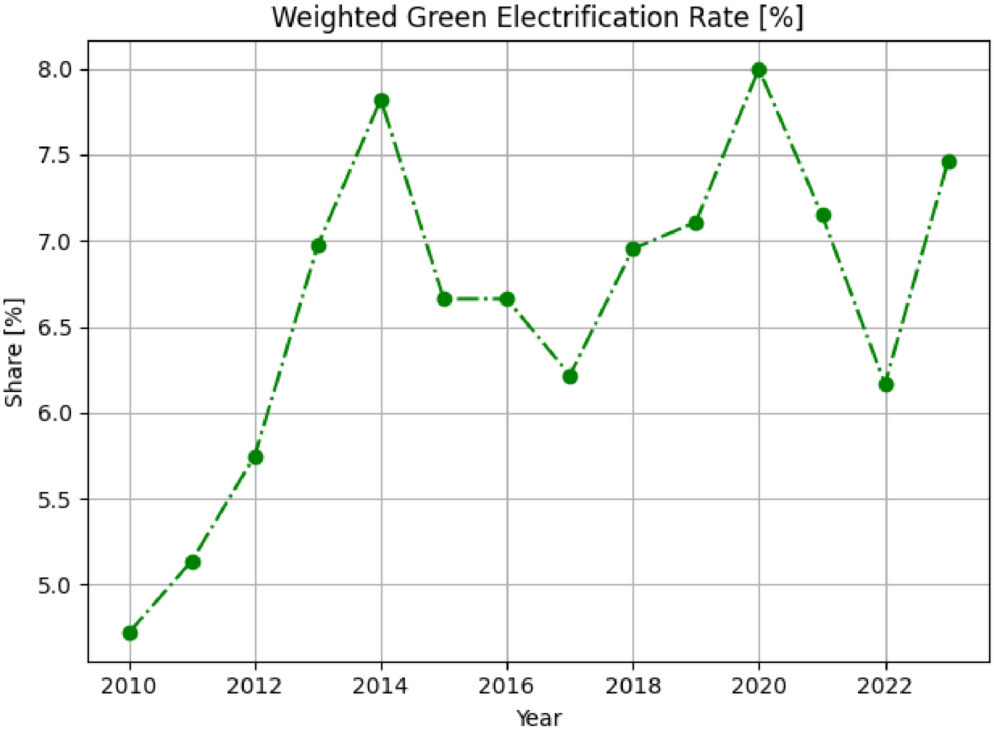


Figure 47: Normalized Green Electrification Rate (Source: Elaborated data from IEA, EUROSTAT and ENEA)

The weighted Green Electrification Rate Figure 47, normalized with the total final energy consumption, follows the same trend of the original Electrification Rate (Figure 45), but its shares result lower as it takes into account the total final energy consumption rather than just electricity consumption. However, the positive trend outlines that Italy is effectively enhancing the quote of electricity in total final consumption as well as increasing the electricity production from low-carbon resources.

Similarly to the energy trilemma, in Electrify Italy [16], the concept of the "electricity triangle" is introduced to describe the scheme of implementation of an effective electrification. The electricity triangle consists of three main elements:

1. Power generation from non-combustible renewable energy sources (mainly wind and solar)
2. Enhancing electrification of energy end-uses (residential, transport, industry and services sectors)
3. Electricity as the main energy vector and power distribution and transmission lines as the main energy transport infrastructure (replacing oil and gas pipelines, vessels, and transport by railways and roads)

Both the first and the second vertexes of the electricity triangle are included in the Green Electrification Rate. In order to include also the third vertex in the electrification assessment, a further indicator aimed at measuring the quality and efficiency of electricity transmission is proposed: the Power System's Transmission Efficiency (T_η).

$$T_\eta = \frac{FC_e + C_{hyd}}{GC_e} \quad [-]$$

Where:

- T_η is the Power System's Transmission Efficiency
- FC_e is the Final Electricity Consumption
- C_{hyd} is the electricity used for hydro pumping storage
- GC_e is the Gross Electricity Production

The difference between the numerator and the denominator depends on the value of losses due to transport (transmission and distribution) of electricity to final users. All information necessary to calculate this indicator is available in Monthly Electricity Statistic (IEA,[116]) up to 2023. The evolution of T_η over time shown in Figure 48 outlines a clear increase in efficiency of transmission and distribution of electricity vector,

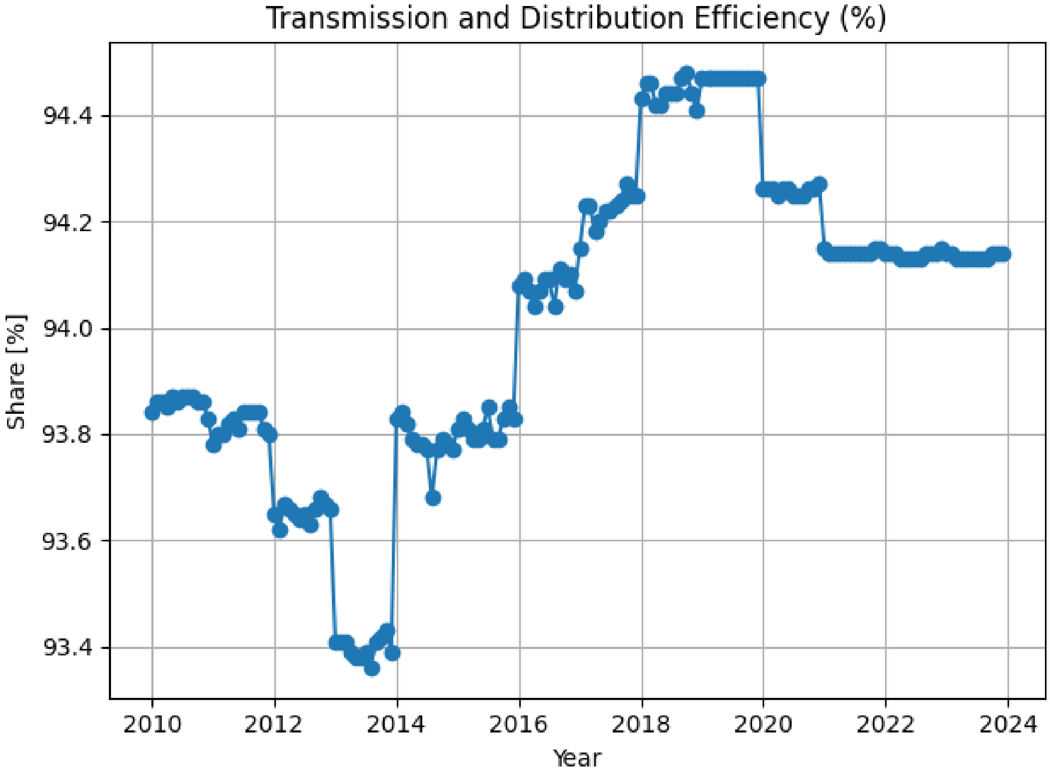


Figure 48: Evolution of Power System's Transmission Efficiency (Source: Elaborated data from IEA Monthly Electricity Statistics)

4.3 Tracking the evolution of urban energy transition on city scale

The European Green Deal, which focuses on reducing fossil fuel consumption and advancing the adoption of renewable energy sources, along with the Climate Law ([19], which establishes 2050 as the target year for achieving carbon neutrality of EU-27 area, stand as tangible evidence of the commitment undertaken by EU member countries to drive forward the energy transition agenda and strive towards carbon neutrality. These initiatives underscore the collective determination to address climate change and promote sustainable development by transitioning to cleaner and more sustainable energy sources. The role of cities in reaching these ambitious goals is crucial. Indeed, the majority of the population is concentrated in urban areas, and cities are major contributors in overall energy consumption and greenhouse gas emissions [117]. As hub of human activity, innovation, and economic development, cities can play a pivotal role in driving successful initiatives, as well as in promoting and accelerating progress towards energy transition and carbon neutrality at larger scale. Given the multitude of variables involved when dealing with multi-dimensional and multi-scale phenomena such as energy transition, understanding the urban performance across various dimensions (e.g., energy, environment, society, economy) becomes crucial in guiding policymakers in evaluating effective policies. Metrics serve as valuable tools for measuring performance across different dimensions, highlighting positive and negative performance trends over time, identifying the criticalities which need further interventions and increased investments. Moreover, by offering a comprehensive view of progress and impacts over time, metrics provide policymakers with the insights needed to formulate new effective strategies, set realistic goals, and evaluate the impact of policies over time. This chapter delves into the topic of assessing energy transition at the city-scale and introduces a novel approach to build the Urban Energy Transition Index (UETI) [117], a composite index measuring the urban energy transition across three main dimensions and designed to continuously track the trend of urban energy transition over time.

4.3.1 Review of metric-based approaches for assessing urban energy transition

Numerous studies have focused on building metrics to measure the impacts and performance towards energy transition across different spatial scales. However, the multitude of approaches available in literature without any commonly recognized framework underscores the inadequacy of a single pre-set "one-size-fits-all" approach [64].

The IRENA’s Energy Transition Welfare Index [67] and the IEA’s Global Energy Transitions Stocktake [97] perform the energy transition performance assessment at the global scale, while other organizations such as WEF with the Energy Transition Index (ETI) [118] and WEC with the Energy Trilemma Index [119] focus on country-scale. Similarly, the Transition Performance Index (TPI) [69] is used by the European Commission to rank countries and to foster constructive competition among them, encouraging emulation of countries with the best performance. Shifting the focus to the city-scale, the International Organization for Standardization (ISO) defined the ISO 37120 standard [120], encompassing a set of 100 indicators to assess the sustainable development of cities. Complementary standards, ISO 37122 [121] and ISO 37123 [122], present additional indicators tailored to evaluate urban resilience and smartness. Although these standards offer a useful framework, they lack guidance on how to perform normalization, weighting allocation, and aggregation steps.

Several European projects aim at developing a comprehensive framework to assess city performance in the context of energy transition. The CITYKEYS project [123] (2015-2017) presented a set of Key Performance Indicators (KPIs) to measure the sustainability and smartness of European cities, while the REPLICATE project [124] (2016-2021) shifted the focus at the district level. Other projects funded under the European Union's Horizon 2020 Programme, like POCITYF [125] (2019-2024), IRIS [126] (2017-2023), and SmartEnCity [127] (2016-2022), aim to quantify the impact and effectiveness of adopted strategies in various contexts (e.g., IRIS and SmartEnCity dealt with urban transport and energy supply, POCITYF is more focused on citizens' need).

As discussed in 2.2.3, simpler methods are often preferred over sophisticated and intricate approaches which hinder the communication and interpretation of findings to the final audience. This holds true especially when the target audience comprises a wide range of audiences such as politicians and citizens. As regards the assessment of city-scale performance, the combination of Min-Max normalization with equal weight additive aggregation is one of the most used methods [53], [54], [68], [70]. Alternatively, rank-based methodologies are widely used for comparative analyses, as seen in the Arcadis Sustainable Cities Index (SCI) [128], IMD Smart City Index [71], Global Cities Report [129], and IESE Cities In Motion Index (CIMI) [72]. Although rankings serve as a useful tool to compare cities, they do not convey the intensity or the extent of differences between cities since they only consider their relative position within the ranking; in addition to this, city rankings generally include the capitals or the few big cities of each country, excluding other important cities. For instance, as regards Italian cities, numerous rankings at the global scale [71], [128], [129] encompass only Milan and Rome. Moreover, apart from some notable studies [65], [130], [131] providing valuable insights on sustainability energy transition performance of Italian cities, the literature review revealed a limited availability of energy transition assessments among Italian countries, highlighting the need to deepen this issue and bridge the existing gap. D'Adamo et al. study [65], [132] adopts the Fondazione Enrico Mattei's methodology to assess the score of 103 Italian cities expressed in terms of level of achievement of the Sustainable Development Goals (SDGs)[133]. Therefore, the evaluation encompasses not only energy transition, but also other

general aspects related to the urban system such as poverty, quality education, and gender equality. However, the focus on all SDGs may not fully capture the nuances of energy transition performance, highlighting the need for more focused assessments in this topic.
Similarly, Legambiente's annual report [130] offers valuable insights into environmental performance trends among Italian cities (104 cities). Though, the adopted framework is mainly focused on environmental aspects (e.g., management of water, soil, and waste), neglecting other aspects relevant for a comprehensive assessment of energy transition performance. For instance, this approach lacks indicators measuring the socio-economic impact of urban energy transition (e.g., investment, employment, added value, energy poverty, etc.). Moreover, among the 18 indicators comprising the composite index "Indice Ecosistema Urbano" (IEU), just a single indicator is intended for the measurement of energy aspects (i.e., kW of installed photovoltaic systems per 1000 inhabitants). Numerous aspects essential for quantifying energy transition performance such as energy intensity by consumption sector (e.g., residential, tertiary, transport, etc.), the penetration of renewables in final consumption and the integration of green vehicles into the urban system, are neglected. Furthermore, the lack of metrics on CO2 emissions makes this approach ineffective for monitoring progress towards carbon neutrality going on with the energy transition process. On the other hand, the Municipal Transition Index (MTI) [131] presents a detailed overview of energy transition in Italian cities, encompassing a broad range of indicators across various dimensions affecting the overall energy transition performance. Although this study offers valuable insights on energy transition performance of a wide range of Italian cities (7904 municipalities are included in the assessment), it does not provide a temporal evolution but only a snapshot. Moreover, the overall score of MTI is obtained by aggregating 18 indicators referring to different years, according to the latest data availability (e.g. some indicators refer to 2021, others to 2019 or 2018). This approach, on the one hand, implies a discrepancy among the real performance in a specific year, and consequently in the overall score too, on the other hand, it poses challenges for interpretation of results and for further comparative analyses with other methodologies. In contrast, Shen et al. [70] in 2023 published a comprehensive assessment of energy transition in 282 Chinese cities from 2003 up to 2019 and including a comparison of their findings with the ETI's score [118] at the country-scale. However, none of the observed approaches includes in the framework indicators referring to the power system, such as grid quality, penetration of electrical vehicles in the urban transport and the adequate installation of infrastructure allowing for integration of electrical vehicles in the urban system.

Ultimately, the review of existing literature on the assessment of energy transition performance at the city scale revealed the lack of a comprehensive composite index framework aimed at monitoring over time the urban energy transition and which satisfies all four essential criteria:

1) covering a wide range of factors crucial for assessing the multifaceted impacts of energy transition, such as energy intensity, carbon emissions, and socio-economic implications, also including metrics to track electrification process (e.g., integration of electric vehicles in the transport sector) and monitor the adequacy of electricity distribution in the city (i.e., power grid quality metrics);
2) being easily understandable and allowing communication of findings to diverse audiences, including non-experts;
3) demonstrating applicability and flexibility across diverse urban settings, even in situations with limited data availability;
4) incorporating correlation and sensitivity analyses to ensure transparency in the study's findings.

To address this gap, in this section is introduced a novel framework designed to evaluate urban-scale energy transition across energy, environmental, and socio-economic dimensions (meeting requirement 1) through the development of the Urban Energy Transition Index (UETI). By prioritizing less intricated and easy-to-communicate methodologies of normalization, weighting allocation, and indicators aggregation, this framework aligns with requirement 2. Additionally, the applicability of this methodology to cities facing data limitations is demonstrated through a case study focusing on the city of Turin, fulfilling requirement 3. Furthermore, to ensure study transparency, both correlation analysis and sensitivity analysis are included, in line with requirement 4. In addition, in line with the aim of enabling the replicability of the proposed approach, the complete list of datasets and data providers utilised to collect data for the case study are reported in APPENDIX, Table 35. Furthermore, to validate the methodology employed, a comparative analysis with other studies is included in the discussion of results. This comparison aims to identify both commonalities and discrepancies: commonalities reinforce reliability of the proposed methodology, whereas discrepancies are discussed in detail, by providing clear explanations for any observed variations.

4.3.2 Development of the Urban Energy Transition Index (UETI)

Aligned with the COIN’s guidelines for building a composite index (section 2.2.3.2), the first step entailed the definition of the conceptual framework and the core pillars at the basis of the hierarchical structure composing the developed Urban Energy Transition Index. Following a thorough analysis of the available literature on this topic, Energy, Environment and Socio-economy have been selected as pillar domains for evaluating the energy transition at urban level. Each domain is further divided into specific sub-domains, as illustrated in Figure 49.

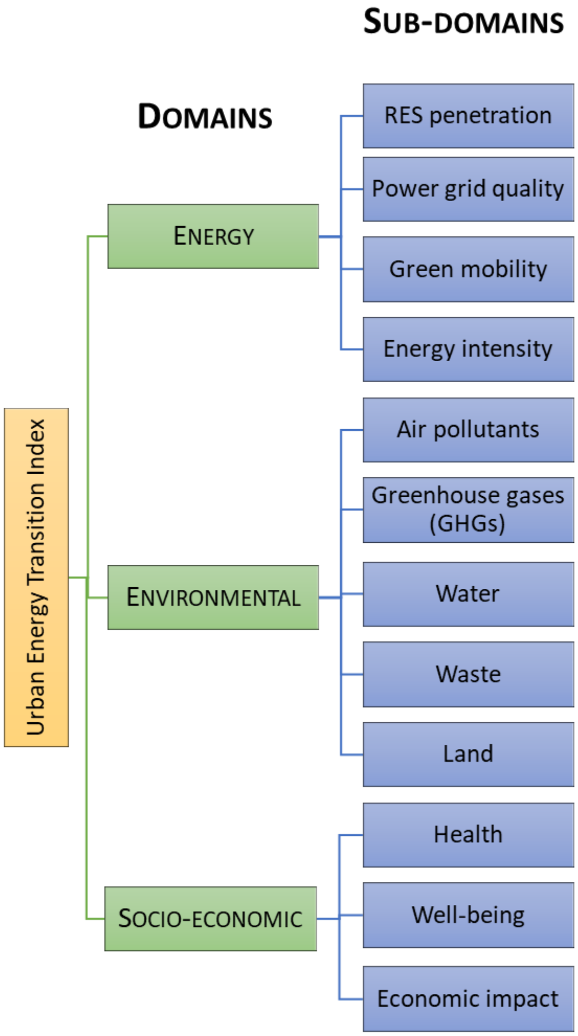


Figure 49: Selected domains and sub-domains of the UETI's framework

The Energy domain seeks to include the main metrics referring to the 7th SDG - Affordable and Clean Energy [133] (2030 Agenda for Sustainable Development) within the urban context. It comprises four sub-domains: Renewable Energy Resource (RES) penetration, power grid quality, green mobility, and energy intensity. The RES penetration sub-domain evaluates the integration of renewable energy resources into the urban energy supply. Power grid quality is devoted to assessing the efficiency of power grid operations (i.e., electricity distribution). Green mobility tracks the integration of electric and hybrid vehicles into the traditional automotive fleet of and the availability of adequate infrastructure (i.e., charging points). Since they offer a valid solution to traditional mobility, the availability of bike lanes in urban area is considered as relevant metric to be included in green mobility. Since generally considered as a proxy for energy efficiency [134], energy intensities of the main energy-consuming sectors in the city (i.e., residential, industrial, tertiary, and transport sectors) are included in the framework within the Energy intensity sub-domain.

As regards the Environmental domain, five key sub-domains have been identified: greenhouse gases, air pollutants, waste, water, and land management. The first sub-domain refers to urban carbon emissions, which is a crucial element to consider in the framework, especially when studying energy transition in urban contexts, since human activities are typically concentrated in cities, leading to higher levels of greenhouse gas (GHG) emissions. Monitoring carbon emissions while evaluating the overall energy transition performance offers insights into the effectiveness of energy transition initiatives in terms of decarbonization. Additionally, understanding the trend of urban carbon footprint serves to inform policymakers and to support them in implementing targeted interventions to mitigate carbon emissions. For similar reasons, air pollution is included in the UETI's framework: indeed, especially in urban areas where human activities are concentrated, the concentration of air pollutants is higher. Tracking the urban air pollution is a key insight to evaluate the benefits of energy transition not only in reducing the carbon emissions but also the levels of atmospheric pollution. Moreover, air pollution has significant implications for human health: exposure to pollutants such as particulate matter (PM10, PM2.5) and nitrogen oxides (NOx) can lead to respiratory problems, cardiovascular diseases, and other adverse health effects. In urban contexts, where population is concentrated, the health risk due to air pollution is a critical issue. Therefore, tracking air pollution levels helps policymakers to evaluate if prioritize interventions to protect public health and to enhance the overall quality of life in urban areas. Apart from GHGs and air pollutants, sustainable use of soil, water consumption and waste management are crucial aspects affecting the overall urban performance; indeed, monitoring these factors enables an exhaustive evaluation of urban sustainability; therefore incorporating these sub-domains into the Environmental domain serves to consider whether the ongoing energy transition meets the conditions of sustainable urban development in a manner that meets the needs of the present generation without compromising the ability of future generations to meet their own needs (SDG 11: Sustainable Cities and Communities and SDG 12: Responsible Consumption and Production) (2030 Agenda for Sustainable Development [133]). Sustainable land use sub-domain serves to monitor whether the city is implementing actions to make urban settlement sustainable, inclusive and resilient. Water consumption is devoted to measure the quality of water management- in city, promoting water conservation practices, and safeguarding water availability and quality for future generations. Similarly, waste management sub-domain aims at tracking the effectiveness of sustainable waste management initiatives implemented in the city, including the reduction of waste production per capita, increasing the quote of recycled waste, and advancing disposal practices. Rapid urbanization results in escalating waste generation, straining waste management systems and exacerbating environmental pollution. By monitoring metrics related to waste generation, recycling rates, and landfill diversion, cities can identify opportunities for waste reduction, resource recovery, and circular economy initiatives, ultimately minimizing environmental impacts and promoting a more sustainable approach to waste management.

The inclusion of socio-economic metrics in the conceptual framework is essential for achieving a holistic understanding of the overall energy transition performance. As evidenced by SDG 8 (Decent Work and Economic Growth) and SDG 10 (Reduced Inequalities) (2030 Agenda for Sustainable Development [133]), socio-economic aspects are indispensable factors for a complete energy transition assessment. Three sub-domains are included in the Socio-economic domain: Economic impact, Well-being and Health. The first sub-domain seeks to provide insights on investments and other benefits brought by the energy transition initiatives such as employment and added value. The other two sub-domains address citizens' welfare both from a physical (health) perspective and in terms of quality of life (well-being). Overall, the proposed conceptual framework is composed by 3 domains and 12 sub-domains.

After defining the conceptual framework, the next step (Step 2 of COIN's guideline, section 2.2.3.2) involves selecting a set of indicators to quantitatively assess the impact of energy transition across the 12 sub-domains. However, in city-scale analyses, data scarcity poses a significant challenge to indicator calculation and therefore in indicators selection. This underscores the need for a flexible methodology that offers a robust yet adaptable framework for assessing and monitoring urban energy transition, even with data limitations. To maintain flexibility and adaptability, specific indicators (listed in Table 28) are not predetermined within the conceptual framework. This choice recognizes the dynamic nature and diversity of urban settings and seeks to provide a comprehensive yet adaptable framework for assessing energy transitions in cities, allowing for adjustments and inclusion of relevant metrics based on the specific characteristics of the city under examination.

The normalization, weighting, and aggregation methods (steps 4,5,6 of COIN guidelines) have been chosen following a thorough and extensive review of the existing literature on composite index construction. The chosen combination includes additive aggregation coupled with equal weighting and Min-Max normalization, in accordance with the criterion 2 outlined in the method's objectives.

As regards the aggregation process, three levels can be distinguished:

1) Sub-domain level: it involves the aggregation of indicators (normalized with Min-Max approach) within the same sub-domain to calculate the sub-domain performance index.
2) Domain level: it involves the aggregation of indexes within the same domain to calculate the domain performance index (i.e., Energy, Environmental, and Socio-Economic index)

3) UETI level: it involves the aggregation of domain performance indexes to obtain the final UETI score.

4.3.3 Assessment of the energy transition evolution in the city of Turin

To test the applicability and to validate the proposed methodology, the UETI's approach was adopted for assessing the energy transition progress in the city of Turin as a case study. The selection of Turin was driven by several key considerations. Firstly, Turin is one of the major cities in Italy and in Europe, though global city-rankings [71], [128], [129] typically focus on Rome and Milan as representative of Italian urban hubs. Furthermore, Turin has been selected as one of the 100 European cities participating in the "Climate-Neutral and Smart Cities by 2030" mission, launched by the European Commission to promote healthy competition on achieving urban carbon neutrality by 2030. The Turin's involvement in this mission reflects its commitment to accelerate EU-27 climate neutrality journey (Climate Law [19]) but it also emphasizes the city's effort to advancing energy transition initiatives and to aligning with the sustainability objectives outlined in the 2030 Agenda [135], [136]. Moreover, Turin's case is particularly noteworthy due to its unique geographical and socio-economic context; due to its geographical location characterized by low wind intensity, in combination with the high volume of vehicles traffic and industrial activities, the concentration of air pollutants such as NO2, PM2.5 and PM10 reaches critical levels, causing negative effects on population health (e.g., increased occurrence of respiratory diseases). As one of the European cities with the highest concentration of air pollutants [41], [137], advancing energy transition initiatives can play a crucial role to decrease the intensity of fossil-based emissions and enhance the overall air quality of the city. Therefore, the Turin's case study aims to track the UETI trend, encompassing the evolution of various domains (Energy, Environment, and Socio-Economic) over time, highlighting relevant insights on energy transition performance and informing policymakers on effectiveness of ongoing initiatives. Ultimately, this study seeks to underscore the effectiveness of a metric-based methodology (UETI) for systematically monitoring the urban energy transition progress and for advancing policy decision making at the city scale.

4.3.3.1 Selected energy transition city-scale performance indicators

Out of over 100 data collected from 34 datasets provided by 12 sources (listed in APPENDIX, Table 35), we selected 90 raw data to calculate the Urban Energy Transition Index (UETI). A set of 30 indicators (Table 28) tailored to Turin's context, were chosen to assess the impact of energy transition across 12 sub-domains. The chosen performance indicators to assess renewable energy penetration in Turin include installed capacity (MW) and the share of renewables (RES) in the total final consumption (TFC). Given the absence of other renewable resources like wind, hydro, and geothermal sources, photovoltaic technology serves as a benchmark for tracking renewable installations in Turin. Additionally, due to the lack of data on heat consumption by energy source, the share of renewables in electricity final consumption (%), excluding heat consumption, is considered. As renewable energy penetration increases, there may be a negative impact on power grid quality. Hence, the UETI framework includes three indicators to measure power grid performance: duration of outages, average disconnections, and power loss. As mentioned above, air pollution is still a critical aspect in the Turin's context, therefore monitoring air pollution evolution deserves particular attention. PM10 exceedances and NO2 concentration are selected as reference metrics to track this aspect. Furthermore, the shift from traditional combustion engine vehicles to electric (EVs) and hybrid vehicles (HVs), plays a crucial role in mitigating air quality issues and reducing the city's overall carbon footprint too. Turin's transport sector is expected to increase the share of EVs and HVs in the coming years [112]; this trend is monitored by taking into consideration the number of EVs and HVs per 1000 passenger vehicles, as well as the Number of EV charging points over 1000 EV + HV private vehicles (n.) and the Number of RES-EV charging points (n.). Cycle lanes distribution is a further factor included in the Green mobility sub-domain since it provides additional information about the urban progress towards more sustainable transportation, and it also reflects the effort to encourage citizens to choose soft mobility (e.g., bikes and e-scooters) over traditional private vehicles. Improving energy efficiency is a pivotal strategy for attaining carbon-neutrality objectives at the urban level. Monitoring energy consumption per unit of economic activity, known as energy intensity, provides valuable insights into the effectiveness of energy efficiency initiatives across various sectors. These include residential (MWh/inhab), tertiary (MWh/kEUR), transport (MWh/Mpkm), industry (MWh/kEUR), and municipal services (MWh/m2). Another important factor to monitor is the city's overall carbon footprint, measured in tons of CO2 emitted per capita (carbon intensity: tCO2/inhab). As discussed above, to obtain a composite index offering an exhaustive view of energy transition progress implemented according to the sustainable urban development goals [133], responsible management of soil, water and waste are imperative. This entails monitoring metrics such as green coverage (ha/100,000 inhab), pedestrian areas (m2/100 inhab), per capita water consumption (l/day·inhab), water distribution loss (%), Municipal waste production per capita (kg/inhab) and percentage of sorted waste (%). Considering specific urban factors such as air quality issues (e.g., high concentrations of PM10 and NO2), high population density, and unique geographical and climatic conditions, indicators such as deaths from respiratory system diseases (%) and mortality rates are of particular importance in assessing the anticipated positive impact of the energy transition on public health in the city of Turin. Furthermore, the UETI encompasses the economic implications of the energy transition by including metrics such as Energy–Environment Investments (%), Energy–Environment Added Value (EUR), and Energy–Environment Employment (%). These metrics offer valuable insights into the benefits of the energy transition for Turin's urban economy, presenting an opportunity for economic diversification and alignment with global sustainability objectives, thereby fostering job creation and attracting green investments. Regarding the well-being of citizens, the combination of income (kEUR/inhab) and energy poverty (%) enables the evaluation of social disparities. While income serves as an average indicator of the overall economic status of the population, the progress of energy poverty underscores worsening vulnerability among certain population segments. Together, these indicators serve to provide relevant insights into ongoing socio-economic phenomena within the context of the energy transition.

Table 28: Selected performance indicators by sub-domain (Source: [117]*).*

Sub-domains	Performance indicators
RES penetration	Installed RES capacity (MW)
	Share RES in electricity consumption (%)
Power grid quality	Duration of outages (-)
	Average number of disconnections (n.)
	Power Loss (%)
Green mobility	Number of RES-EV charging points (n.)
	Number of EV charging points over 1000 EV+HV private vehicles (n.)
	Number of EV+HV over 1000 passenger vehicles (-)
	Cycle lanes (km/100 km^2)
Energy intensity	Energy intensity residential sector (MWh/inhab)
	Energy intensity tertiary sector (MWh/k€)
	Energy intensity transport (MWh/Mpkm)
	Energy intensity industry (MWh/k€)
	Energy intensity municipal service (MWh/m^2)
Land use	Green coverage (ha/100,000 inhab)
	Pedestrian areas (m^2/ 100 inhab)
Waste	Municipal Waste (kg/inhab)
	Sorted waste (%)
Water	Water Consumption (l/day*inhab)
	Water Loss (%)
Air pollutants	PM10 exceedances (n. days/year)
	NO_2 concentration (µg/m^3)
GHGs	Carbon intensity (tCO_2/inhab)

Health	Deaths from respiratory system diseases (%) Mortality rate (n deaths/10000 inhab)
Economic impact	Energy-Environment Investments (%) Energy-Environment Added value (€) Energy-Environment Employment (%)
Well-being	Income (k€/inhab) Energy poverty (%)

4.3.3.2 Application of the UETI's approach to assess the Turin's energy transition progress

Following the selection of key indicators to evaluate comprehensively the advancement of energy transition in the city of Truin across the three macro-dimensions of Energy, Environment and Socio-economy, a thorough mapping of all available datasets for these indicators was performed. Consequently, the case study has been conducted considering the latest available update for each dataset. As shown in APPENDIX, Table 35, almost all datasets have been updated beyond 2019. However, the choice of limiting the study period up to 2019 has been constrained by the lack of updated data from the Turin Action Plan for Energy – TAPE (DT26 in APPENDIX, Table 35). Indeed, DT26 serves as main source for Turin's energy and environmental data. Since these data include are essential for calculating sub-indices composing the UETI and measuring crucial aspects of urban energy transition, such as the energy intensity by sector and urban carbon intensity, they cannot be excluded from the index framework. Moreover, rather than using the latest available data from each dataset and obtaining a heterogeneous final score referring to various years, it was considered more appropriate to extend the temporal range of the analysis up to the year when all indicators were calculable (2019). Nevertheless, despite this limitation, it was still feasible to discern trends in the UETI index and its dimensions (Figure 50).

As regards the normalization, weighting allocation and aggregation procedures, the considerations mentioned in section 2.2.3 have been followed. Min–Max normalization is employed to standardize each of the 30 indicators. This conversion ensures that a score of 1 corresponds to the best performance observed and 0 to the worst performance over the period considered (2014–2019). Subsequently, three stages of additive aggregation with equal weight are conducted. The initial aggregation accounts 12 performance indexes (listed in Table 29): 4 for the Energy domain, 5 for the Environment domain, and 3 for the Socio-Economic domain. Similarly, the subsequent aggregation calculates performance indexes for each domain. These indexes are then combined in a third aggregation step to derive the UETI, with overall scores depicted in Figure 50.

Table 29: Trend of Turin's UETI over the 2014-2019 period (Source: [117]*)*

	2014	**2015**	**2016**	**2017**	**2018**	**2019**
RES penetration	0.50	0.37	0.29	0.27	0.44	0.55
Power grid quality	0.62	0.58	0.47	0.50	0.57	0.61
Green mobility	0.00	0.08	0.20	0.34	0.62	1.00
Energy intensity	0.21	0.58	0.65	0.74	0.52	0.83
Energy index	0.33	0.40	0.40	0.46	0.54	0.75
Land use	0.05	0.14	0.27	0.61	0.79	1.00
Waste	0.39	0.43	0.54	0.56	0.41	0.66
Water	0.46	0.12	0.29	0.36	0.33	1.00
Air pollutants	0.37	0.08	0.46	0.13	1.00	0.79
GHGs	0.00	0.46	0.49	0.53	0.85	1.00
Environmental index	0.26	0.25	0.41	0.44	0.68	0.89
Health	1.00	0.56	0.82	0.30	0.03	0.20
Economic impact	0.49	0.30	0.11	0.17	0.68	0.81
Well-being	0.30	0.59	0.59	0.72	0.62	0.50
Socio-economic index	0.59	0.48	0.50	0.40	0.44	0.50
UETI	**0.39**	**0.38**	**0.44**	**0.43**	**0.55**	**0.71**

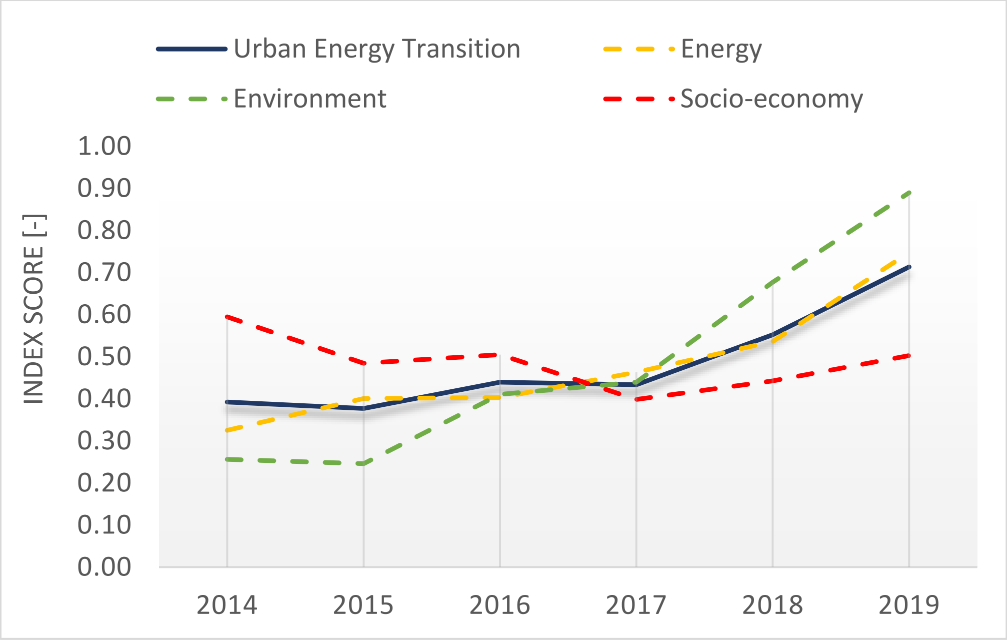


Figure 50: Evolution of Turin's UETI and its three domains over the 2014-2019 period (Source: [117].

Table 30: Performance indicators of the city of Turin (2014-2019)

Perfomance Indicators	2014	2015	2016	2017	2018	2019
Installed RES capacity (MW)	18.5	18.9	19.7	21.3	22.4	23.6
Share RES in electricity consumption (%)	4.8	4.2	3.7	3.0	3.3	3.2
Duration of outages (-)	21.5	19.8	31.0	25.4	28.7	25.7
Average number of disconnections (-)	1.2	1.4	1.3	1.7	1.4	1.4
Power Loss (%)	6.1	5.9	4.7	3.9	4.2	4.2
Number of RES-EV charging points (-)	0.0	0.0	2.0	2.0	2.0	10.0
Number of EV charging points over 1000 EV+HV private vehicles (-)	4.0	3.8	4.3	15.6	45.9	53.5
Number of EV+hybrid over 1000 passenger vehicles (-)	2.6	2.9	4.1	6.8	10.3	14.1
Cycle lanes (km/100 km2)	139.0	146.6	151.6	153.8	159.2	166.1
Energy intensity residential sector (MWh/inhab)	8.9	6.8	6.8	6.7	6.4	6.1
Energy intensity tertiary sector (MWh/k€)	0.2	0.2	0.2	0.2	0.2	0.2
Energy intensity transport (MWh/inhab)	3.2	3.2	3.2	3.1	3.2	2.9
Energy intensity industry (MWh/k€)	0.1	0.1	0.1	0.1	0.2	0.2
Energy intensity municipal service (MWh/m^2)	3.6	3.3	3.0	2.8	2.8	2.6
Green surface (ha/100,000 inhab)	220.0	219.2	219.8	223.9	225.0	226.2
Pedestrian areas (m^2/ 100 inhab)	139.0	146.6	151.6	153.8	159.2	166.1
Municipal Waste (kg/inhab)	491.4	493.8	482.3	498.0	523.3	510.3
Sorted waste (%)	41.6	42.4	42.1	44.7	46.6	47.7
Consumption (l/day*inhab)	293.0	292.0	288.0	287.0	286.0	282.5
Loss (%)	22.4	24.6	24.7	24.6	25.0	22.2
PM10 exceedances (n days/year)	58.5	85.0	63.5	94.5	36.0	45.0
NO_2 concentration (µg/m^3)	39.5	40.5	37.5	38.5	33.0	35.0
Carbon intensity (tCO2/inhab)	3.9	3.5	3.4	3.4	3.1	3.0
Deaths from respiratory system diseases (%)	14.1	14.2	14.2	14.8	15.3	14.8
Mortality rate (n deaths/10000 inhab)	103.1	113.6	106.6	113.5	114.7	115.5

Energy-Environment Investments (%)	4.9	3.7	4.9	3.3	9.0	9.7
Energy-Environment Added value (€)	1761.4	1795.4	1709.9	1836.2	1961.9	1899.7
Energy-Environment Employment (%)	4.4	4.3	4.2	4.2	4.2	4.3
Income (k€/inhab)	16.9	17.3	17.6	17.6	18.4	18.6
Energy poverty (%)	4.8	4.4	4.6	4.3	5.2	5.6

As underscored by the Urban Energy Transition Index (UETI) trend from 2014 to 2019 in Figure 50, the city of Turin registered a notable improvement in the overall energy transition performance. Specifically, the Environmental domain shows the highest performance in 2019, followed by the Energy domain. In contrast, the performance of Socio-Economic domain decreased over the study period. This worsening can be justified by analysing the trend of indicators composing the Socio-economic sub-domains: in particular, health-related indicators such as mortality rate and deaths from respiratory diseases (Table 30Table 28) recorded a significant deterioration over 2014-2019 period. Despite these indicators pertains to the province of Turin due to the lack of city-specific data, as Turin is the main city by population within the province, it is reasonable to infer this result reflects urban trend. Similarly, Energy-Environment Added Value and Employment, were evaluated at the provincial level, whereas Energy Poverty and Energy-Environment Investment, were assessed at the regional level, due to the unavailability of urban and provincial information. Among the three domains, the Socio-Economic one mostly suffered from the scarcity of city-specific datasets. Although provincial and regional metrics offer valuable insights, city-specific data are necessary to enhance the accuracy of urban performance trends. For instance, Well-being sub-domain trend, it is clearly influenced by the deterioration of regional energy poverty, in contrast with the positive trend (Table 30) of Turin's Income (+10% in 2019 with respect to 2014). The choice of using provincial or regional indicators when city-scale data are not available reflects one of the pillars of the proposed methodology, namely flexibility and adaptability stated in criterion introduced in the in section 2.2.3. Moreover, this additional consideration has been taken into account: to solve the problem of data scarcity the alternative solution would involve the exclusion of these metrics from the composite index assessment, leading to a loss of relevant information and consequently affecting the completeness of the evaluation. Encompassing all factors involved in urban energy transition process is one of the main objectives of the proposed approach, thus, coherently with this objective, it was deemed more appropriate to use provincial and regional data to fill the gaps in urban data. Nonetheless, this study underscores the essential need to improve the availability of city-specific datasets by advancing new data collection systems, especially to fill the gap on socio-economic information, in order to enhance the accuracy and reliability of metric-based assessments.

As regards environmental performances, GHG emissions, water consumption, and land use showed the best performances in 2019 compared to the period from 2014 to 2019 (Table 29Table 29: Trend of Turin's UETI over the 2014-2019 period (Source: [117])). Particularly, the GHG emission index, normalized by CO2 emissions per inhabitant, exhibited a consistent and significant improvement trend. Conversely, air pollutant performance displayed a fluctuating trend, with a sharp increase between 2018 and 2019, while waste performance demonstrated steady, though moderate, improvement over time. Similar to the Environmental domain, Energy performance shows a notable increase from 2014 to 2019, driven by advancements in green mobility and energy efficiency in residential buildings. However, the trend in RES penetration showed limited growth in 2019 compared to 2014, possibly influenced by the omission of heat generation data from the share of RES in TFC due to data unavailability. Additionally, the stability of grid quality performance in 2019 compared to 2014 suggests a lack of significant progress in reducing power losses and disconnection issues, therefore, given the expected rise in electricity demand lead by an increased electrification of final consumption in the upcoming years, it becomes imperative to promote initiatives aimed at preserving the quality of the grid and ensuring the reliability of suitable infrastructure. The positive trend in green mobility highlights the city's commitment to incorporate electric vehicles (EVs) into the urban transport fleet, while ensuring the expansion of electric mobility is supported by appropriate infrastructure, such as the installation of recharging points, to meet the rising electricity demand from the transportation sector.

Recognizing the relevance of comparison with other methodologies in order to validate the reliability of these results, an exhaustive comparative analysis was performed, including all the available studies dealing with energy transition and sustainable development in Italian cities found in literature. The comparison revealed various commonalities in key findings and trends, strengthening the credibility of UETI's approach in evaluating urban energy transition dynamics. For instance, although D'Adamo et al. [65] provide just a snapshot of the SDG performance of Italian cities therefore comparing the trend over the 2014-2019 period is not possible, also their findings underscore air pollution as one of the most critical aspects in Turin: PM10 index is indeed notably lower (0.057) than the national average (0.498). Further similarities are observed on good performance for waste management and carbon intensity, as the score of municipal waste management results equal to 0.695 (above the national average of 0.595) and CO2 emission score is equal to 0.487 (slightly below the national average of 0.501). Similarly to D'Adamo et al., the MTI's study [131] provides a snapshot of the transition status of Italian cities, making a year-by-year comparison unfeasible. Moreover, as the goal of MTI's assessment is to highlight eventual disparities among Italian regions rather than focus on individual cities, city-specific performances are not provided. Therefore, in order to compare

MTI's results with the findings from UETI's approach, Turin's performances are inferred from thematic maps provided in the study. Although deducing precise values for the city of Turin from thematic maps is challenging, the overall comparative analysis appears to confirm that Turin has good performance in waste management and sustainable mobility compared to the average of Italian cities. On the contrary, the performance of Energy, Climate and Resources (ECR) appears low: despite good performance in resource management (e.g., water and soil) and in renewable energy penetration in line with UETI's results, there is still the influence of air quality which decreases the overall ECR score. Additionally, the ECR performance is incomplete since it does not take into account carbon emissions metric even though it is an essential factor to thoroughly assess the energy, environmental and climate performance.

Despite D'Adamo et al. and MTI's study, the Legambiente's annual reports assessing the Ecostistema Urbano Index (EUI) for Italian cities [130] enabled a comparison over time with UETI's trend. The comparative analysis on Turin performances revealed a similar evolution up to 2017, then the trends diverge (Figure 51): while the UETI maintains a continuous positive trend, reaching the peak in 2019, the EUI shows a moderate growth in 2018 and decreases in 2019 (-11% compared to 2018). This variation is caused by intrinsic differenced in the adopted conceptual frameworks: in particular, while the UETI seeks to encompass both energy, environmental and socio-economic factors in its structure, EUI focuses instead on environmental aspects, overlooking numerous indicators. This difference justifies the discrepancy between trends since EUI neglects indicators such as energy intensity, power network quality, renewables penetration, green mobility and CO2 emissions, which indeed experienced significant improvement between 2018 and 2019, thus contributing to the overall increase in the UETI's trend.

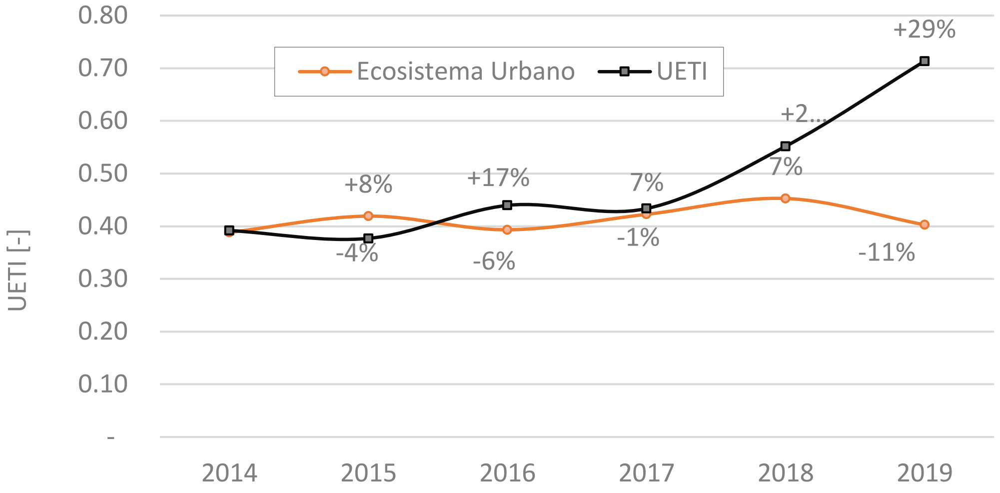


Figure 51: Comparison of UETI's trend with Ecosistema Urbano's trend over the 2014-2019 period (Source:[117]*)*

Correlation and sensitivity analyses results

Following the validation of methodology by means of comparative assessment with other studies, correlation and sensitivity analyses are extensively discussed. Indeed, as stated in the objectives of the UETI's methodology and in line with Step 7 and Step 8 of COIN guidelines (section 2.2.3.2), correlation and sensitivity analyses cannot be omitted when presenting a novel metric-based approach; sensitivity analysis enables the evaluation of composite index robustness, while correlation analysis assesses the relationships between variables and the overall effectiveness of the composite index in capturing the factors it aims to measure. In summary, sensitivity and correlation analyses play complementary roles in the presentation of a metric-based methodology since they offer a complete understanding of the method and contribute to enhance its credibility and applicability.

Despite the equal-weighting approach is employed, it does not guarantee that each sub-domain contributes equally to the Urban Energy Transition Index. The correlation analysis serves to evaluate the real contribution of each sub-domain to the final UETI's score. The correlation analysis involved the calculation of Pearson coefficient r (Table 31). Pearson correlation is indeed the standard method for assessing the linear correlation between two variables. The magnitude of the coefficient indicates the strength of the correlation, ranging from 1 (perfect correlation) to 0 (no correlation), while the sign ("+" or "-") indicates the direction (positive or negative) of the correlation. Positive correlation occurs when both variables change in the same direction, whereas negative correlation occurs when they change in opposite directions. When assessing the correlation coefficient between the composite metric (e.g., UETI) and its sub-components (e.g., Energy, Environmental, and Socio-Economic), a strong correlation (|r|> 0.6) is desirable, as it demonstrates that the composite index effectively represents the behaviour of its components. In contrast, weak correlation is preferred when calculating the correlation between components of the same composite index, since it implies their independence and therefore no information redundancy.

First, the correlation analysis focused on examining the relationships between sub-domains, domains, and the composite index UETI. Notably, the Energy and Environmental domains exhibit very strong correlation (|r|> 0.80) with UETI, whereas the Socio-Economic domain demonstrates very weak correlation (|r|< 0.19). This implies that the overall UETI score for Turin over the period from 2014 to 2019 is less influenced by the performance of Socio-Economic domain. Additionally, Power Grid Quality exhibits weak correlation (0.27) with the Energy domain, and Economic Impact displays weak correlation (0.21) with the Socio-Economic domain. Nonetheless, more than 60% of the 15 analysed relationships demonstrate strong and very strong correlation. The complete list of findings from correlation analysis is reported in Table 31.

Table 31: Pearson correlation coefficient between the UETI, its domains and sub-domains (Source: [117]*)*

Correlation analysis ranges			
Very Weak |r|≤ 0.19	Weak |r|= 0.2 – 0.39	Moderate |r|= 0.4 – 0.59	Strong or Very Strong |r|≥ 0.60
22%	11%	6%	61%

Correlation of Urban Energy Transition Index (UETI) with its domains:

DOMAINS	**r**
Energy	0.97
Environmental	0.98
Socio-economic	- 0.12

Correlation of Energy Index with its sub-domains:

SUB-DOMAINS	**r**
RES penetration	0.49
Power grid quality	0.27
Green mobility	0.98
Energy intensity	0.73

Correlation of Environmental Index with its sub-domains:

SUB-DOMAINS	**r**
Land use	0.96
Waste	0.62
Water	0.77
Air pollutants	0.79
GHGs	0.89

Correlation of Socio-Economic Index with its sub-domains:

SUB-DOMAINS	**r**
Health	0.75
Economic impact	0.21
Well-being	- 0.96

Recognizing its importance within the presentation of the methodology, the correlation analysis has been performed in order to offer a thorough and transparent understanding of the UETI's framework at this stage. However, it is necessary to extend the temporal range in order to strengthen the accuracy of these findings.

As regards the sensitivity analysis, it focuses on how changes in input parameters or weights affect the overall results. By subjecting the composite index to sensitivity analysis, we can evaluate its stability against variations in methodology, such as weighting methods, ensuring that specific variables do not disproportionately impact the final measure. Moreover, as that UETI's methodology aims to be adaptable to diverse urban contexts while providing a comprehensive framework, sensitivity analysis becomes even more pertinent for enhancing the credibility of the composite index. To this purpose, three cases were developed to test the robustness of the UETI (Table 32).

Table 32: Sensitivity analysis scheme (Source: [117]*)*

Case	Objective	Description
C1	• |r|≥ 0.4 between Power Grid Quality and Energy domain • |r|≥ 0.4 between Economic Impact and Socio-Economic domain	• Power Grid Quality weight: +80% w.r.t. EW • Economic Impact weight: +10% w.r.t. EW
C2	Omitting the sub-domains with the strongest correlations to assess how their exclusion impacts the overall composite index	Excluding the sub-domains with the strongest correlation (Green Mobility, Land Use, Well-being)
C3	Understanding how the exclusion of a specific domain influences the score of UETI	Excluding one specific domain (Socio-Economic) and measuring the perfect compensability effect from additive aggregation

In the first case (C1) included in the analysis, the weights of sub-domains with weak correlations were increased until a moderate level (|r|≥ 0.4) of correlation was achieved. For instance, the weight of Power Grid Quality was increased by 80%, while the weight of Economic Impact was increased by 10% compared to the reference case of equal weighting (EW). The second case (C2) studied the UETI's behaviour when excluding sub-domains with the strongest correlations from each domain. The third case (C3) explored the effect of excluding an entire domain, specifically the Socio-Economic domain, characterized by the least positive trend. All these cases are encompassed in Figure 52 which illustrates the results of sensitivity analysis, showing that the composite index remains relatively stable even with significant variations in weight allocation and index structure. Case C1 closely follows the reference case trend, with moderate variations ranging from +5.9% to -1.0% over the study period. Despite Cases C2 and C3 exhibit more pronounced variations, reflecting their more substantial modifications to the index structure, they do not affect significantly the final UETI score, evidencing the overall robustness of the composite index.

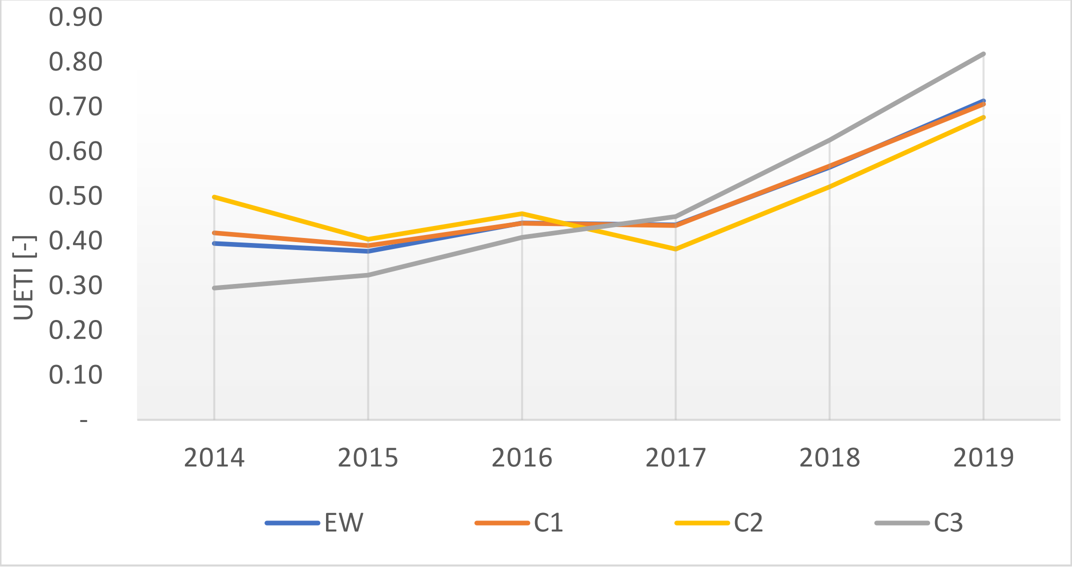


Figure 52: Sensitivity analysis findings (Source: [117]*)*

Discussion of policy implications

This case study revealed both strengths and weaknesses in Turin's multidimensional evolution towards energy transition. In terms of energy, Turin exhibits a consistent enhancement, notably driven by significant renewable energy integration into the urban energy mix, advancements in green mobility, and reduced energy intensity reflecting and increase in energy efficiency across sectors (such as residential). Additionally, there has been a gradual even though moderate improvement in power grid quality. Within the environmental domain, disparities among its sub-domains are noticeable: while there is a positive trend in the performance of urban carbon emissions and resource management, air quality exhibits poor performance. This result underscores that air pollution remains a persistent and critical issue for Turin, demanding intensified efforts, investments, and targeted measures for effective mitigation. Furthermore, the study underscores the imperative of greater attention to the socio-economic dimension, particularly regarding the health and well-being of citizens which are too often overshadowed by technical and economic objectives.

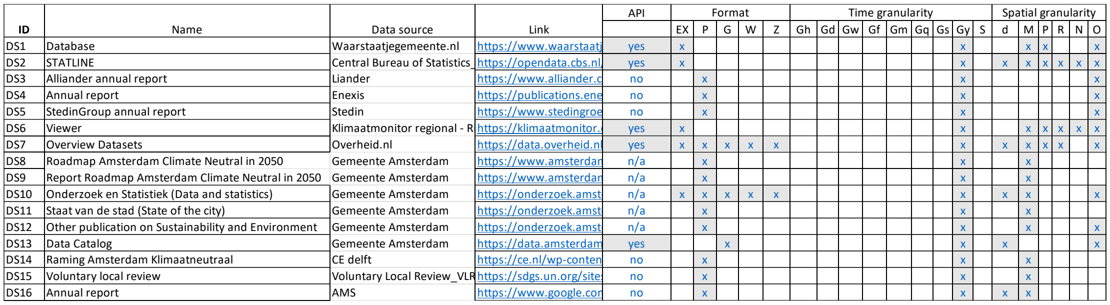
Another aspect underscored in this study is the issue of urban data scarcity, particularly concerning the social domain, which instead deserves more attention by considering its negative trend between 2014 and 2019. Since the goal of this methodology is to track comprehensively energy transition and highlight eventual criticalities, enhancing availability of data is a priority to provide accurate insights and to enable an effective informed-policy decision making. Furthermore, the lack of data restricts the temporal range of the assessment and undermines the accuracy of sensitivity and correlation analyses too.

In conclusion, this study highlights the significance and efficacy of continuous monitoring of the city's journey towards energy transition through a comprehensive index framework, encompassing not only energy and environmental aspects but also economic and social domains. It also underscores the urban fields deserving more attention and efforts (e.g., air pollution), demonstrating the efficacy of systematic monitoring through a metric-based approach (i.e., UETI) in identifying weaknesses and critical areas within the energy transition process. these insights can support policymaker in establishing action strategies, prioritizing investments, and fostering effective and targeted measures to address the specific challenges encountered by the city and carry out a balanced energy transition.

4.3.4 Validating the UETI's methodology: Comparative Analysis of Dutch Urban Energy Transition

To test the applicability and adaptability of the UETI methodology to other urban contexts, the energy transition assessment has been extended to other four municipalities in the Netherlands, selected by the European Commission to participate to the EU's "100 Cities Mission" [41]: Amsterdam, Eindhoven, Rotterdam, and Utrecht. For this comparative study across multiple cities, the formalisation method (outlined in section 3) was employed to identify data providers and to screen the specific characteristics of the datasets (e.g., data format, temporal resolution, API availability, etc.). The output of the data sources mapping is reported in Figure 53 which shows 16 datasets. The comparative analysis of urban data availability showed that Dutch municipalities have higher quality and greater availability of data compared to the Italian case study (section 4.3.3). Specifically, Waarstaatjegemeente and Klimaatmonitor Regional Rijkswaterstaat (Figure 53) are the main providers of urban-scale raw data for the Netherlands, covering a total of 342 municipalities. The providers collect local data from each city and integrate it into a single database, organised into macro-categories, which is easily accessible through a user-friendly and interactive web interface that facilitates data exploration and allows users to download desired information in preformatted format (i.e., Excel format). Additionally, the majority of data providers listed in Figure 53 offer API (Application Programming Interface) access, facilitating data acquisition and storage in the database.

As observed in the Turin case study, urban data are not sufficient for all Italian municipalities, necessitating the integration of data from several providers, often compromising information quality (e.g., missing data, normalisation, assumptions, etc.) and making data collection more challenging. In addition, APIs are not provided by Italian data providers, except for Terna which provides APIs for accessing Load, Generation, Transmission and Market data.
Therefore, a preliminary comparison of data availability between the Italian and Dutch case studies reveals that the open-source tools available for Dutch cities are more developed and advanced than those available for Italian cities, which are fragmented and inconsistent. Thanks to the greater availability of urban data, the UETI case study for Dutch cities covers a spatial range from 2013 to 2022, which is broader than the Turin case study (limited to 2014-2019 due to the lack of updated data). However, similar to the Turin case study, some data are not available at the city level, necessitating the use of provincial (e.g., green areas) or national data (e.g., water consumption, number of deaths, etc.).



				API	Format					Time granularity									Spatial granularity					
ID	Name	Data source	Link		EX	P	G	W	Z	Gh	Gd	Gw	Gf	Gm	Gq	Gs	Gy	S	d	M	P	R	N	O
DS1	Database	Waarstaatjegemeente.nl	https://www.waarstaatj	yes	x												x			x	x			x
DS2	STATLINE	Central Bureau of Statistics_	https://opendata.cbs.nl/	yes	x												x		x	x	x	x	x	x
DS3	Alliander annual report	Liander	https://www.alliander.c	no		x											x							x
DS4	Annual report	Enexis	https://publications.ene	no		x											x							x
DS5	StedinGroup annual report	Stedin	https://www.stedingroe	no		x											x							x
DS6	Viewer	Klimaatmonitor regional - R	https://klimaatmonitor.	yes	x												x			x	x	x	x	x
DS7	Overview Datasets	Overheid.nl	https://data.overheid.nl	yes	x	x	x	x	x								x		x	x	x	x		x
DS8	Roadmap Amsterdam Climate Neutral in 2050	Gemeente Amsterdam	https://www.amsterdan	n/a		x											x			x				
DS9	Report Roadmap Amsterdam Climate Neutral in 2050	Gemeente Amsterdam	https://www.amsterdan	n/a		x											x			x				
DS10	Onderzoek en Statistiek (Data and statistics)	Gemeente Amsterdam	https://onderzoek.amst	n/a	x	x	x	x	x								x		x	x				x
DS11	Staat van de stad (State of the city)	Gemeente Amsterdam	https://onderzoek.amst	n/a		x											x			x				
DS12	Other publication on Sustainability and Environment	Gemeente Amsterdam	https://onderzoek.amst	n/a		x											x			x				x
DS13	Data Catalog	Gemeente Amsterdam	https://data.amsterdam	yes			x										x		x					x
DS14	Raming Amsterdam Klimaatneutraal	CE delft	https://ce.nl/wp-conten	no		x											x			x				
DS15	Voluntary local review	Voluntary Local Review_VLR	https://sdgs.un.org/site	no		x											x			x				
DS16	Annual report	AMS	https://www.google.con	no		x											x		x	x				

Figure 53: Formalisation of datasets used to assess the UETI's trend in Dutch cities

Once the relevant datasets were identified, raw data for Amsterdam, Eindhoven, Rotterdam, and Utrecht were collected. Although the data quality was better compared to the Italian case study, data cleaning and handling of missing values were still necessary. Specifically, linear interpolation was used to address intermediate missing values, while linear regression was applied to manage missing values at the historical series endpoints. To minimise the impact of missing data management on the analysis results, the study period was restricted to the timeframe from 2013 to 2022, characterised by higher data availability, thus interpolation and regression are used to handle just a small amount of missing data. After raw data cleaning and storage in the database, indicators calculation is performed: each indicator is mapped to the domains and sub-domains characterizing the UETI conceptual framework outlined in section 4.3.2.

Two intermediate steps were performed before aggregating indicators:

1. Determination of the orientation (positive or negative) of each indicator relative to the corresponding composite index.

2. Normalisation of indicators using the Min-Max method (based on the historical minimum and maximum values recorded for each indicator in each city).

Subsequently, three levels of aggregation were conducted: first level aggregation between normalised indicators calculates the performances disaggregated by Sub-Domain; the second level of aggregation estimates the performance indices by domain (Energy, Environment, and Socio-Economy), and the third level of aggregation provides the final score of the composite UETI index. Table 33 presents the annual UETI values disaggregated by domain and by municipality.

Table 33: UETI trends of Amsterdam, Eindhoven, Rotterdam, and Utrecht (2nd and 3rd level of aggregation)

City	Domain	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Amsterdam	Energy	0.48	0.62	0.65	0.63	0.64	0.43	0.59	0.68	0.77	0.91
	Environment	0.32	0.39	0.55	0.59	0.59	0.62	0.69	0.71	0.86	0.83
	Socio-Economy	0.30	0.52	0.43	0.54	0.66	0.71	0.80	0.89	0.89	0.80
	UETI	**0.37**	**0.51**	**0.54**	**0.58**	**0.63**	**0.59**	**0.69**	**0.76**	**0.84**	**0.85**
Eindhoven	Energy	0.40	0.56	0.65	0.64	0.65	0.56	0.62	0.78	0.76	0.94
	Environment	0.40	0.45	0.59	0.62	0.64	0.60	0.58	0.67	0.71	0.71
	Socio-Economy	0.35	0.50	0.45	0.55	0.57	0.61	0.68	0.77	0.84	0.76
	UETI	**0.38**	**0.50**	**0.56**	**0.61**	**0.62**	**0.59**	**0.63**	**0.74**	**0.77**	**0.80**
Rotterdam	Energy	0.56	0.55	0.56	0.66	0.63	0.62	0.61	0.63	0.75	0.84
	Environment	0.40	0.47	0.55	0.62	0.65	0.64	0.70	0.64	0.78	0.84
	Socio-Economy	0.36	0.53	0.51	0.58	0.66	0.70	0.77	0.84	0.84	0.73
	UETI	**0.44**	**0.52**	**0.54**	**0.62**	**0.64**	**0.66**	**0.69**	**0.70**	**0.79**	**0.80**
Utrecht	Energy	0.49	0.53	0.53	0.65	0.67	0.63	0.60	0.64	0.80	0.86
	Environment	0.32	0.41	0.49	0.56	0.72	0.61	0.65	0.71	0.74	0.82
	Socio-Economy	0.28	0.44	0.43	0.51	0.59	0.63	0.70	0.84	0.87	0.74
	UETI	**0.36**	**0.46**	**0.48**	**0.58**	**0.66**	**0.62**	**0.65**	**0.73**	**0.80**	**0.81**

Figure 54 illustrates the evolving trend of the UETI for each city: in 2022 Amsterdam achieved the highest UETI score (0.85), followed by Utrecht (0.81), Rotterdam (0.80) and Eindhoven (0.80). Given that the normalisation of indicators is based on each city's own historical minimum and maximum values, these results should not be interpreted as a city ranking. Instead, they highlight the degree of improvement or decline in each city's energy transition performance. Indeed, the choice of perform Min-Max normalisation based on each city’s historical range ensures that the energy transition assessment of a specific municipality is not affected by the performances of other urban contexts.

The comparative analysis of UETI evolution for each city (Figure 54) demonstrates a significant enhancement in energy transition performance across all four cities.

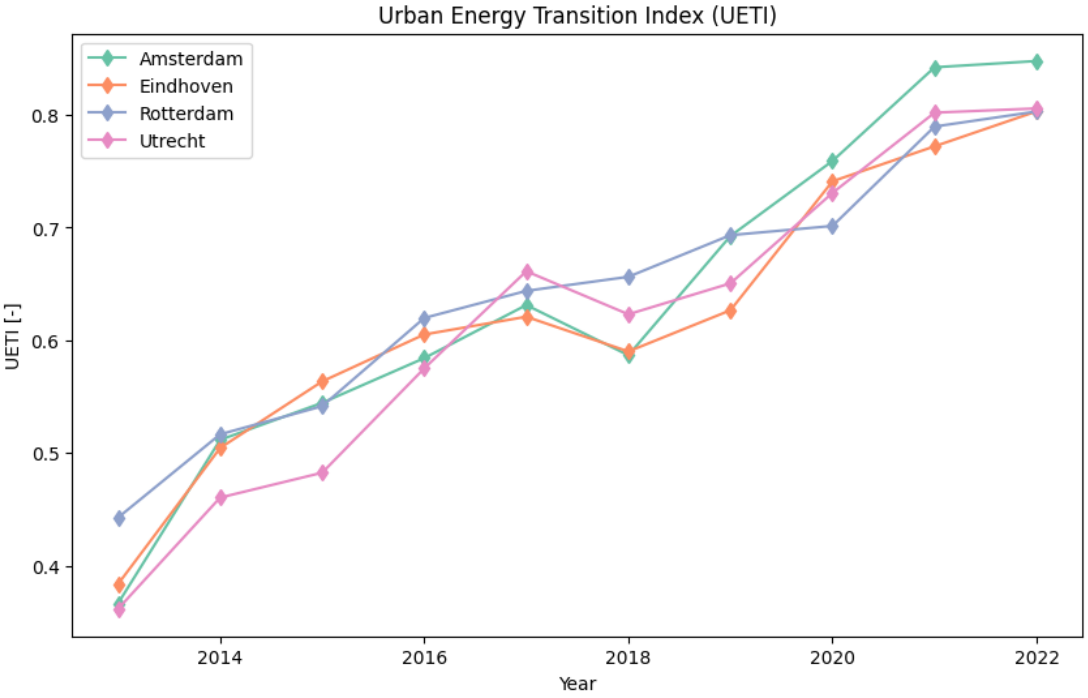


Figure 54: UETI annual trend of Amsterdam, Eindhoven, Rotterdam, Utrecht (2013-2022)

To gain a clearer understanding of the UETI trends for each city, it is essential to examine the performance trends across the three domains depicted in Figure 55:

- Amsterdam shows a notable improvement across all three domains from 2013 to 2022, except for the Energy domain, which experienced a significant decline in 2018. This drop is primarily attributed to issues with Power Grid Quality, specifically a peak in the duration of electricity outages. Overall, the UETI confirms Amsterdam's progress towards a more sustainable paradigm, characterised by reduced carbon emissions, increased renewable energy in the energy mix, enhanced electrification, and improved building efficiency. As regards the socio-economic domain, Amsterdam is successfully advancing the energy transition without negatively impacting its population or economic well-being. However, a notable increase in energy costs relative to average household income occurred in 2022, resulting in a decline in Well-being. This trend is observed across all Dutch cities, including Rotterdam, Utrecht, and Eindhoven.

- Utrecht exhibits a positive trend across all three domains, reflecting growth in renewable energy within the energy mix, particularly PV generation, accompanied by an increase in PV installed capacity (from approximately 1 MW in 2014 to over 200 MW in 2023). Improvements are also noted in building efficiency, reduced residential sector consumption, and effective promotion of green mobility. In the Environment domain, significant improvements are achieved in GHG and air pollutants emissions, demonstrating the effectiveness of decarbonisation, electrification, and energy efficiency measures on air quality and urban carbon footprint. Health performance also shows a positive trend, indicating that the transition to a more sustainable paradigm benefits public health too. However, Well-being declined in 2022, similar to other cities, due to rising energy prices driven by a sharp increase in gas prices in the European market, as a result of EU sanctions on Russian oil and gas export following the Russia’s invasion of Ukraine in 2022.
- Rotterdam shows a generally positive trend in UETI performance. However, its initial UETI score in 2013 was the highest among the cities analysed, but it was subsequently matched by Eindhoven and surpassed by Amsterdam and Utrecht. This indicates that, although Rotterdam's performance improved between 2013 and 2022, the rate of improvement was less pronounced compared to other cities. Similarly, in the socio-economic domain, Rotterdam had the highest value from 2013 to 2016 but was overtaken by Amsterdam from 2016 and by Utrecht and Eindhoven from 2021 onwards, recording the lowest socio-economic performance value in 2022. In the Energy domain, the most significant gap compared to other cities is observed between 2019 and 2020 due to low renewable energy penetration, combined with a notable increase in the average duration of electricity outages (from 21 minutes in 2019 to 27 minutes in 2020). The performance trend in the Environment domain aligns with those recorded in the other cities.
- Eindhoven demonstrates an improvement in energy transition performance and, in 2022, achieved the highest performance value in the Energy domain. This reflects the city's commitment across various areas: enhancing renewable energy penetration, promoting green mobility, reducing energy intensity in high-consumption sectors, and maintaining good electricity supply quality. The domain facing the greatest challenge is socio-economy, although it has shown a clear upward trend since 2020, which was interrupted in 2022 due to a decline in Well-being observed across all cities because of rising energy prices. The Environment domain also shows a positive trend, consistent with other cities, though with generally lower values. Notably, the Waste sub-domain has seen a significant deterioration since 2018, highlighting the need for

more effective measures to reduce waste at the source, enhance recycling, and decrease residual waste, which are crucial for developing a circular economy in the urban context.

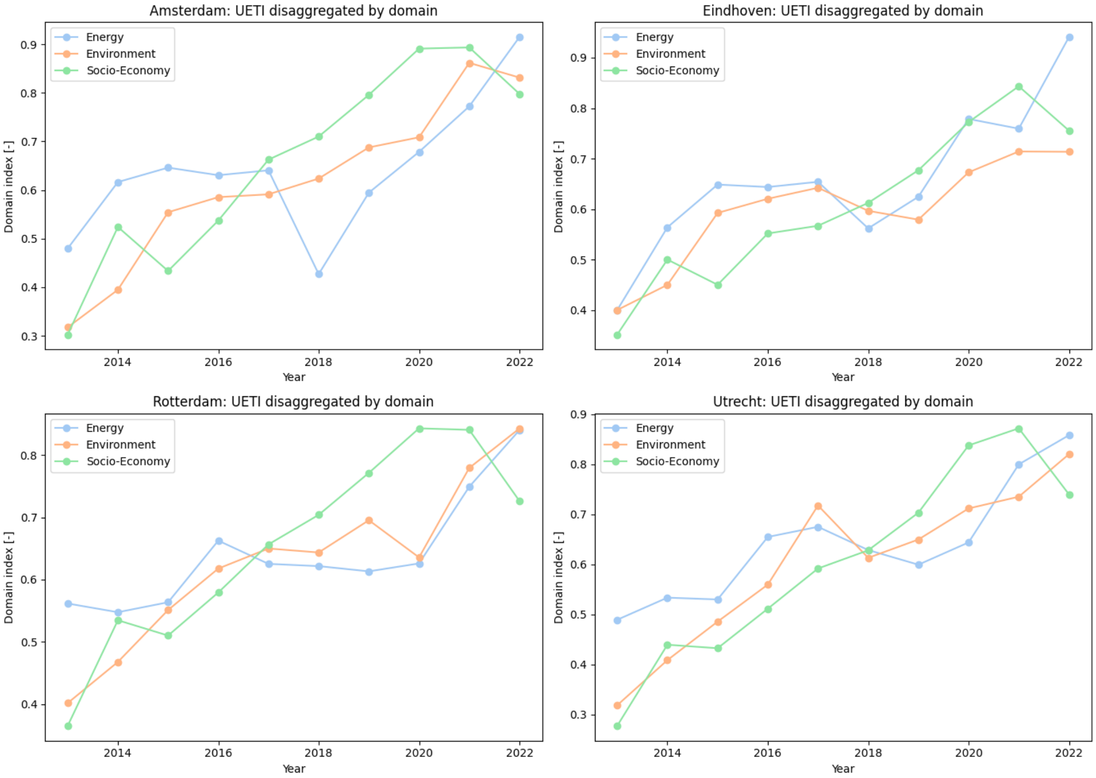


Figure 55: UETI trend disaggregated by domain for Amsterdam, Eindhoven, Rotterdam, Utrecht (2013-2022)

Chapter 5

5 Development of interactive platforms for policymakers

To promote evidence-based policymaking and public engagement, it is essential to move beyond the traditional scientific approach which tends to communicate results in a highly accurate, yet complex, technical language. This traditional approach can undermine public understanding, discouraging audience attention, and widening the gap between stakeholders and scientists. Therefore, it is crucial to foster public interest by changing this approach and prioritizing the effective communication of scientific results to a broader audience; this novel and more inclusive approach would facilitate public engagement and enable the public comprehension of the energy transition benefits, and it would improve stakeholders understanding of policies and sustainability objectives, such as carbon neutrality commitment, as well as electrification and decarbonization actions. Moreover, promoting more effective communication of scientific evidence raises also the awareness of stakeholders about their contribution to the transition, encouraging sustainable lifestyle.

In this context, indicators, and especially composite indices, have the advantage of quantifying complex aspects through a single value, simplifying the visual representation of the results, as well as enabling comparative analysis and the identification of trends or patterns that may not be evident from raw data analysis. Therefore, indices can play as a valuable tool to promote more inclusive and effective communication of scientific evidence to a wider audience.

Although data visualization and evidence communication can be simplified thanks to the use a set of composite indices, to promote public engagement and to bridge the science-policy gap, a further step is required: interactive and user-friendly IT tools. These tools are designed for facilitating data exploration, collection and analysis, for enhancing effective and interactive data visualization and for enabling public comprehension of science-based insights.

While the COIN Excel tool developed according to the COIN’s guidelines [51] proves to be a robust instrument for constructing and refining composite indicators, it requires technical knowledge and comprehensive understanding of the methodologies to build such indicators, as this tool allows to calculate the composite index starting from the input data, but the users have to choose the weighting, normalization and aggregation methods. Furthermore, the tool offers additional analyses and insights into the correlations between indicators, sensitivity analysis, and uncertainty assessments. However, these functionalities may be challenging for users lacking sufficient background knowledge in this field. Interpreting the results and navigating the program effectively, as well, demands a background in scientific disciplines, data analysis, or statistics, rather than being well-suited for policymakers or citizens.

To bridge the existing science-policy gap and promote effective communication with stakeholders, it is crucial to promote a more inclusive approach supported by novel IT tools user-friendly and accessible even by non-expert users. Among the possible functionalities, IT tools can simplify and speed up data collection from diverse sources, providing the latest available data through a single interface, organised into categories that make data exploration easier for users. Another important aspect to be included in the IT functionalities to promote public engagement is the use of "storytelling" to convey certain themes such as the penetration of renewables in the energy mix, trends in energy demand by commodity, and carbon emissions trends. Storytelling needs infographics, designed to encourage user interest and comprehension, and it can be empowered by interactive tools allowing users to set their preferences (e.g., choice of chart type, filtering of displayed information, selection of temporal resolution, etc.).

Recently, many national and international research institutions (Figure 56, Figure 57 and Figure 58) have been transitioning from 'static' to 'dynamic' and inclusive data reporting by developing interactive web platforms, enabling simpler data exploration and analysis.

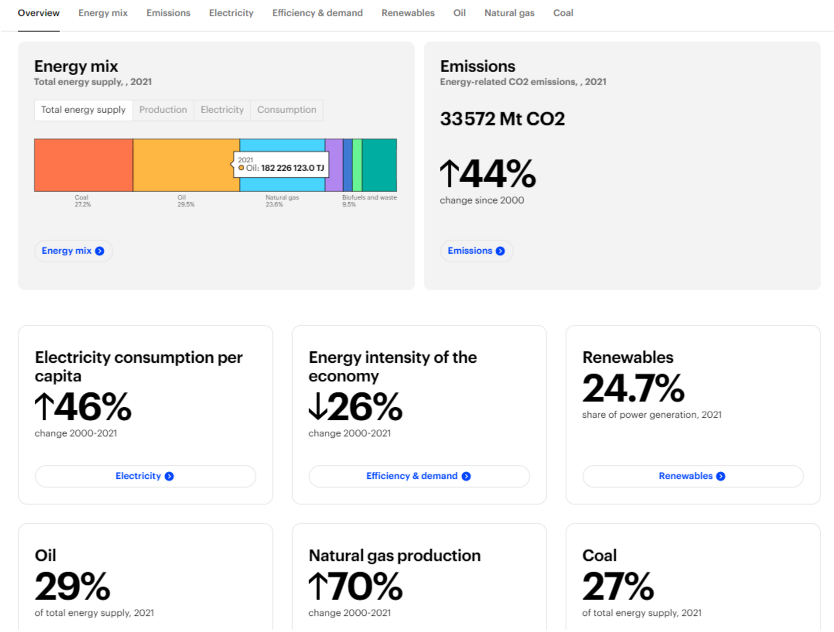


Figure 56: Example of interactive dashboard showing key performance indicators on the energy transition trend at the global scale (Source: IEA's Countries and Regions Data Browser)

Figure 57: Example of interactive dashboard showing the monthly electricity consumption disaggregated by type of energy source at the national scale (Source: Mobile App by Terna)

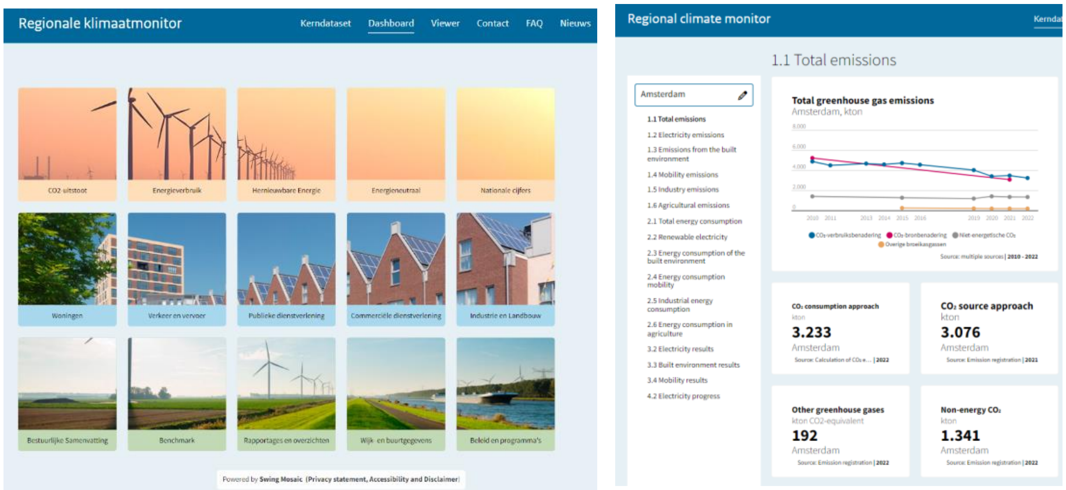


Figure 58: Example of interactive dashboard showing key performance indicators on urban carbon footprint in Netherland (Source: Klimaatmonitor Databank)

Therefore, the traditional 'static' format used to present analysis outputs, such as long and detailed technical reports, is increasingly being complemented by interactive storytelling and dashboards. These tools enhance communication to a broader audience, promote public engagement, and facilitate evidence-based policymaking.

In line with this objective, to demonstrate the potential of IT tools in supporting informed policymaking, especially for addressing complex and multidimensional issues, such as decarbonization process, my research activity encompassed the development of three IT tools (web platforms). These platforms are part of a larger EST-Lab project aimed at creating a system of specialised platforms (EST-platforms). Each platform focuses on a specific theme but shares the overarching commitment of supporting informed policy decisions and providing science-based guidance to steer policies towards a sustainable and secure energy transition. Defining the conceptual framework, identifying stakeholders, outlining functionalities, and managing the entire development process of these platforms were integral parts of my doctoral activities. Each of the three platforms presented in the following sections focuses on a specific theme and aims to simplify understanding and enhance effective communication to a wide range of stakeholders, including citizens and policymakers:

1. The Energy Transition Analysis - Italian Tracker (ET@IT) for monitoring the national energy transition.
2. The European Electricity Explorer (E3) for scenario analysis of the impacts of intermittent renewable generation on the European power system.
3. The Supply Energy Risk Tracker (SERT) for extending the analysis of risks in energy supply corridors, crucial for ensuring the stability and security of the energy system during this transition.

5.1 ET@IT: Energy Transition Analysis – Italian Tracker

The ET@IT platform is an innovative collaborative research initiative born from the partnership between ENEA (Italian National Agency for New Technologies, Energy, and Sustainable Economic Development) and the EST@energy center, included within my research activity. This platform embodies the integration of expertise, consultations with stakeholders, and needs identified to support informed policy decision-making. Therefore, this platform is the culmination of know-how and stakeholders' input; it has been structured following COIN guidelines (section 2.2.3.2) on data visualization and storytelling (steps 9 and 10) and represents the practical application of these theoretical concepts. Although a prototype, it showcases the potential of IT tool in supporting evidence-based policymaking and in engaging population in the national transition process. As mentioned in section 4.2.2, this work is part of a wider project comprising three main interconnected pillars:

1. Revision and enhancement of ISPRED structure and indicators employed in the "Analisi Trimestrale" report to measure the multidimensional trends of energy transition in Italy across the three dimensions of the energy trilemma (Energy Security, Energy Sustainability and Energy Equity).

2. Systematic and formal characterization of data, including datasets, input data, elaborated data, calculations, and levels of aggregation.
3. Development of a prototype integrated IT tool, user-friendly, available online and intended for a broad spectrum of stakeholders involved in the national energy transition process (including institutional bodies, public and private companies, citizens and policymakers).

The first and the second pillar are essential to achieve the main goal of the third pillar. Furthermore, the third pillar encompasses diverse specific objectives which are summarised below:

- Enabling an integrated and comprehensive access, by means of a single interface, to multiple datasets that characterize the national energy system. These datasets are consistently updated via an automated system, encompassing both national and international sources.
- Automating the entire data management process, from the download of raw data to the generation of final processed metrics, minimizing manual intervention by operators.
- Establishing a centralized proprietary database, periodically refreshed using specialized web-crawlers or API, to store raw data collected from diverse datasets.
- Developing a set of functions dedicated to calculating key metrics for monitoring the trends in Italian energy transition.
- Developing a web platform - ET@IT (Energy Transition Analysis Italian Tracker) - accessible online to authorized users. This platform draws data from the proprietary database, providing access to national and international energy data and reference metrics. Users can perform customized analyses or choose from pre-set analyses (stories) and visualize or download the results in various formats, including interactive tables, graphs, and maps.

Identification of Stakeholders' categories and needs

ET@IT is a versatile tool designed to accommodate the needs of various stakeholders within the national energy transition landscape, each with distinct requirements and objectives:

- Policy decision-makers and their technical teams seek access to limited but crucial data, requiring continuous updates and immediate availability (e.g., primary energy consumption by source, carbon intensity by sector, etc)
- Sector-specific experts and analysts, such as analysts and technicians from entities like Terna, SNAM, and Enel, interested in additional information beyond their expertise.

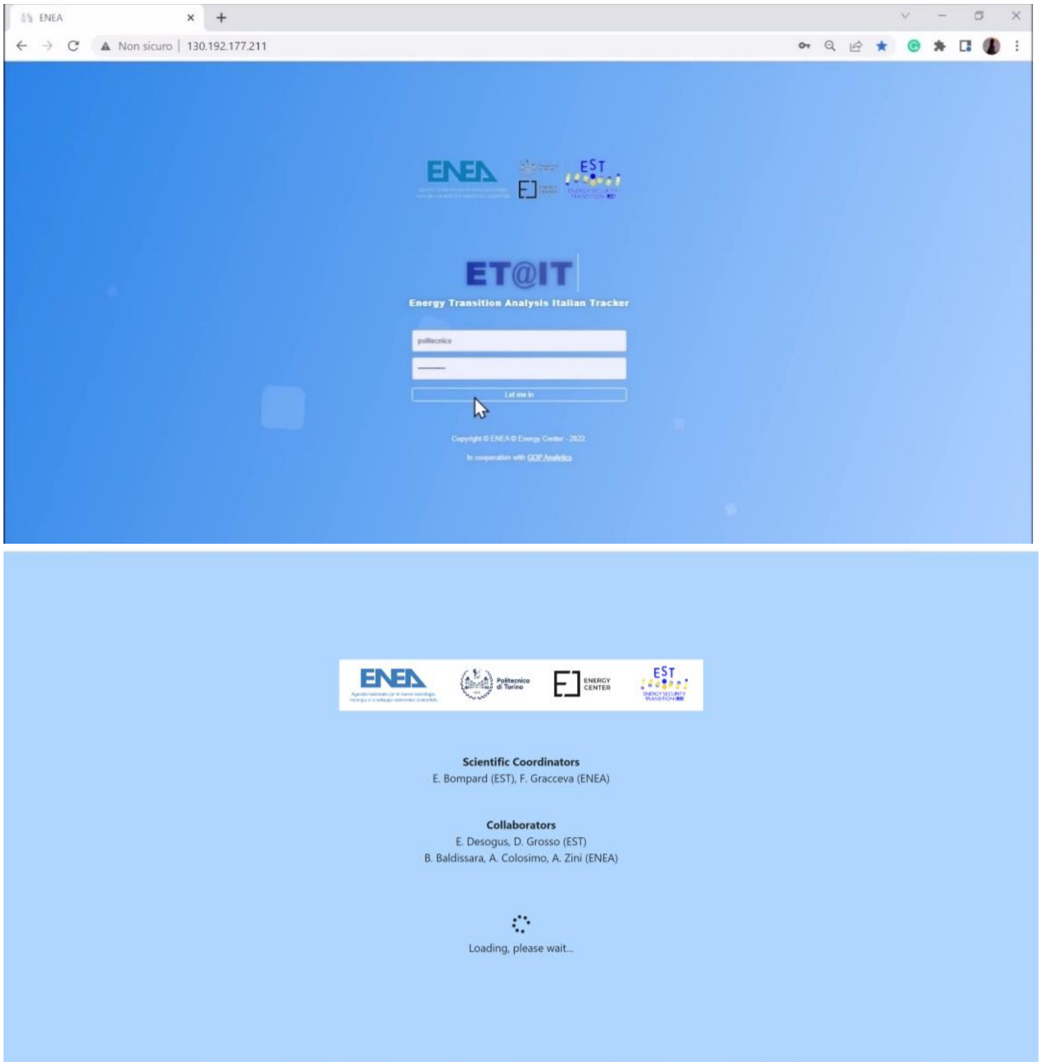
They seek a comprehensive and updated overview of diverse energy system trends, including short-term forecasts, comparisons between current trends and targets. Updated values of ISPRED index and its sub-components provide valuable insights on progress of Italian energy transition over time.

- Sector-specific journalists are interested in accessing key data related to the national energy system. This includes energy balance information (imports, exports, gross inland consumption), presented through graphical representations like Sankey diagrams, as well as energy prices and pre-set analyses (stories) for easy comprehension.
- Researchers focusing on the energy system require access to comprehensive time series data, covering a wide range of aspects involved in the energy transition (e.g., energy consumption by sector and commodity, energy prices, carbon emissions, etc.)

Ultimately, ET@IT can serve as a valuable tool for supporting energy analysis and planning processes, as well as for communicating to a broad range of audiences the results of Italian energy system's trajectory relatively to energy policy objectives.

ET@IT functionalities

Access to the ET@IT platform is granted to registered users, each provided with unique login credentials comprising usernames and passwords. Different levels of access privileges are allocated based on user roles and responsibilities, ensuring a secure and tailored user experience. The platform consists of 5 main sections: 1) Dashboard, 2) Data, 3) Indices, 4) Stories, and 5) Balance.



ET@IT

Energy Transition Analysis Italian Tracker

politecnico

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In cooperation with GDP Analytics

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Loading, please wait...

Figure 59: Screenshot of user's login interface and credits of ET@IT development (Source:[138] *).*

Section 1: Dashboard

The homepage displays a user-friendly and interactive interface, with essential data presented in a visually engaging manner into the dashboard framework. This dashboard serves as a central hub for accessing the key insights into the Italian energy transition trends (e.g., ISPRED score, variations in Energy security, Prices, Decarbonization, etc.). The dashboard is organized into three sub-sections:

1. Sidebars (left and right): providing numerical information on national energy consumption by energy commodity (left side) and on ENEA indices (right side) for tracking the national energy transition (i.e., ISPRED, Security, Decarbonization, Prices). The user can select the commodity (left side) and the index (right side) to be displayed; automatically the following values are updated: the "current value", reflecting the latest available quarter; the quarterly average value over the year; the percentage change in trend compared to the same quarter of the previous year; and the percentage change in the quarter compared to the previous quarter.
2. Central area: containing graphical representation of information contained in the sidebars. In addition, graphs show the historical trends, facilitating the identification of trends and patterns.
3. Bottom tabs: comprising the tabs to access to the other four sections of the platform (Data, Indices, Stories and Balance), the button to access ENEA reports ("Analisi Trimestrale"), and the "info bar" button for logging out and viewing platform development credits.

Non sicuro | 130.192.177.211/dashboard/homepage

Hi Politecnico!

Gross Inland Consumption (Q4 2021): Electricity

Current value 1.91 Mtoe

Average Year 2.24 Mtoe

Tendential -29% ↓

Conjunctural -25% ↓

Index (Q4 2021): ISPRED

Current value 0.31

Average Year 0.50

Tendential -45% ↓

Conjunctural -30% ↓

Figure 60: Screenshot of ET@IT's homepage: Dashboard (Source: [138]*).*

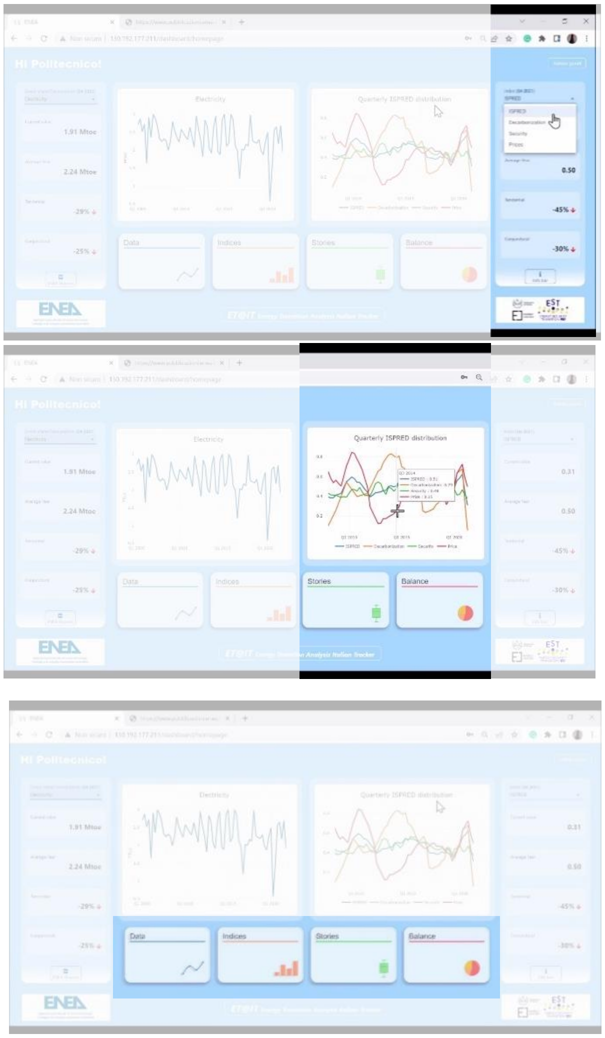


Figure 61: ET@IT sections and Dashboard functionalities: interactive tabs and graphs (Source: [138]*).*

The quarterly ENEA's "Analisi trimestrale" reports are easily accessible by selecting the desired year and quarter in the tab at the left-bottom of the dashboard.

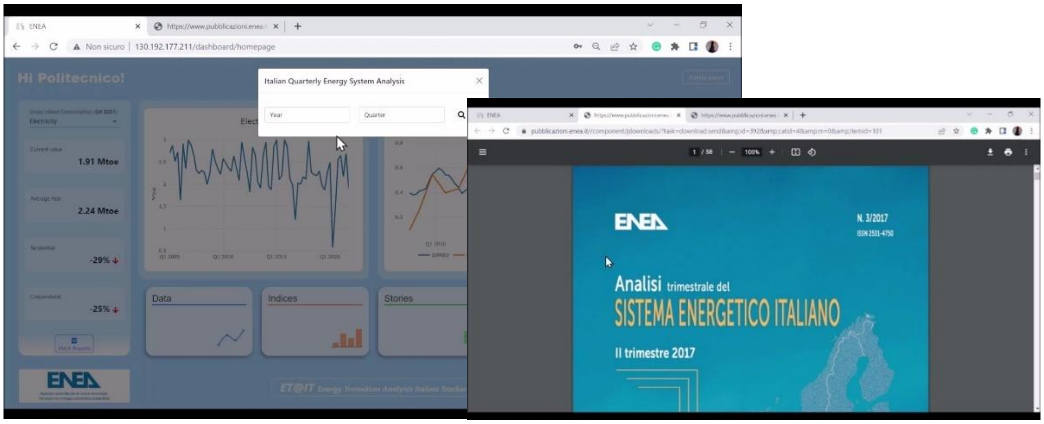
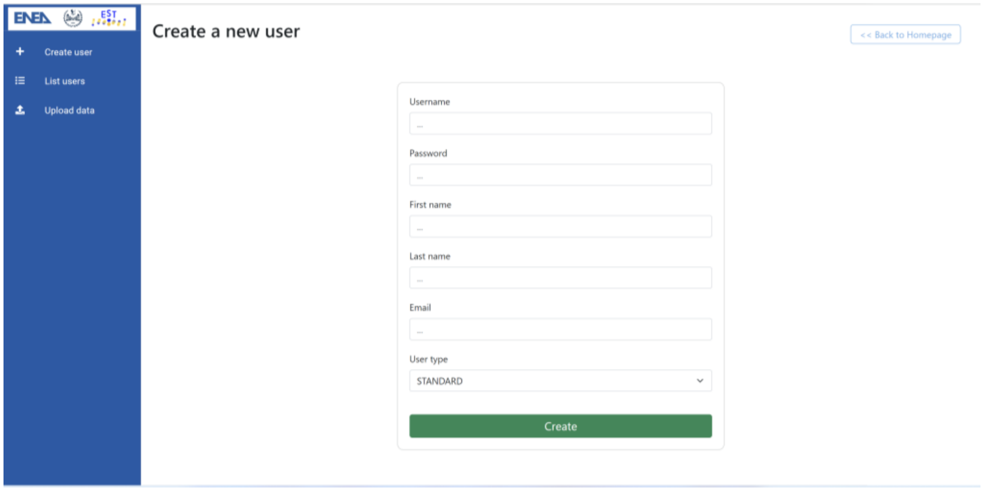


Figure 62: Access to ENEA's "Analisti trimestrale" full report (Source: [138]*).*

Additionally, the "Admin panel" button, located in the top right corner of the screen, allows users with administrator privileges to access the page for creating new users (Figure 63). From this page, administrators can also view the list of currently active users and their status in terms of access privileges (administrator or standard user).



User type: STANDARD

Figure 63: Admin panel window (Source: [138]*).*

Section 2: Data

The Data section of the ET@IT platform serves as a comprehensive repository of energy-related datasets, collected both from national and international data providers, continuously updated to capture the latest trends. Users can interact with these tables by using a range of features and functionalities such as sorting and filtering, and they can also generate customized tables by means of the pivot function, enabling in-depth data exploration and extraction of valuable insights. Moreover, the platform offers an export function that allows users to download the data in Excel format, facilitating further analysis and integration with other analytical tools and applications (Figure 64).

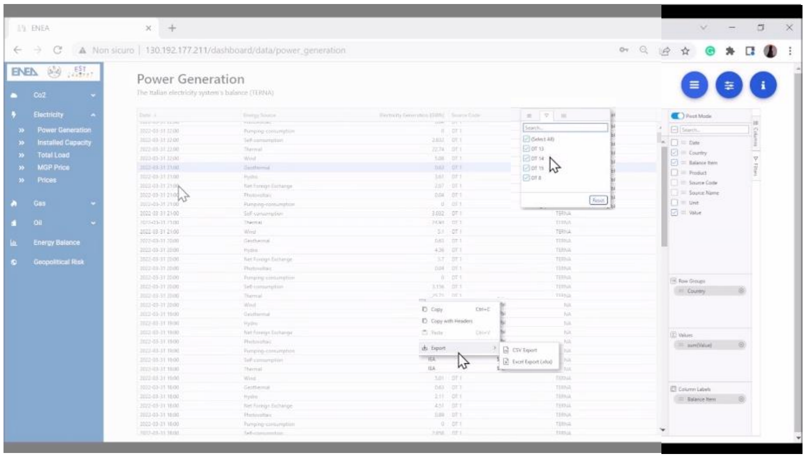


Figure 64: Data section functionalities: filtering, sorting, pivot table and export into excel file (Source: [138]*).*

Utilizing advanced web crawling technologies, the platform aggregates data from a wide range of sources, encompassing over 31 datasets and drawing from 16 distinct data providers and institutions such as Terna, GME, Eurostat, ENEA, SNAM, JODI, OPEC, MiSE, and The World Bank. The platform comprises over 13,000 lines of code and more than 6 million records. It aims to facilitates access to a diverse range of raw data, collected from numerous datasets in various formats (e.g., excel, pdf, and GIS) and covering a wide range of topics, including energy consumption by commodity and by sector, renewable energy generation, energy price, and emissions data. Collected data are then organized into a singular structured database and allocated to one of the main categories (i.e., Electricity, Gas, Oil, CO2, etc.). These datasets are continuously updated through an automated web crawling system integrated in the platform.

As an example of data organization for each category, the detailed contents of the Electricity category, which consolidates data from various data providers, are outlined below:

1. Power Generation: includes Italian power generation by source (geothermal, hydro, photovoltaic, wind, thermal), self-consumption (self-consumption, pumping-

consumption), and net exchange with foreign countries (net foreign exchange), with hourly granularity (Source: TERNA).

2. Installed capacity: reports national installed electrical capacity by source (geothermal, hydro, photovoltaic, wind, thermal), expressed in GW, with annual granularity (Source: TERNA).

3. Total Demand: presents total Italian demand and demand per market zone (North, South, Centre-North, Centre-South, Sicily, Sardinia, Calabria), both actual (Total Demand) and estimated from the previous day (Forecast Total Demand), expressed in MW, with 15-minute granularity (Source: TERNA).

4. MGP Price: comprises electricity prices on the day-ahead market (MGP), expressed in €/MWh, with reference to the Prezzo Unico Nazionale (PUN) and values related to the 7 market zones and foreign interconnections (Greece, Austria, Slovenia, Corsica, France, Montenegro, Switzerland), with hourly granularity (Source: Gestore dei Mercati Energetici - GME).

5. Prices: includes electricity prices, expressed in monetary value/MWh for residential and non-residential users, for various consumption bands (5 bands for domestic users; 7 bands for industrial users) and tax levels, with monthly granularity (Source: Eurostat).

Section 3: Indices

In addition to raw data exploration, the ET@IT platform provides dedicated sections for analysing indices relevant to the energy transition process. These indices are automatically calculated using the latest available data, providing users with valuable insights into the Italy's performance across various aspects of energy trilemma (e.g., energy security, energy sustainability, energy equity) within the energy transition contexts. Each table refers to a specific index of the ISPRED framework, displaying the historical trends of the sub-indices and indicators that comprise the composite index, accompanied by informative pop-up descriptions. By means of this multi-layers visualisation which highlights the intermediate calculations necessary to obtain the final index, users gain a better knowledge and understanding of the final score of indices.

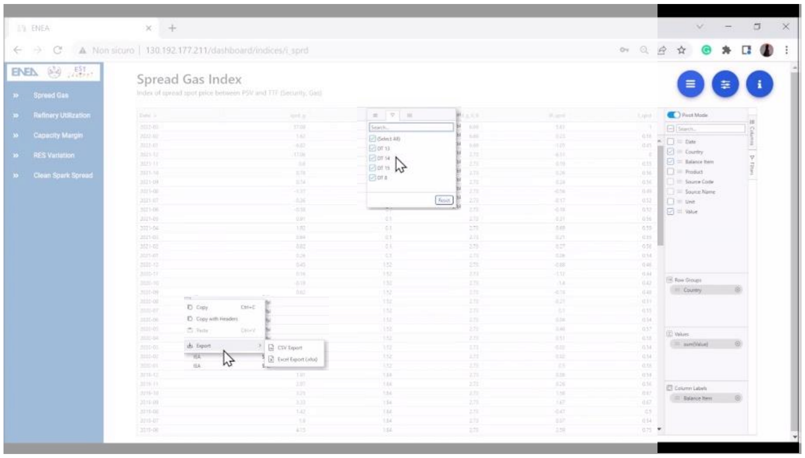


Figure 65: Indices section functionalities: data filtering and sorting, pivot table and download into excel file (Source: [138]*).*

As an example, the Clean Spark Spread Index and the RES Variation Index, both referring to the Security sub-domain and Electricity category of ISPRED framework, are discussed in detail.

The Clean Spark Spread Index, ranging from 0 to 1, measures the difference between the electricity price, the fuel cost of a gas-fired power plant, and the cost of CO2 emission allowances. The final value is normalized over the last 6 months. The table displays not only the final score of the Clean Spark Spread Index (I_CSS) but also the other metrics included in its calculation:

- PUN_m: average electricity price on a monthly scale (PUN: National Single Price);
- ss_m: difference between the price received for electricity production and the cost of natural gas required to produce it, on a monthly scale;
- EUA_m: average CO2 price on a monthly scale;
- CSS_m: net income for an electricity producer, calculated by subtracting the cost of natural gas required for production and the cost of associated emission allowances from the revenue generated by selling electricity, measured on a monthly scale;
- CSS_6m: average clean spark spread over the last 6 months.

The RES Variation Index, ranging from 0 to 1, assesses the hourly variation of electricity generation from renewable sources (wind and photovoltaic solar) compared to national demand. The table displays not only the value of the RES Variation Index (I_FRNP) but also the values of the indices involved in its calculation, namely:

- FRNP%_0975: 97.5th percentile of the hourly variation of wind and photovoltaic solar generation compared to the demand of the (i-1)-th hour, on a monthly scale;
- FRNP%_0025: 2.5th percentile of the hourly variation of wind and photovoltaic solar generation compared to the demand of the (i-1)-th hour, on a monthly scale.

Both Clean Spark Spread Index and the RES Variation Index are calculated on a monthly time scale and involve the electricity security dimension.

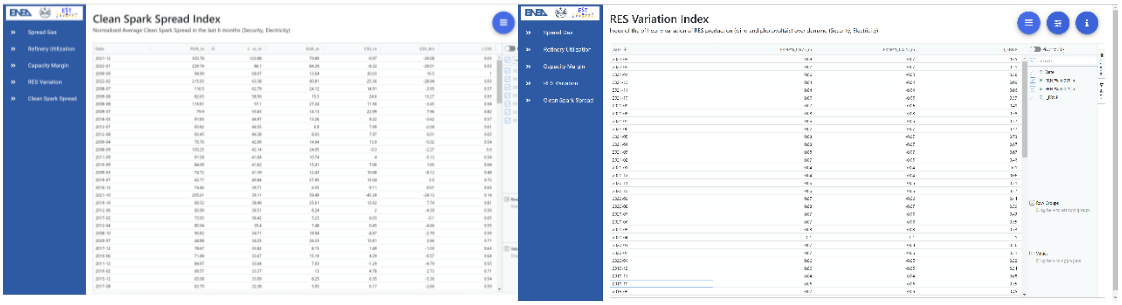


Figure 66: Clean Spark Spread Index and RES Variation Index (Source: [138]*).*

Section 4: Stories

The Stories section of the ET@IT platform introduces a dynamic approach to data analysis, known as “interactive storytelling”. Interactive, as these stories adapt dynamically to user preferences, allowing users to tailor the analysis based on selected parameters such as time period and country of interest. Additionally, users can interact with tables and graphics contained in the story, and export the customized stories in PDF format; storytelling, as stories consist of pre-set analyses including of textual narratives, numbers and graphics. The objective of this specific section is to provide users with a quick and straightforward response to specific inquiries by presenting essential, constantly updated information in the form of an interactive document, thereby facilitating easy tracking of temporal evolution. The content of each story focuses on a specific topic and is crafted in collaboration with specific-topic experts, offering users a curated selection of narratives that contextualize complex data in a clear and engaging manner.

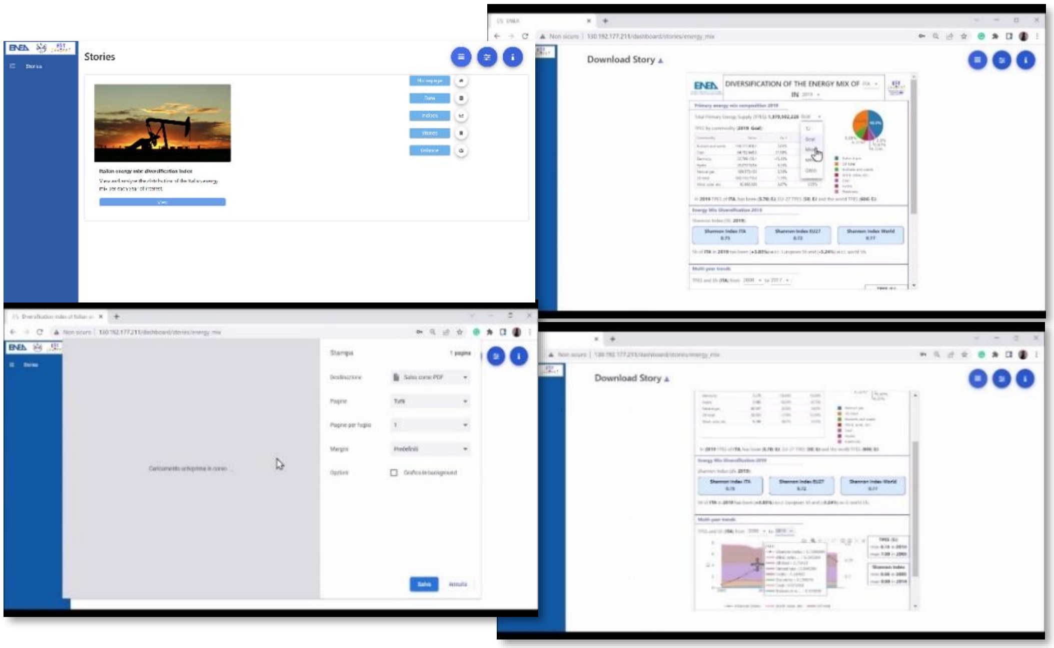
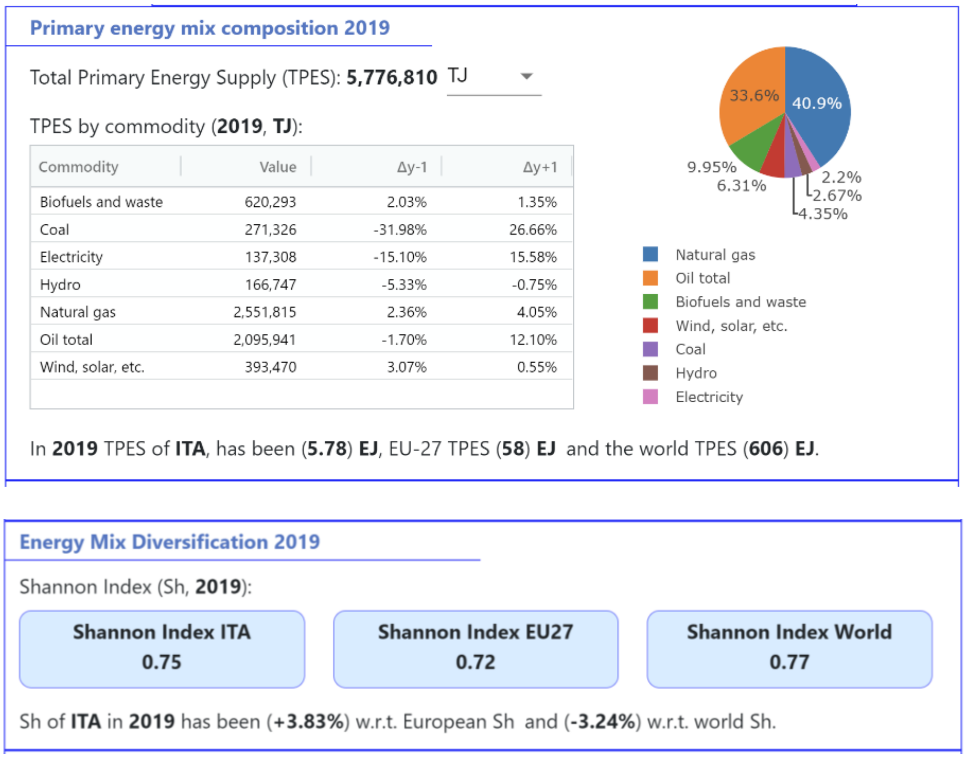


Figure 67: Interactive storytelling functionalities: interactive tabs and graphs (Source: [138]*)*

The available story is presented in the form of a navigable A4-sized page. Within the title ("Diversification of the energy mix of <Country> in <Year>"), users can select the Country and the Year of interest (with historical series starting from 1990) through a dropdown menu, and automatically the information displayed are updated. The story is structured in three main sections: 1) Primary energy mix composition, 2) Energy mix diversification, and 3) Multi-year trend. The first section displays the value of the total Primary Energy Supply (TPES) of the selected country in the chosen year, expressed in diverse unit of measurement (TJ, Gcal, Mtoe, MBtu, GWh). Additionally, TPES by commodity (Hydro, Natural gas, etc.) is reported in an interactive table. The table is interactive and includes the advanced filtering and sorting system previously described in the "Data" and "Indices" sections. Adjacent to the table, a pie chart illustrates the percentage contributions of individual commodities to the total TPES for the selected country and year (Figure 68). Finally, at the bottom of the section, a comparison is shown between the TPES of the selected country and that of the 27-country European Union and the world in the year of interest. The second presents the value of the Shannon index which measures the diversification of the primary energy mix in terms of commodities. The index is provided for the selected country, the average of EU-27, and the global average in the chosen year (Figure 68).



Primary energy mix composition 2019

Total Primary Energy Supply (TPES): **5,776,810** TJ

TPES by commodity (**2019**, **TJ**):

Commodity	Value	Δy-1	Δy+1
Biofuels and waste	620,293	2.03%	1.35%
Coal	271,326	-31.98%	26.66%
Electricity	137,308	-15.10%	15.58%
Hydro	166,747	-5.33%	-0.75%
Natural gas	2,551,815	2.36%	4.05%
Oil total	2,095,941	-1.70%	12.10%
Wind, solar, etc.	393,470	3.07%	0.55%

In **2019** TPES of **ITA**, has been (**5.78**) **EJ**, EU-27 TPES (**58**) **EJ** and the world TPES (**606**) **EJ**.

Energy Mix Diversification 2019

Shannon Index (Sh, **2019**):

Shannon Index ITA
0.75

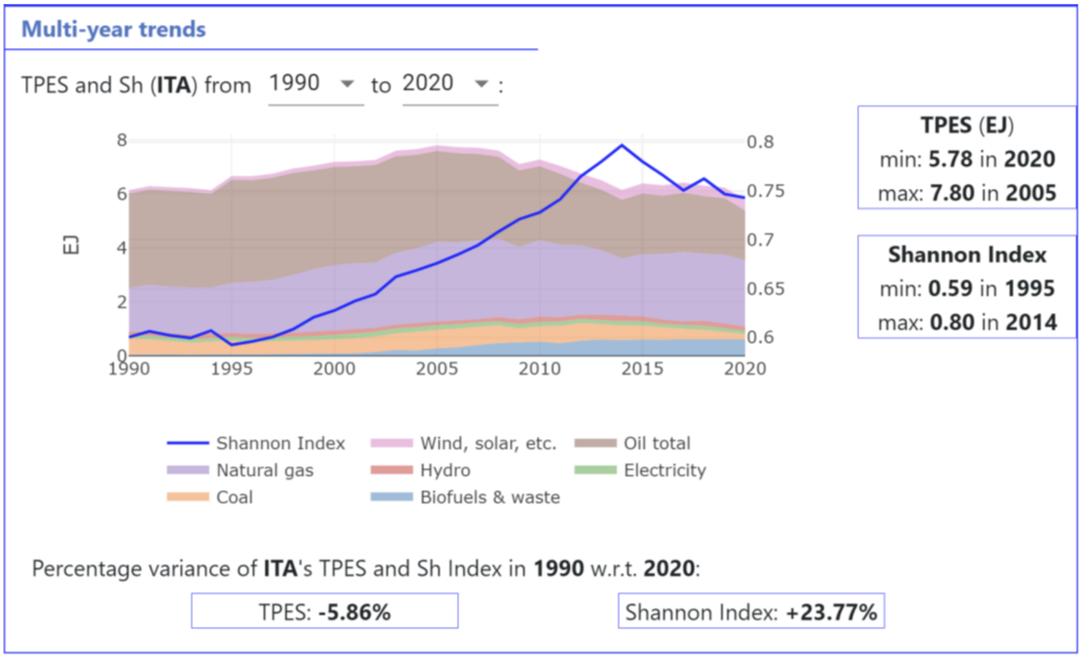
Shannon Index EU27
0.72

Shannon Index World
0.77

Sh of **ITA** in **2019** has been (**+3.83%**) w.r.t. European Sh and (**-3.24%**) w.r.t. world Sh.

Figure 68: Example of primary energy mix composition and Shannon index assessment (Source: [138]*).*

The third section of this story focuses on the temporal trend of the TPES and the Shannon index over a selectable range of years through a dropdown menu. The graph is interactive, allowing users to zoom in on specific areas, view individual values by hovering over the graph, toggle the display of one or more legend items, and export the image in .png format. To the right of the graph, two boxes display the maximum and minimum values and their respective years within the selected time frame, both for TPES and the Shannon index. Finally, at the bottom, the percentage variation between the two extreme years of the temporal horizon under examination is reported for the selected country, with reference to both TPES and the Shannon index (Figure 69).


Multi-year trends

TPES and Sh (**ITA**) from 1990 to 2020 :

TPES (**EJ**)
min: **5.78** in **2020**
max: **7.80** in **2005**

Shannon Index
min: **0.59** in **1995**
max: **0.80** in **2014**

Percentage variance of **ITA**'s TPES and Sh Index in **1990** w.r.t. **2020**:

TPES: **-5.86%**

Shannon Index: **+23.77%**

Figure 69: Example of Multi-years trends visualization (Source: [138]*).*

Section 5: Balance

The Balance section of the ET@IT platform provides users with comprehensive tools for analysing the national energy balance over time with quarterly resolution. Through intuitive visualization offered by the Sankey diagram, users can access a visually compelling representation of energy flows within the national context, including interdependencies among energy production by commodity and final consumption by sector. After choosing the quarter and year of interest, users can view updated data in both tabular and graphical formats. Additionally, they have the option to export information in Excel format for tables and image format for Sankey diagrams. Additionally, the platform enables comparative analysis between diverse energy balances referring to different quarters and years, facilitating deeper insights into trends and patterns in Italian energy supply and consumption. The export feature allows users to extract and incorporate balance data into their analytical processes, aiding in informed decision-making and strategic planning aimed at advancing energy transition actions.

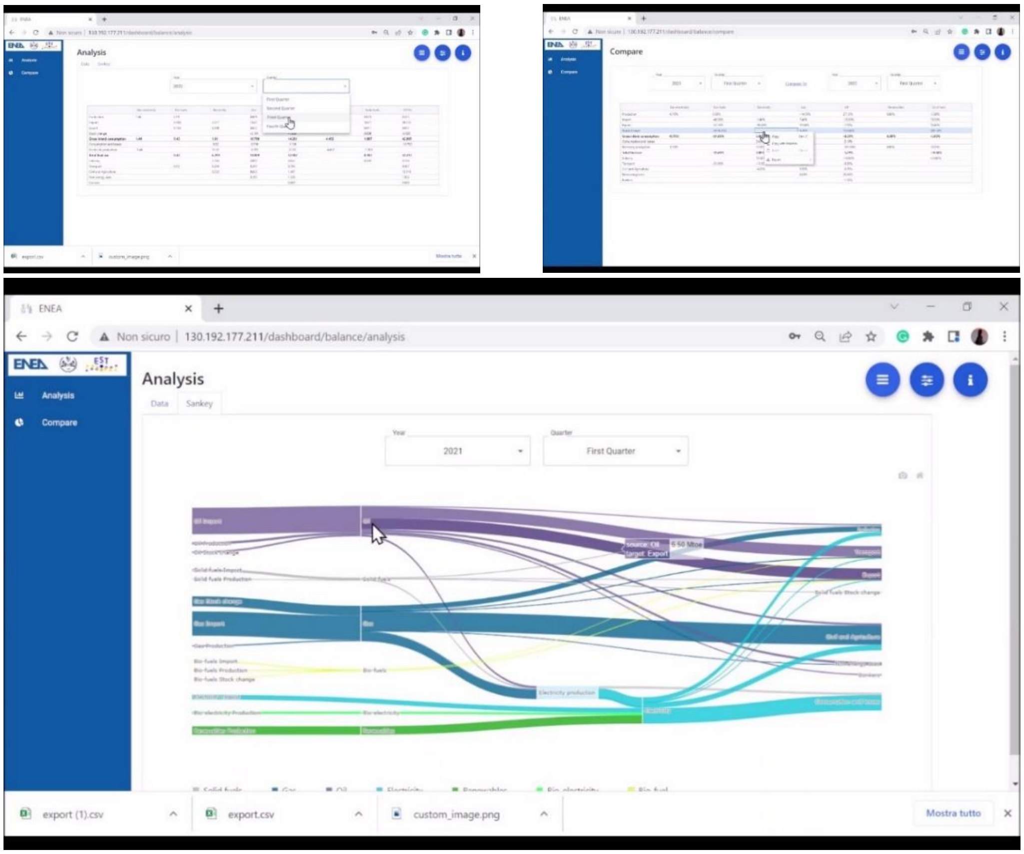


Figure 70: Analysis section functionalities: energy balance visualization in interactive tables and Sankey diagrams (Source: [138]*)*

Consistency and platform technology

The current platform consists of over 13,000 lines of code and its database contains over 6 million records stored, including 101 raw data collected from 31 datasets characterized by different formats (.xlsx, .csv, .pdf, etc.). The platform seeks to unify into a unique database the variety of energy data, provided by 16 national and international data sources (e.g., Terna, GME, Eurostat, ENEA, SNAM, JODI, OPEC, MiSE, The World Bank, etc.), and necessary to track national energy transition progress across multiple dimensions such as energy sustainability and energy affordability. Another aim of the platform is to ensure the automatic updating of data through APIs and web crawlers, which extract information directly from datasets and store the updated data in the database. Additionally, a Python-based library of functions facilitates the computation of indicators and indices featured in ENEA's "Analisi

Trimestrale" report. The current version of ET@IT incorporates more than 90 indicators/indices.

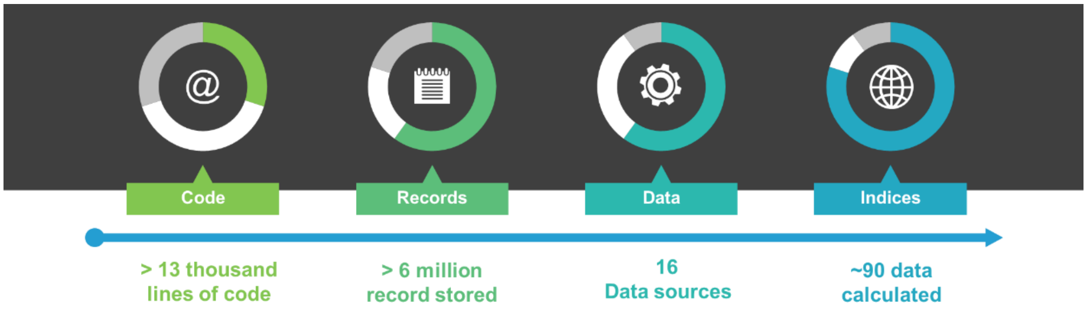


Figure 71: Consistency numbers of the current version of ET@IT (Source: GDP Analytics)

For a comprehensive overview of the platform's features, the technical details are provided below. ET@IT utilizes a "three-tier" architecture, comprising three fundamental components: Frontend, Backend, and Database.

1. Frontend: powered by the React JavaScript (ReactJS) framework. Th flexibility and modularity of its structure allows for easy integration and implementation. Application management is efficiently handled both internally by each component and externally through Redux.
2. Backend: utilizes the Django-REST Python web framework, known for its scalability and efficiency. It facilitates API queries and user management via a REST API, supporting various HTTP methods such as GET, POST, PUT, DELETE, and PATCH. Key dependencies include Django, djangorestframework, django-rest-knox, numpy, pandas, psycopg2, and sqlparse.
3. Database: relies on PostgresSQL, a robust and open-source relational database management system (RDBMS). PostgresSQL prioritizes extensibility and SQL compliance.

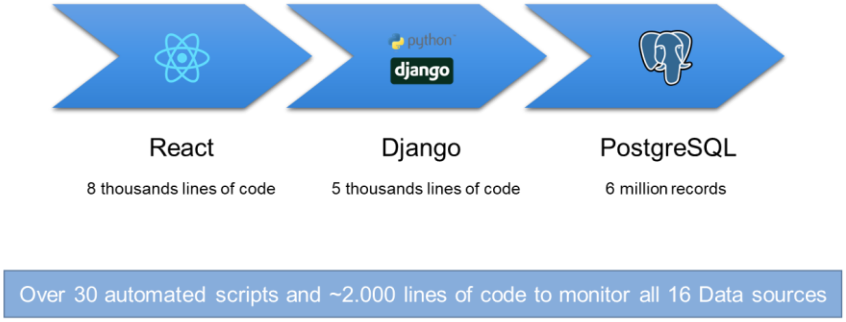


Figure 72: The ET@IT architecture: Frontend, Backend, Database (Source: GDP Analytics).

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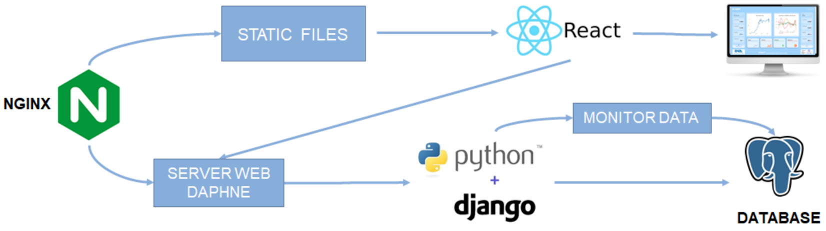


Figure 73: The architectural scheme of the ET@IT platform (Source: GDP Analytics).

5.2 E3: European Electricity Explorer

As outlined by the scenarios presented in ENTSOE study [139], two main solutions can be identified to achieve the common goal of reaching a -55% reduction (compared to 1990 emissions) in EU-27's carbon emissions by 2030 and carbon neutrality by 2050: 1) Distributed Small Scale RES penetration (included in the ENTSOE's Distributed Energy scenario) and 2) Centralized Large Scale RES penetration (included in the ENTSOE's Global Ambition scenario). The first approach prioritizes distributed energy generation from small-scale renewable installations, promoting self-consumption and the utilization of indigenous RES. On the other hand, the second approach favours centralized power generation from large-scale renewable plants (e.g., offshore wind farms) located in areas with abundant RES resources (e.g., high wind intensity regions). In general, the Northern Europe (North Sea Energy Hubs) is estimated to have higher offshore wind productivity, while solar power has greater potential in Southern Europe. Additionally, looking ahead to 2030 and 2050, a significant increase in electricity demand is projected due to the progressive electrification of final consumption sectors (e.g., transportation and residential). As highlighted in the ENTSOE report on the Needs of the System [93], the current configuration of the power transmission system, based on alternating current (AC), cannot support such power flows, leading to congestion issues. The ENTSOE's report discusses in detail the need to expand the existing transmission network and the required investments.

Considering the Centralized Large Scale generation scenario, integrating the current High Voltage Alternating Current (HVAC) network with an additional network of High Voltage Direct Current (HVDC) is a potential solution to address congestion issues and facilitate the transfer of high-power values over long distances. This integration could reduce losses over long distances, facilitate interconnection between centralized-generation areas (e.g., Northern Europe for wind and Southern Europe/North Africa for solar) and load concentration areas (e.g., Central Europe), also maximizing the utilization of renewable generation potential. In addition, to ensure the security of power system and address the problems caused by non-programmability and variability of renewable energy generation, the hybrid HVAC-HVDC network needs the integration of large-scale energy storage systems.

In this context, it is essential to provide science-based tools that assist policymakers in evaluating potential solutions to face the challenges related to the development of the European transmission network, including congestion issues. Enhanced data visualization can serve as a powerful tool to foster informed decision-making and support decision-makers in planning strategic actions and prioritizing investments.

The European Electricity Explores (E3) is a prototype IT tool designed to enhance data visualization and effectively communicate valuable insights on this crucial topic to policymakers and stakeholders. Indeed, the current E3's version allows users to visualize on map the European transmission network and to evaluate the effects of diverse policy scenarios [140] with a multi-dimensional perspective and employing an interactive interface to enhance audience engagement and comprehension.

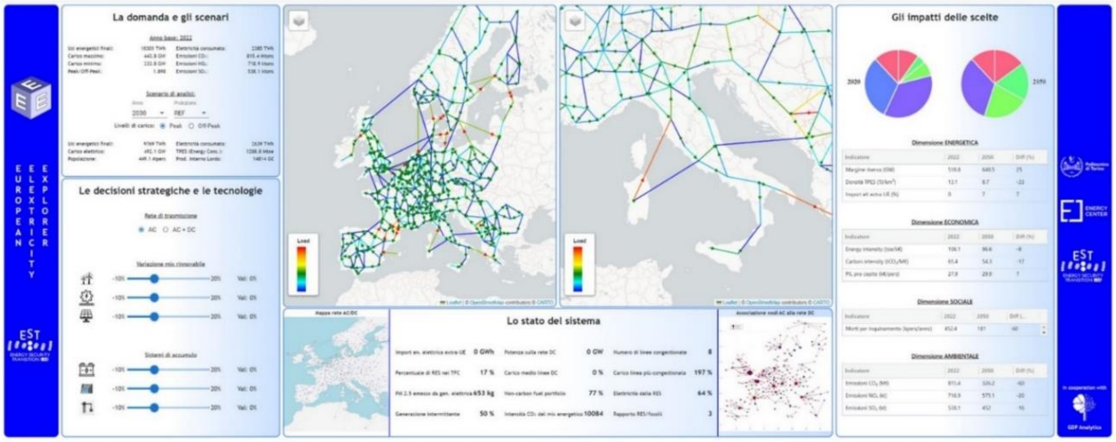


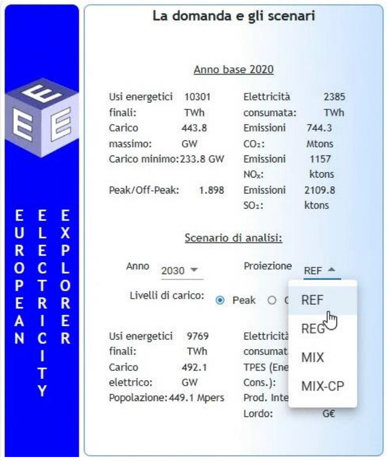
Figure 74: European Electricity Explorer interactive interface (Source: [141]*).*

This application presents a simplified yet significant representation of the European power network consisting of 256 AC buses obtained from Pypsa-Europe [83], an open-source python-based multi-energy modelling software, integrated with another layer composed by 40 DC buses (obtained from ABB study [24]). The aim is to offer a graphical and user-friendly representation of the European power network through interactive maps which enable users to delve into the impacts of three European Commission's policy scenarios [140] describing the initiatives presented in July 2021 with the European Green Deal policy package.

- REG: relying on intensified energy and transport policies but without any carbon pricing in road transport and buildings, therefore assuming carbon pricing according to the existing EU ETS (Emissions Trading System) which includes the maritime transport but excludes both road transport and building sectors.
- MIX: combining carbon pricing for road transport and buildings with strong energy and transport policies. It encompasses a uniform carbon price, representing either an extended integrated EU ETS, including transport and building, or a new ETS for road transport and buildings separated from the existing EU ETS.
- MIX-CP: it emphasizes a carbon price-driven policy mix with revised but less intensive energy policies. Unlike MIX scenario, it differentiates carbon pricing between the existing ETS system and a new ETS system.

Additionally, the platform enables users to perform power flow simulation based on Wu H. et al [86] model. The prototype version of this platform consists of a comprehensive dashboard organized into five main sections: top-right sidebar, bottom-right sidebar, top-central section, bottom-central section, left sidebar.

Top-right sidebar: it provides a concise overview of general information regarding the European energy system in 2020, including: total final consumption (TWh), maximum and minimum demand (GW, electricity consumption (TWh), CO2, NOx and SO2 emissions (Mton). By clicking in the specific tabs, users can select the desired year and scenario name, and opt for either peak or off-peak analysis. Once the preferred combination is selected, key indicators referring to the scenario of interest are automatically updated: total final consumption in TWh, total demand in GW, population in millions of people, primary energy consumption in Mtoe, electricity consumption in TWh and GDP in G€.



La domanda e gli scenari

Anno base 2020

Usi energetici finali: 10301 TWh
Carico massimo: 443.8 GW
Carico minimo: 233.8 GW
Peak/Off-Peak: 1.898
Elettricità consumata: 2385 TWh
Emissioni CO_2: 744.3 Mtons
Emissioni NO_x: 1157 ktons
Emissioni SO_2: 2109.8 ktons

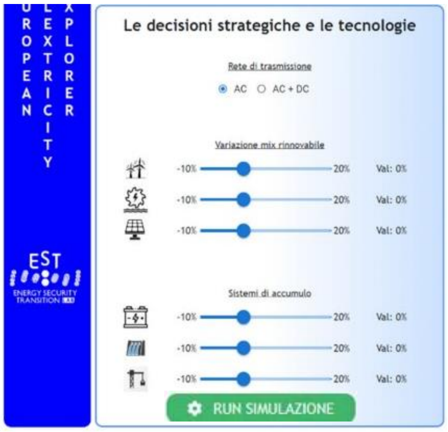
Scenario di analisi:

Anno 2030
Proiezione REF
Livelli di carico: ● Peak ○

Usi energetici finali: 9769 TWh
Carico elettrico: 492.1 GW
Popolazione: 449.1 Mpers
Elettricità consumat
TPES (Ene Cons.):
Prod. Inte Lordo: G€

Figure 75: Window for the selection of scenario to simulate (Source: [141]*).*

Bottom-right sidebar: it is dedicated to configuring the generation mix of renewable sources (solar, wind, and hydro) and the storage systems by setting the percentage increase (+%) or decrease (-%) with respect to the configuration of the previously selected baseline scenario. Additionally, at this point users have also the option to activate the DC layer (integrated with the AC network) or to consider just the AC network, before initiating the scenario simulation. Once the preferences are defined, users can run the simulation.



Le decisioni strategiche e le tecnologie

Rete di trasmissione

● AC ○ AC + DC

Variazione mix rinnovabile

-10% 20% Val: 0%

-10% 20% Val: 0%

-10% 20% Val: 0%

Sistemi di accumulo

-10% 20% Val: 0%

-10% 20% Val: 0%

-10% 20% Val: 0%

Figure 76: Window for Renewable and Storage system configuration (Source: [141]*).*

Top-central section: it presents the graphical representation on map of the European transmission network. By default, two interactive maps are displayed: Map 1 (left side) illustrates power flows with moving arrows indicating the direction and the intensity of the flow. Map 2 (right side) illustrates the geographic distribution of generation nodes with pie charts showing, for each generation node, the intensity and the composition of the electricity generation mix by commodity.

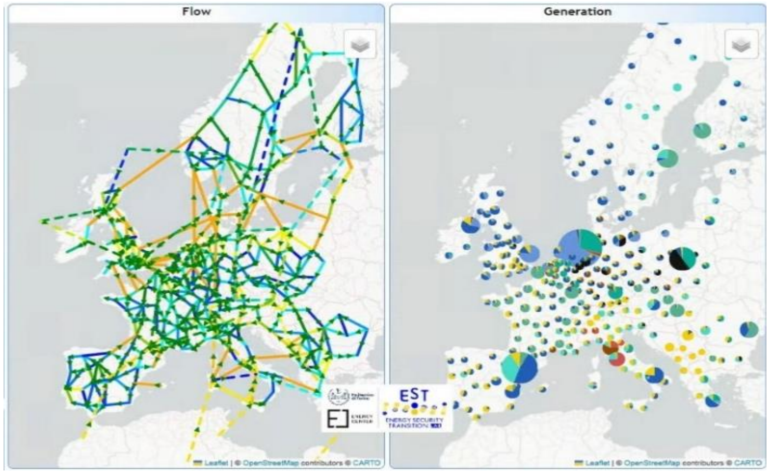


Figure 77: Power flow map (on the left) and generation mix (on the right) map (Source: [141]*).*

Bottom-central section: it presents the key outcomes derived from the power flow simulation based on the scenario configuration defined by the user. In the prototype version of E3, 12 metrics are included in this window aimed at providing a synthetic but comprehensive representation of transmission system performance, including the percentage of renewables in total final consumption (%), the percentage of intermittent generation in the generation mix (%) and the import of electricity from non-European countries (GWh). Additionally, insights on air pollution and CO2 emissions from power generation are provided, including air pollutant emissions (kg of PM 2.5) and carbon intensity (ton CO2/GWh). Operational information is also furnished, including the power (GW) and average demand (%) on DC lines, the number and the average demand (%) of congested lines. These metrics collectively offer a comprehensive overview of the system's performance and provide valuable insights into its operational characteristics.

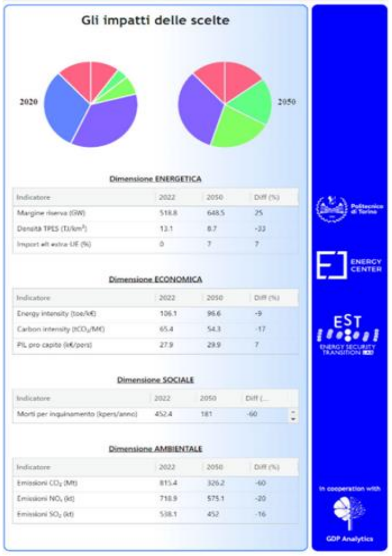
Lo stato del sistema

Import en. elettrica extra-UE	0 GWh	Potenza sulla rete DC	0 GW	Numero di linee congestionate	8
Percentuale di RES nel TFC	17 %	Carico medio linee DC	0 %	Carico linea più congestionata	197 %
PM 2.5 emesso da gen. elettrica	653 kg	Non-carbon fuel portfolio	77 %	Elettricità dalla RES	64 %
Generazione intermittente	50 %	Intensità CO_2 del mix energetico	10084	Rapporto RES/fossili	3

Figure 78: Output of power flow simulation (Source: [141]*).*

Left sidebar: in this section users can analyse with a multi-dimensional perspective the effects of selected scenario by means of a set of indicators offering a multi-dimensional overview of implications on energy systems, environmental sustainability, economic performance, and societal well-being. On the top of the sidebar two pie charts illustrate the current and projected generation mix, while the lower section provides evaluation indicators. This enables users to compare improvements or deteriorations between current and hypothetical scenarios in terms of energy, economics, societal impacts, and environmental sustainability. In the current version of E3 10 indicators are selected:

- Energy dimension: Reserve Margin (GW), Total Primary Energy Supply (TPES) Density (TJ/km2), Extra-European electricity imports (%).
- Environmental dimension: CO2 emissions (Mt), NOx emissions (Mt), SO2 emissions (Mt).
- Economic dimension: Energy intensity (toe/k€), Carbon intensity (tCO2/M€), GDP per capita (k€/per capita).
- Social dimension: Deaths due to pollution (1,000 people/year).



Gli impatti delle scelte

Dimensione ENERGETICA

Indicatore	2022	2050	Diff (%)
Margine riserva (GW)	518.8	648.5	25
Densità TPES (TJ/km^2)	13.1	8.7	-33
Import elt extra UE (%)	0	7	7

Dimensione ECONOMICA

Indicatore	2022	2050	Diff (%)
Energy intensity (toe/k€)	106.1	96.6	-9
Carbon intensity (tCO$_2$/M€)	65.4	54.3	-17
PIL pro capite (k€/pers)	27.9	29.9	7

Dimensione SOCIALE

Indicatore	2022	2050	Diff (...
Morti per inquinamento (kpers/anno)	452.4	181	-60

Dimensione AMBIENTALE

Indicatore	2022	2050	Diff (%)
Emissioni CO$_2$ (Mt)	815.4	326.2	-60
Emissioni NO$_x$ (kt)	718.9	575.1	-20
Emissioni SO$_2$ (kt)	538.1	452	-16

Figure 79: Metric-based output: key performance indicators for the energy, economic, social, and environmental dimensions (Source: [141]*).*

5.3 SERT: Supply Energy Risk Tracker

The research activity, focused on developing metric-based approaches and tools to support policy makers in addressing the multi-scale and multi-dimensional challenges posed by the energy transition, revealed a certain vulnerability both in the European and Italian energy systems, caused by dependence on energy commodities, in particular natural gas and oil, imported from third countries often characterized by poor geopolitical stability. Although the trend of fossil share in the European energy mix is continuously decreasing [88] in accordance with goals set by the European Commission ([17], [18], [19]), the complete transition needs time to be achieved and the European energy system still depends on third countries to meet the fossil demand [88] (e.g., natural gas from Russia, crude from Azerbaijan, Kazakhstan, etc.). As evidenced by the energy crisis following the Russia-Ukraine's war in 2022, this dependency still represents a real threat not only for the security of energy systems but also for global energy markets (i.e., oil market, natural gas market, etc.), leading to an overall increase of energy prices (e.g., electricity prices) and consequently also to higher prices for goods and services, affecting the most economically vulnerable people. Recognizing the urgent need to address the problem of dependency on Russian energy commodities, in particular on natural gas which accounted for almost 40% of EU-27's gas import in 2021, the European Commission prioritized the reduction of Russian gas demand (REPowerEU plan [18]), even employing short-term countermeasures such as gas to coal switching, to mitigate the immediate challenges, though potentially conflicting with long-term sustainability goals (Fit for 55 plan [17]). In this context, energy security assumes a pivotal role in energy policies together with decarbonization and electrification initiatives. By consistently monitoring the external risk related to importing energy commodities from third countries, it is possible to track in real-time the energy supply corridors, underscoring eventual criticalities in the supply systems (e.g. risky corridors), and identifying adequate alternative supply corridors and supply countries in case of corridors disruption.

The development of the SERT platform [142] fits within the context of the doctoral research as an IT tool that addresses the need for a decision-support tool for policymakers to assess and prevent risk scenarios related to energy supply from third countries in the delicate context of ongoing transition. SERT translates the complexity of the external-risk model presented by Desogus E. et al [143] into an interactive and user-friendly platform, allowing the application of the model to various contexts and scenarios chosen by the user, following COIN guidelines (section 2.2). SERT platform seeks at providing valuable insights to policy makers in order to advance informed decision-making and proactive risk management strategies to prevent critical situation (prevention strategies) and intervene promptly to mitigate any loss of energy commodity (protection strategies) in case of supply disruption. In addition to providing access to a wide range of energy-related data, focusing on liquid fuels trade (e.g., liquified natural gas, crude and refined oil products, biofuels, etc), the platform enables users to create and examine risk scenarios involving the disruption of supply from one or more corridors. By simulating potential disruptions and tracking the energy supply corridors in real-time, policymakers better understand the entity of risks associated with diverse commodities and supply corridors and can evaluate alternative solutions to recover the amount of missing commodity in case of supply disruptions.

SERT functionalities

Likewise in the ET@IT platform, access to SERT platform is granted through the login page, where users are required to enter their credentials (username and password) to gain access.

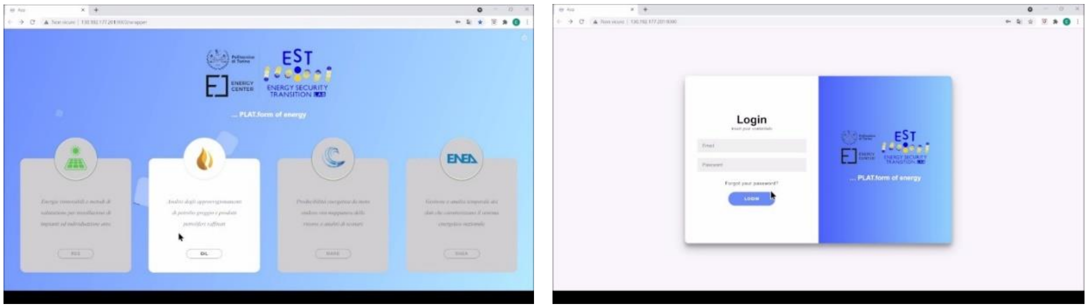


Figure 80: Login page to access to the SERT platform (Source: EST-plat [142]*).*

Once the login credentials for the main Energy Plat-EST platform are entered, users can access the SERT platform by clicking on the "OIL" option. The platform is structured into 5 main sections:

1. "MAPS" section is aimed at enhancing user-visualization of supply corridors, underscoring the areas characterized by high geopolitical risk and piracy zones, and at localizing strategic infrastructure (e.g., ports and pipelines) involved in the global trade of energy commodities.
2. "DATA" section is intended for facilitating data exploration by means of interactive tables which allow users to access to a wide range of data. Thanks to the pivot table functions, users can customize the information displayed in the table through sorting and filtering functionalities. Once customized the table content, user can proceed with direct download of table as excel file.
3. "CASES" section is dedicated to creating risk scenarios through 6 steps: 1) commodity selection, 2) time and country selection, 3) monthly demand setting, 4) supply

interruption setting, 5) supply covering setting, and 6) definition of scenario's name and description.

4. "ANALYSIS" section enables users to access to the complete list of scenarios already created, to visualize specific information and to modify parameters before running the simulation. Once completed the simulation the output is accessible in the Results section.
5. "RESULTS" section provides the results of the risk scenario simulation both in interactive table and graphical (map and graph) format in order to enhance efficiency in data visualization.

Section 1: MAPS section offers valuable insights into the geographical factors influencing energy security: the length of supply corridor (including both transport along pipelines and maritime route), the presence of piracy areas, and geopolitical stability of countries crossed by the corridor. Three types of maps are provided: risk of failure map, geopolitical risk map and piracy areas map. The first one provides visual representation of ports, pipelines and typical maritime route. The second map underscores the geopolitical risk score of each country, and the third one highlights the zones characterized by frequent piracy attacks. This section seeks to provide an overall overview of logistical aspects of international energy commodity trade, focusing on liquid fuels which are mainly transported by sea. This visualization helps in identifying strategic hubs, critical chokepoints, and risky areas, as well as alternative supply corridors.

Risk of failure map (Figure 81): maritime routes are delineated by a colour indicative of the associated probability of failure index (red line: high value, green line: low value) calculated by considering the length of the corridor via pipelines and sea, the presence of straits or canals, geopolitical stability in traversed areas, and the presence of piracy zones along the route.

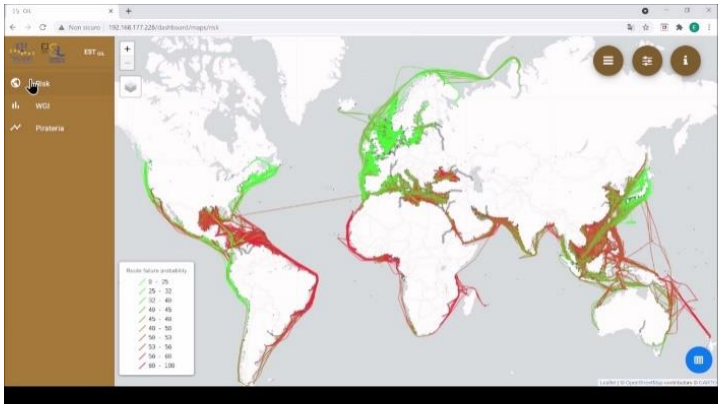


Figure 81: Risk of supply failure map

Geopolitical Risk map (Figure 82): all countries are characterized by a colour representing the geopolitical risk index, derived by processing the WGI indicators provided by the World Bank [76].

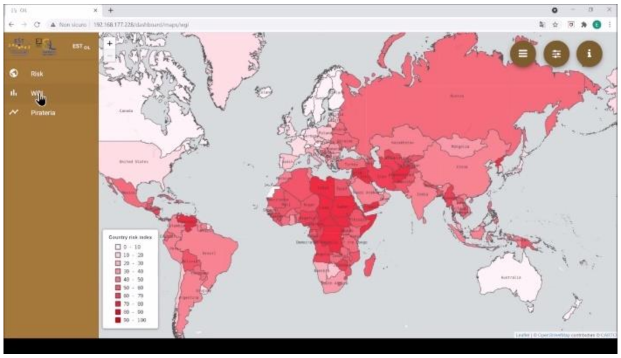


Figure 82: Geopolitical risk map

Piracy Areas map (Figure 82): the highlighted areas show the zone characterized by high frequency of piracy attacks. The colour-coding is based on the Piracy index score, derived by Maritime Security [144] .

Figure 83: Piracy areas map

To enhance map visualization, the platform allows users to choose one of the five available base maps (shows in Figure 84: Topology, Satellite, Classic, Light), to decide which layers to be displayed in the map (ports, routes, pipelines), to zoom in on the map and to click on a specific route for visualizing the pop-up window containing all specific information about the corridor (Figure 85): load port, discharge port, name and group of the commodity being transported, average probability of failure index for the overall corridor (%), average energy transported (expressed in various units of measurement: MWh, tonnes of oil equivalent, TJ, Gcal).

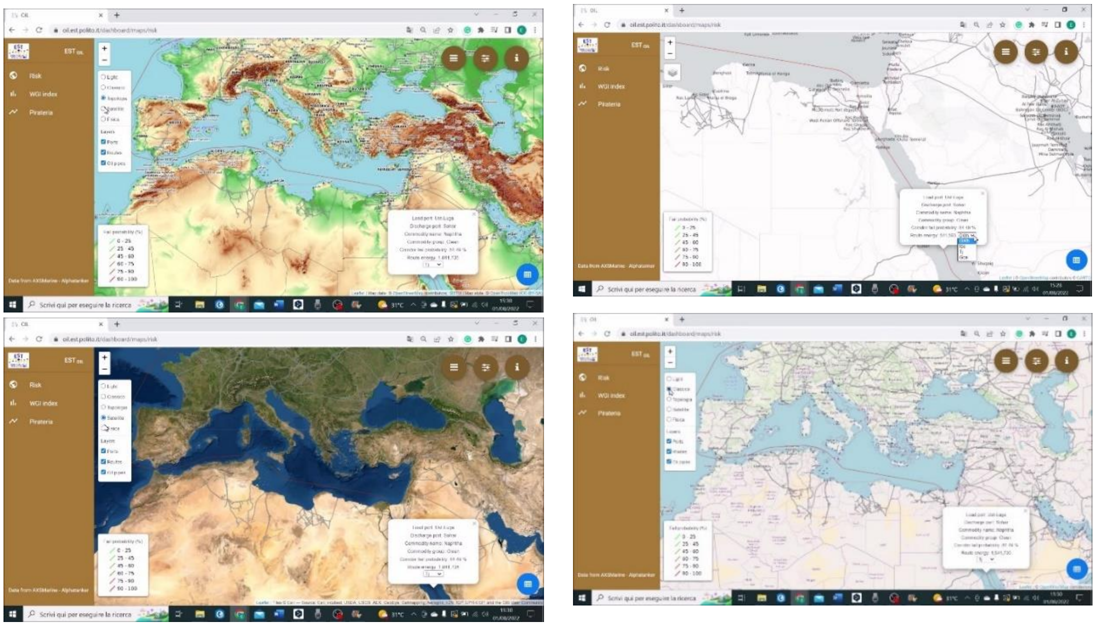


Figure 84: Base maps and layouts (Source: EST-plat [142]*)*

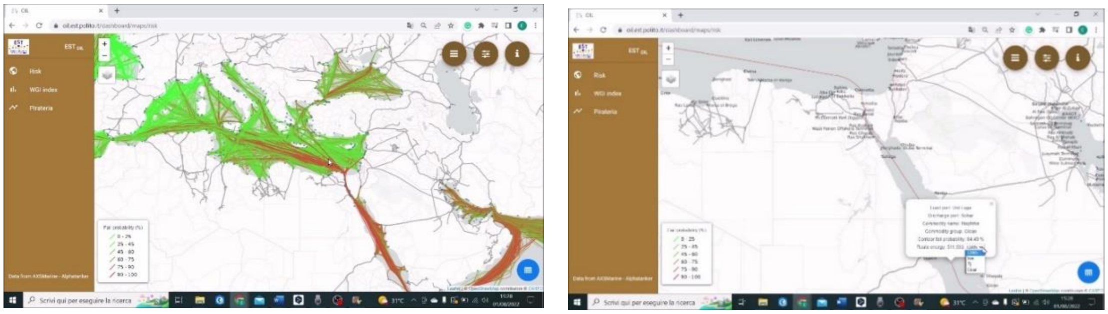


Figure 85: Routes visualization and pop-up description for a specific route (Source: EST-plat [142]*)*

To visualize a specific sub-set of routes, users can apply filters using the dedicated function in the interactive table, accessible by clicking the "ROUTES" blue icon at the bottom left. Users can apply one or more filters directly to individual columns or by suing "FILTERS" function for quick selection of multiple filters. Additionally, users can arrange data alphabetically or in ascending/descending order by means of “SORT" function. By clicking the "APPLY" button, the risk map is updated and only routes meeting the filter conditions set by the user are displayed in the map (Figure 85).

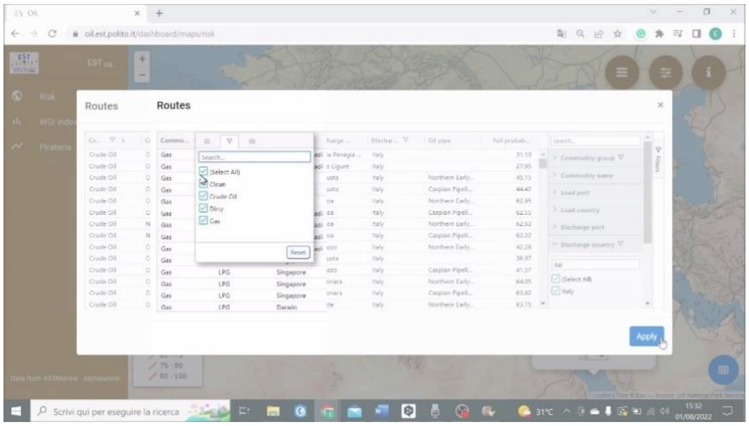


Figure 86: Route stats functionalities: exploring and filtering routes by means of interactive table (Source: EST-plat [142]*)*

Section 2: DATA section enables users to explore and analyse data stored in the database, including import/export statistics, production volumes, and prices. Data are organized into three main sub-sections:

1. "ITALY": comprises Italian petroleum data, sourced from the “Bollettino Petrolifero” [145] by the Ministry of Economic Development (MiSE). These data encompass imported quantities of crude oil categorized by country of origin and quality (including API grade and sulphur content), national fossil fuels production (both crude oil and gas), amounts of refined products imported and exported, as well as price information.
2. "WORLD": contains data on global petroleum sector sourced from the Joint Organizations Data Initiative (JODI). Users can explore statistics such as consumption, imports, exports, local production and refining output for a wide range of global countries.
3. "ROUTES STATS": is dedicated specifically to maritime trade. Users can access information regarding maritime routes, such as volumes of transported commodity, load and discharge date, and load and discharge points [146].

The interactive table system facilitates data filtering and sorting (Figure 86 and Figure 87). Moreover, in ROUTES STATS sub-section, the "pivot" function allows users to set the table structure (rows and columns) according to their needs, apply filtering through the "filter" function, and aggregate data using available functions (e.g., sum, average, minimum, maximum, count values, etc.). Once the structure and contents are defined, users can directly download the table in Excel format (.csv or .xlsx) by right clicking the mouse.

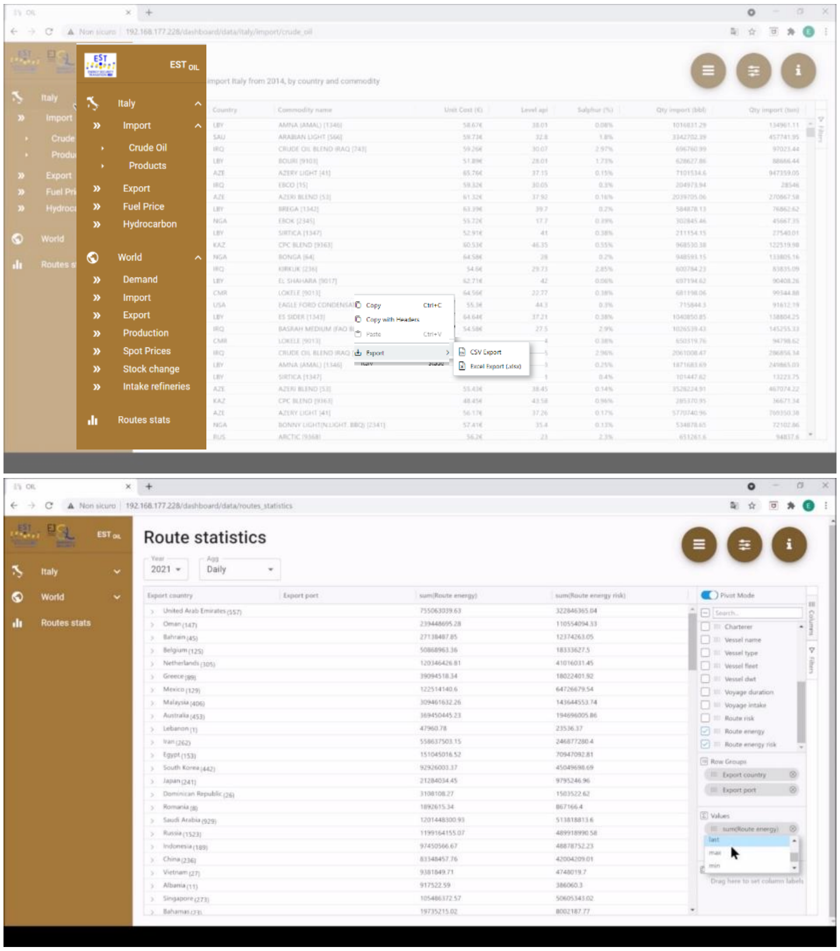


Figure 87: Data exploration section: pivot table, sorting, filtering and download functions (Source: EST-plat [142]*).*

Section 3: CASES section is dedicated to the creation of new risk scenarios through a step-by-step process guiding the user in setting the scenario variables (Figure 88). By customizing scenarios based on specific variables, stakeholders can simulate diverse risk scenarios and evaluate suitable measures to prevent supply disruptions. In the event of a disruption, this section supports in model a range of alternative countermeasures to collect the amount of lost commodity from alternative corridors.

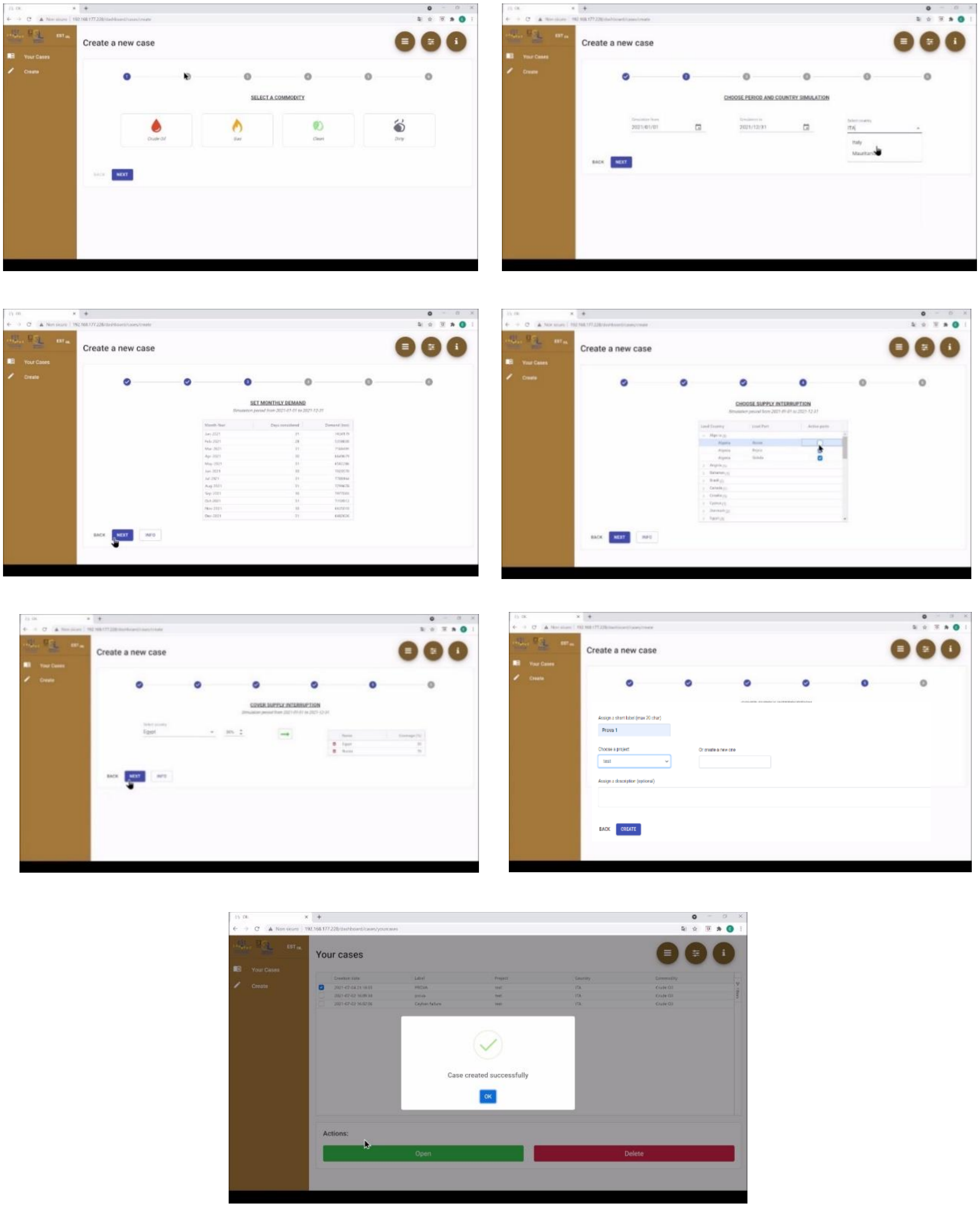
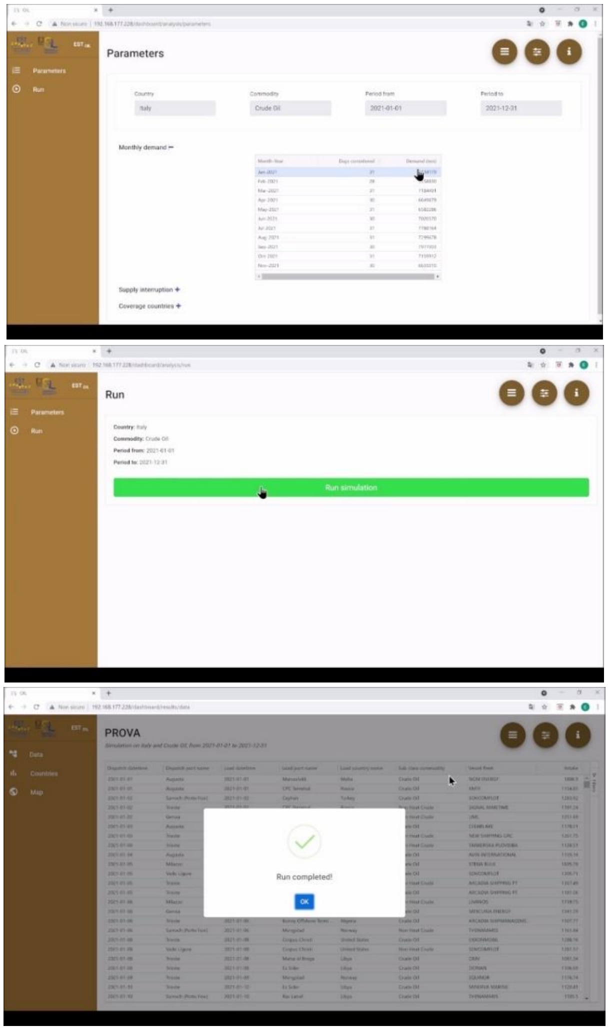


Figure 88: Creation of a new risk scenario: 6 steps (Source: EST-plat [142]*)*

Section 4: ANALYSIS allows users to open one of the created risk scenarios and run the simulation. At this stage users can still adjust simulation inputs: 1) the monthly quantities imported, 2) the exporting ports assumed to experience supply interruptions, 3) the import shares from alternative supplier countries to cover the missing commodity amount. Once all variables are configured, simulation is initiated by clicking on "RUN SIMULATION" (Figure 89). By testing multiple scenarios, users can quantify and compare the potential impact of diverse supply disruptions scenarios.



Country: Italy
Commodity: Crude Oil
Period from: 2021-01-01
Period to: 2021-12-31

Simulation on Italy and Crude Oil from 2021-01-01 to 2021-12-31

Figure 89: Scenario analysis and simulation (Source: EST-plat [142]*)*

Section 5: RESULTS section displays simulation outputs through interactive tables, graph, and map. This section facilitates data visualization and interpretation, enabling users to identify trends, patterns, and risk factors affecting oil supply dynamics.

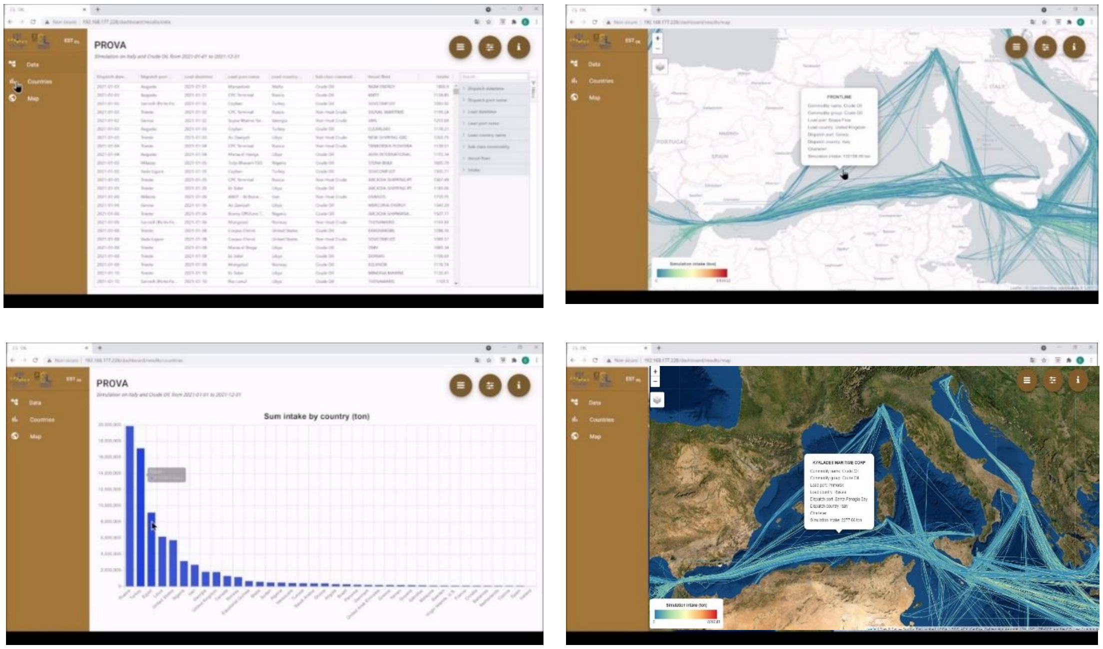


Figure 90: Results visualization: interactive tables, graphs and maps (Source: EST-plat [142]*)*

5.4 Data acquisition and data cleaning

Data acquisition is generally defined as the process of converting real-world signals and measurements to digital format, enabling their storage into a database, as well as their elaboration and visualization into digital interfaces. However, this definition can be revised by considering data acquisition as the process of gathering real-world data already collected by third parties (data providers). Data providers (e.g., IEA, Eurostat, CBS, etc.) aim to deliver accurate, usable and timely information, by converting real-world measurement into digital format through a robust and reliable data acquisition system (DAS). On the other hand, “data processing platforms” such as ET@IT, E3 and SERT, are specialised in transforming raw information gathered from data providers into valuable insights for policy makers through science-based methodologies. When dealing with data processing platforms, data acquisition can be regarded as equivalent to data collection, including data cleaning process. While data providers have to handle errors from real-world measurements, data processing platforms have to manage inconsistencies in data supplied by various data providers. In both the cases, data cleaning is a fundamental step of data acquisition. Data cleaning includes detecting and rectifying inconsistencies, such as outliers, duplicates, and missing values, as well as data validation and standardization. Upgrading DAS with an advanced data cleaning leads to enhanced quality of information and reliability of data providers.

In developing platforms aimed to policy-decision making (ET@IT, E3 and SERT), data acquisition system is crucial to ensure precise, timely, and comprehensive information from reliable data providers, enabling policymakers to make evidence-based decisions and engage stakeholders with transparency and confidence. In this context, data acquisition involves various steps: firstly, a preliminary analysis of available datasets and data providers is performed. In this preliminary step, the formalization methodology presented in Section 3 is a powerful tool to distinguish specific characteristics of each dataset and to identify the most reliable data providers and the most comprehensive datasets for gathering raw data. Indeed, through the formalization methodology it is possible to collect a wide range of useful information for guiding the choice of data sources: the spatial resolution (e.g., national scale, regional scale, provincial scale), the temporal resolution (e.g., annual, monthly, weekly) and the data extent (e.g., temporal extent, spatial extent) of each dataset. The API availability is a further crucial element to take into account in order to ensure a more efficient and robust automated data collection system. In absence of API, data reading and extraction (web scraping) from third party website, as well as web crawling (i.e., periodically updating the database) is more challenging and requires more advanced techniques. Three main approaches of web scraping for data collection in ET@IT, E3 and SERT can be distinguished: web scraping via API, Preformatted File scraping, and HTML parsing of the webpage content. In all three cases, Python is used both to handle data extraction and to perform further elaborations (e.g., data cleaning, normalization, etc.) before being saved to the database.

1. Web Scraping via API involves accessing data through an Application Programming Interface (API) which facilitates interaction and direct download of structured data from the data provider’s website.
2. File scraping through HTML parsing is adopted when already structured files, such as CSV, XML, or JSON, are provided in the data provider’s website; it involves the HTML parsing aimed at downloading the preformatted files.
3. HTML scraping allows to read the entire content of the data provider’s website and to extract the desired information by parsing the HTML content of web pages through customised and more advanced scripts.

Table 34: Comparison among web scraping methodologies

Method	Advantages	Disadvantages
Web Scraping via API	- Efficiency and Ease of use - Structured Data: Provides well-organized and structured data - Reliability: more stable compared to the other HTML parsing methods - Easy maintenance - Documentation: well-documented - Compliance with terms of service: it adheres to terms of service and legal regulations	- Limited Access restricted to data availability offered by the API - Usage restrictions and rate limits - Need of API Authentication to access the data - Cost: May incur costs if the API is a paid service
Preformatted File Scraping HTML parsing	- Ease of Use: it requires simple scripts to download well-structured files - Tools: Availability of tools for easy parsing (e.g., pandas for Excel files) -Automation: Allows for automation of data extraction from multiple documents.	- Availability: it depends on availability of preformatted files in web page - Format and Structure Variability: requires further processing after downloading - Memory Usage: Large files may consume significant memory
HTML parsing	- No rate limits: free from rate limits imposed by the data provider - Data access: enables access also to data not available through API or as Preformatted File - Flexibility: it allows to extract any data provided in the web page even in absence of APIs or preformatted files for download	- Fragility: scraping scripts can break whether data provider makes changes in HTML structure of website - HTML handling: it requires advanced knowledge of HTML and scripting languages - Increased complexity in Setup and Maintenance - Compliance with terms of service: it may violate terms of service, data privacy and usage

When data providers offer the API service for data extraction, scraping through APIs is the preferred approach due to its significant advantages highlighted in table Table 34. However, HTML parsing content scraping provides a viable alternative when APIs are not available.

Indeed, a limited number of data providers offer APIs to access data, and only a few of them provide the API service for free; therefore, whether data provider offers preformatted files containing the desired information, the second method is preferred as alternative of API. The third method is adopted when neither APIs nor preformatted files are available. Unlike data extraction through API, more reliable and stable thanks to its independence from any change in the web interface structure, HTML web scraping scripts must be revised whenever the data provider alters the layout and organization of website elements.

Unlike E3 platform, characterized by a simple data collection system as input data are gathered from a single data provider (European Commission [140]) supplying preformatted files in Excel format, data collection system of ET@IT and SERT are more complex. Especially ET@IT platform is characterized by a more advanced data collection system as it needs input data from a wide range of data providers. The 92% of input data are collected through the second method in Excel format, due to the lack of available APIs; the remaining data (8% of the total) are gathered through the third methodology. Once the data extraction through web scraping is complete, data storage process follows; this step involves initially loading the extracted information into Python, followed by data cleaning and any necessary processing before the data storage in the database.

For each platform, a custom Entity-Relationship (ER) database has been developed using PostgreSQL, structured into tables (Entities) and links between tables (Relations). If the input data does not match the table structure, the storage process halts with an error, preventing data from being saved in the database without proper data cleaning and standardization procedures. Therefore, the choice of using the ER database design inherently requires data cleaning to perform data storage; this system ensures that all input data is systematically entered into the database in a well-organized and structured way.

Despite the most complicate data collection system is observed in ET@IT platform due to the variety of data sources, when comparing the database structures of the developed platforms, SERT's database structure results the most intricate one. By comparing ET@IT and SERT databases, it is possible to better understand the differences among ER database structures:

- ET@IT Database Structure (APPENDIX, Figure 97) is designed with independent tables, reflecting a simpler database structure compared to SERT platform (characterized by interlinked tables). Therefore, data collection and data cleaning require more intricate and labour-intensive procedures than other platforms due to the multitude of data sources, whereas both data storage, as well as calculation of indexes, result less complex as each table (i.e., Entity) into the database operates independently.
- SERT Database Structure (APPENDIX, Figure 98) is characterized by interlinked tables, resulting in more complex data storage and data processing processes. Links (relations) between tables highlight the relationships among different tables (entities). This structure is necessary to effectively manage the interdependencies between

entities included in the database. This complexity in database structure, while providing a more nuanced view of relationships among input data, increases the difficulty of data processing. Queries and data retrieval operations become more challenging due to the multiple relationships and dependencies among tables.

Since the dimensionality of downloaded data for ET@IT, SERT and E3 is not sufficiently large to require data reduction, it has been maintained the highest available data resolution to preserve all potentially valuable information for subsequent analyses, rather than implementing data reduction which would result in the inevitable loss of information to decrease the volume. After input data are stored in the database, further elaborations are typically needed before presenting final data in the User Interface (UI). These elaborations may include various operations such as removing duplicates, handling missing data and eventual outliers, standardizing nomenclatures and unit of measurements. These operations resulted less challenging for ET@IT and E3 platforms compared to SERT platform, as the majority of input data came from preformatted files provided by official sources such as IEA, MiSE and Eurostat for ET@IT and European Commision for E3. Conversely, these elaborations resulted more problematic for SERT platform: data extraction from Alphatanker [146] (data source responsible for supplying data about maritime routes transporting energy commodity) brought indeed several problems such as unrealist vessels trajectories (i.e., ships passing through continents) and overestimated number of routes, therefore diagnostics were necessary to identify the causes of these issues. In the first case, a cross-check was conducted between the coordinates provided by Alphatanker and other sources, identifying approximately 400 ports with incorrect coordinates. This issue was reported to the data provider, and the coordinates were updated with those from the alternative data source.

As regard the overestimated number of routes, the issue was due to different IDs assigned by Alphatanker to some routes which are actually the same, resulting in duplicates being stored in the database as separated routes. Therefore, to remove duplicates, instead of the route ID the vessel name and the date of departure have been used as criteria to distinguish the routes.

In the last version of SERT, these issues have been solved thanks to the new APIs provided by Alphatenker which simplifies the direct access and extraction of desired information from the data provider webpage.

Chapter 6

6 Conclusions

This dissertation addresses the crucial need of science-based support to aid policymaking in addressing the ongoing multi-scale and multi-sectorial energy transition challenges, including decarbonization and electrification as key solutions to achieve the ambitious targets introduced by the European Climate Law in 2021 (-55% of EU's carbon emissions compared to 1990 by 2030 and carbon neutrality by 2050). To meet these targets within the deadlines, it is necessary to plan ad-hoc policies and implement integrated strategic actions across multiple dimensions (e.g., energy, environmental, social, economic dimensions) and multiple spatial scales (e.g., international, national, regional, and municipal scales). Due to the magnitude and the complexity of this challenge, policymakers need to be empowered by scientific evidence, enabling data-driven decisions and the so-called "Evidence-Informed Policymaking". Scientific evidence in evidence-informed policymaking is a crucial tool for evaluating the most effective solutions through a systematic and objective approach. It also helps increasing public trust and awareness, as data-driven decisions can be legitimated by objective and quantitative evidence of their benefits.

To integrate scientific evidence in policymaking, it is necessary to overcome the barriers between the scientific community and the policy environment. To bridge this gap, the scientific community must shift from traditional, selective, curiosity-driven research to a more inclusive, instance-based approach ('Science 2.0' [45]), promptly responding to policymaker's requests and needs, and becoming a reliable 'advisor' for policymakers ('Science for Policy').

As scientific evidence is not self-explanatory, effective evidence communication plays a crucial role in Science for Policy: scientists have the responsibility to 'translate' complex findings by means of innovative data visualization methods and tools for facilitating audience comprehension and promoting interactions with stakeholders and policymakers. In contrast to the high impact in scientific community, where research novelty is often prioritized, conciseness and clarity of findings take priority for achieving high impact in the policy environment. Metrics are powerful practical tools to synthetise scientific evidence, ensuring clarity and conciseness, therefore metric-based methodologies serve as effective solutions for enhancing the communication of policy-relevant insights (e.g., quantitative information of policy impacts and benefits) enabling real-time adjustments and supporting the evaluation of future strategies.

By integrating clarity and conciseness of metric-based methodologies with the interactivity of user-friendly IT tools aimed at prioritizing clear data visualization and audience understanding, it is possible to further improve the effectiveness of scientific evidence communication. Additionally, since these IT tools are designed to be accessible also to non-experts, they can play a pivotal role in raising public awareness and in promoting transparent policy. By highlighting relevant insights of policymaking's performance, IT tools can be used to evaluate policy performance and set up real-time adjustments, as well as to legitimate policymakers' choices by showing quantitative evidence of the improvements achieved, leading to an increase of public confidence in policy.

The research activity was focused on developing metric-based methodologies (i.e., building metrics framework and composite indices) to assess energy transition, electrification and decarbonization trends at different spatial scales, then digitalised and transformed into IT tools (web platforms) to adopt a more inclusive approach and communicate more effectively to a wider audience, facilitating data exploration and findings visualization through user-friendly and interactive interfaces.

The utility and broad applicability of the novel proposed formalisation approach is evidenced by its use as preliminary step for setting up the metric-based assessments discussed in the dissertation. This methodology effectively highlighted key features of available data and datasets, also outlining interdependences between datasets and input data, as well as hierarchies between output data (indicators and composite indices) and input data (raw data). Moreover, this approach resulted highly effective in designing well-structured Entity-Relation (ER) databases and automated data collection systems for web platforms (IT tools) handling a large volume of diverse data and datasets.

The application of the developed metrics framework to real cases demonstrated the wide applicability and efficacy of metric-based methodologies to obtain concise but relevant insights on diverse aspects of energy transition at different spatial scales: impacts and benefits of projected increase of intermittent renewable power generation on the European power network in 2030, 2040 and 2050 (European scale), the effects of energy transition on country-scale trends of the 'energy trilemma' dimensions (energy security, energy affordability and energy sustainability), and urban-scale improvement and worsening across multiple dimensions (energy, environmental, and socio-economic domain).

The analysis of the effects of intermittent renewable penetration in the European power system revealed significant benefits in terms of reduced air pollution emissions; indeed, Distributed Energy (DE) and Global Ambition (GA) scenarios, reflecting the two main policy directions aimed at achieving the European decarbonization targets, show sharp reduction in air pollutants emission, especially in SOx and NOx emissions. Moreover, Germany results the first country in pollutant emissions, although significant reductions are observed in 2040 and 2050 thanks to the progressive shift from combustible source to non-combustible RES (wind and solar sources); in contrast, France already in 2025 exhibits low pollutant emissions, despite being the second-largest electricity producer in Europe after Germany, thanks to nuclear power accounting for the majority of power generation. Similar findings are observed in the carbon emission analysis, showing sharp CO2 emission reduction in both DE and GA scenarios; however, the comparative analysis between the Activity-Based and the Life-Cycle approaches, revealed the Life-Cycle's fairness issue in quantifying the equivalent CO2 emissions in DE and GA scenarios. The evaluation of impacts in power system stability, instead, outlined an increased variability in residual load due to renewable integration, as evidenced by the higher percentage of hours with exceedance of the residual load variation limit in power generation mix characterized by higher wind and solar shares. On the national scale, the revision of existing ISPRED framework, led to the development of new metrics related to the energy security (i.e., dispatched inertia indicator, index of diversification of suppliers and index of national energy mix diversification, integrated index of diversification and stability of suppliers), to the decarbonization through electrification of final uses (i.e., green electrification rate, electricity transmission efficiency). The UETI's assessments conducted at the urban scale evidenced the relevance of continuous monitoring through a comprehensive index framework to identify critical areas of intervention, aiding policymakers in achieving a balanced energy transition across the energy, environmental, and socio-economic dimensions. The Turin's case study underscored both strengths and weaknesses in the city's transition performances, highlighting the sectors requiring more urgent interventions: on one hand, it is observed a consistent progress in energy transition, driven by significant integration of renewable energy, advancements in green mobility, and decreased energy intensity; on the other hand, persistent issues in air quality are detected by the air pollution metrics, underscoring the need of intensified efforts and investments in this field. The application of the UETI's framework to track the temporal evolution (2013-2022) of energy transition performances in Amsterdam, Eindhoven, Rotterdam, and Utrecht, demonstrated the adaptability and applicability of the UETI's methodology to diverse urban contexts. The study outlined significant enhancements in energy transition: in particular, Amsterdam shows the most pronounced improvement in the overall UETI's score. This result reflects the city's efforts to achieve carbon neutrality by 2050 accordingly with the "Amsterdam Climate Neutral" plan which aims to boost solar and wind power generation, promote circular-economy and improve energy efficiency. However, as evidenced by the drop of Power Grid Quality in 2018, the increase in intermittent generation from wind and solar sources may affect negatively the stability of the power grid (i.e., frequency and duration of electricity outages per year). As regards the Socio-Economic domain, although a significant energy price increase after the Russia-Ukraine's war impacted the Well-Being performance of all the Dutch cities in 2022, the overall trend of Amsterdam's Well-Being index demonstrates that energy transition policies are not negatively affecting the city's well-being. Similarly, Utrecht and Eindhoven showed positive trends in all the UETI's macro-domains, in particular in Energy domain, thanks to the significant penetration of solar power generation, the increase in electric and hybrid vehicles and the progressive decrease in residential energy intensity. Despite the worsening in Eindhoven's waste management since 2018, the positive trend in Environment performance of Utrecht and Eindhoven reflects the effectiveness of implemented measures to improve air quality and reduce the urban carbon footprint. Although the overall positive trend across all domains, compared to the other three municipalities, Rotterdam shows less pronounced improvements; this gap is mainly due to moderate improvement in Energy and Socio-Economic domain whereas the Environment domain aligns with those recorded in the other cities. The significant drop of Energy domain observed between 2019 and 2020 is the consequence of low growth in RES generation and an increase in electricity outages duration (from 21 minutes in 2019 to 27 minutes in 2020).

This analysis not only confirmed the UETI's approach as a powerful tool to assess city-specific performance across multiple domains involved in the energy transition, but it also highlighted significant differences of data availability and quality between Dutch and Italian municipalities. Indeed, compared to Italy, Dutch cities have more advanced tools for collecting urban data required to perform energy transition assessment. This comparative analysis underscored the need of improving the availability of Italian city-scale data to solve the problems of inaccuracy due to the lack of data and to extend the UETI's approach to all Italian municipalities.

Aligned with the commitment of developing interactive and user-friendly IT tools for empowering informed policy making and for advancing stakeholders' engagement, three web platforms have been successfully developed: ET@IT is devoted to monitor the national energy transition in Italy through the quarterly 'energy trilemma' assessment adopted by ENEA; E3 platform is aimed at evaluating the impacts of large-scale RES penetration on the European power network; SERT platform has been developed to conduct detailed analyses on the risk of failure of supplying corridors transporting energy commodities by sea and to perform risk scenario assessments involving partial or total disruption of one or more supply corridors. All three platforms have been designed in alignment with the COIN guidelines for advancing effective data visualization through interactive tools and storytelling empowered by clear and concise infographics. Each platform is tailored with specific functions to serve its intended purpose. These platforms share the common goal of assisting policymakers in making informed decisions and effectively engaging stakeholders by providing science-based insights in a more accessible and inclusive way, facilitating communication of key evidence and contributing to the achievement of the ambitious sustainable energy targets while favouring public trust and transparent policy.

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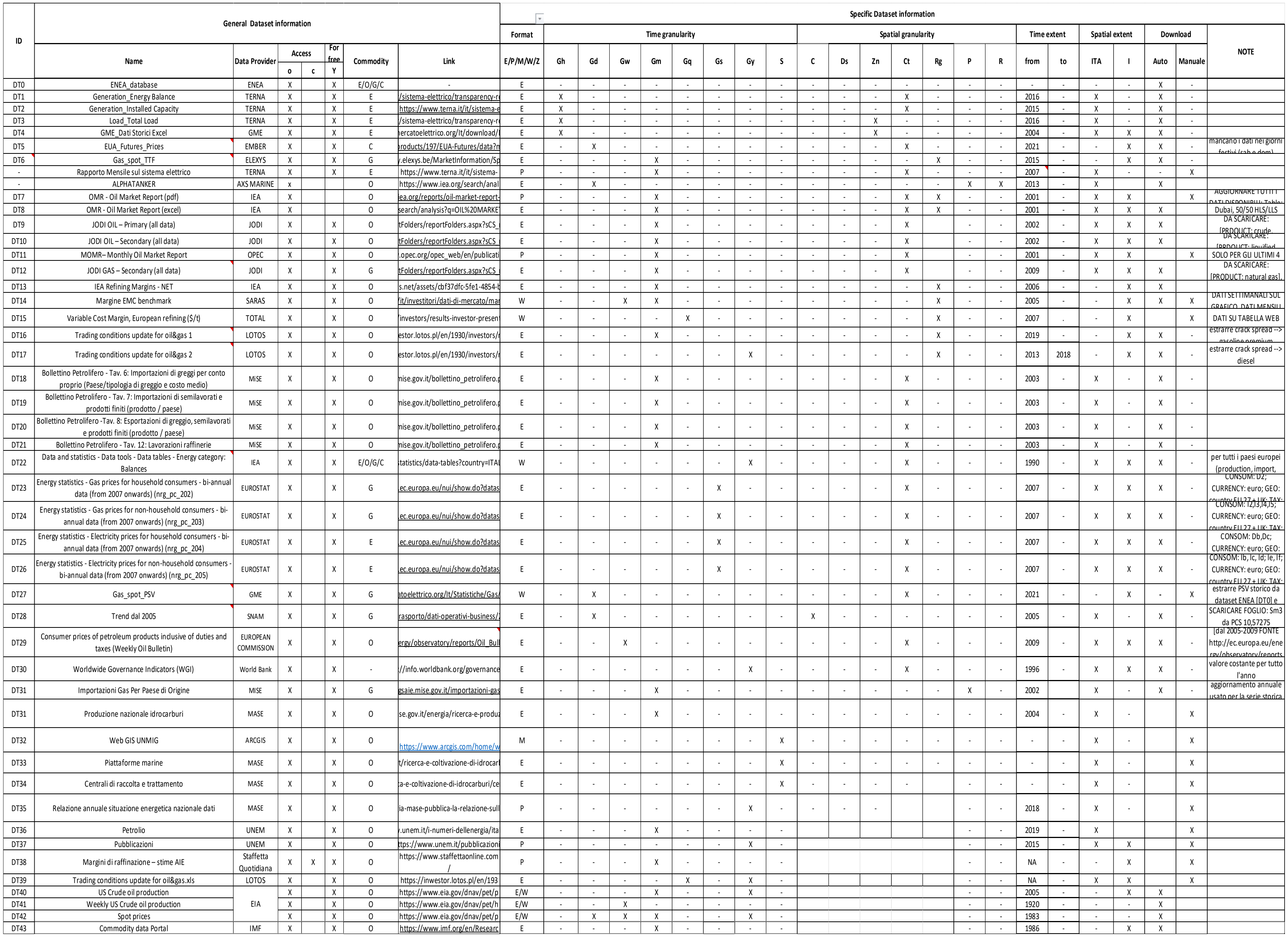
I. APPENDIX



ID	General Dataset information							Specific Dataset information																						NOTE
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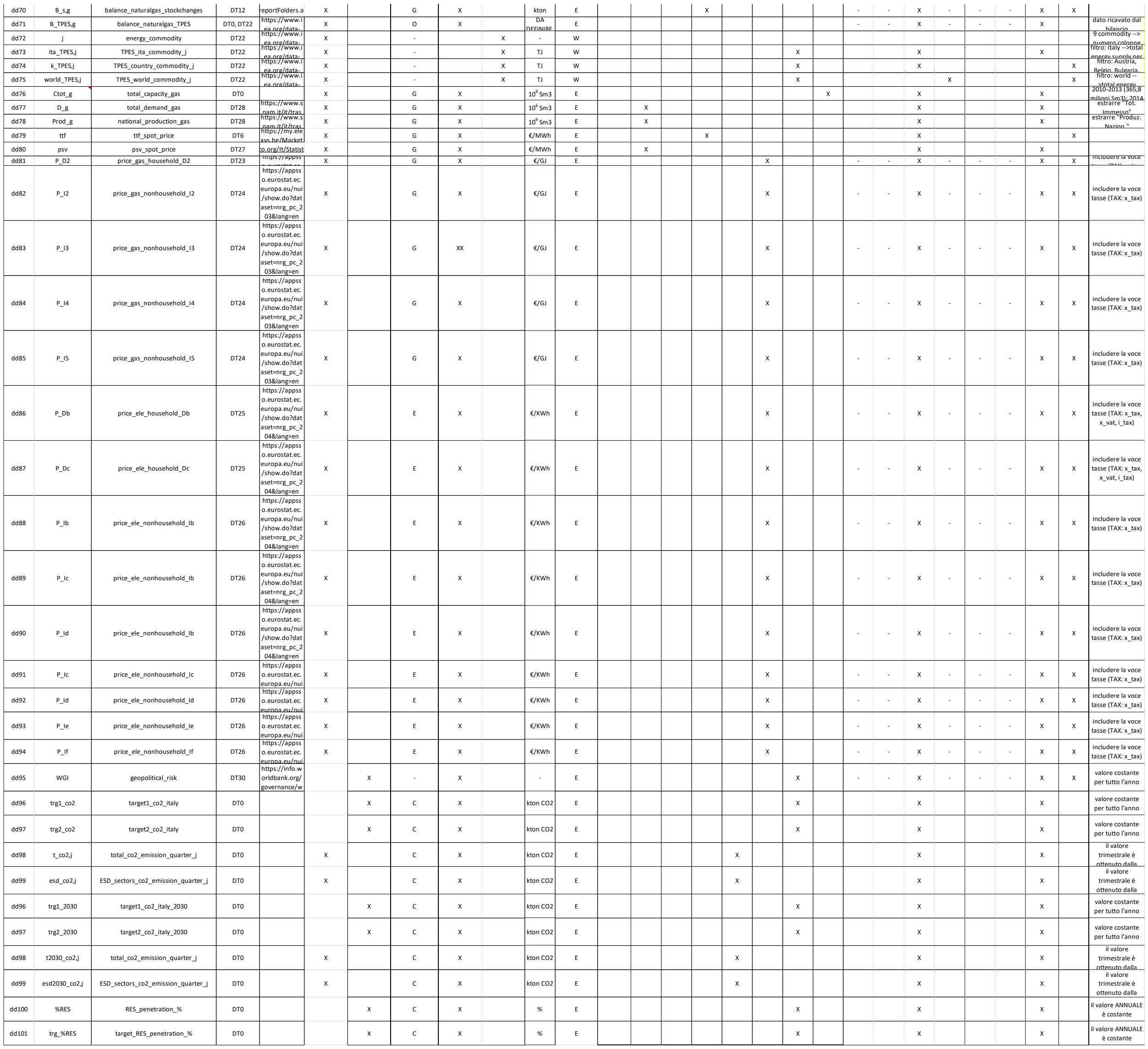
DT0	ENEA_database	ENEA	X		X	E/O/G/C	-	E	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	X	-	
DT1	Generation_Energy Balance	TERNA	X		X	E	/sistema-elettrico/transparency-r	E	X	-	-	-	-	-	-	-	-	-	-	X	-	-	-	2016	-	X	-	X	-	
DT2	Generation_Installed Capacity	TERNA	X		X	E	https://www.terna.it/it/sistema-e	E	X	-	-	-	-	-	-	-	-	-	-	X	-	-	-	2015	-	X	-	X	-	
DT3	Load_Total Load	TERNA	X		X	E	/sistema-elettrico/transparency-r	E	X	-	-	-	-	-	-	-	-	-	X	-	-	-	-	2016	-	X	-	X	-	
DT4	GME_Dati Storici Excel	GME	X		X	E	ercatoelettrico.org/It/download/	E	X	-	-	-	-	-	-	-	-	-	X	-	-	-	-	2004	-	X	X	X	-	
DT5	EUA_Futures_Prices	EMBER	X		X	C	roducts/197/EUA-Futures/data?m	E	-	X	-	-	-	-	-	-	-	-	-	X	-	-	-	2021	-	-	X	X	-	mancano i dati nei giorni festivi (sab e dom)
DT6	Gas_spot_TTF	ELEXYS	X		X	G	.elexys.be/MarketInformation/Sp	E	-	-	-	X	-	-	-	-	-	-	-	-	X	-	-	2015	-	-	X	X	-	
-	Rapporto Mensile sul sistema elettrico	TERNA	X		X	E	https://www.terna.it/it/sistema-	P	-	-	-	X	-	-	-	-	-	-	-	X	-	-	-	2007	-	X	-	-	X	
-	ALPHATANKER	AXS MARINE	x			O	https://www.iea.org/search/anal	E	-	X	-	-	-	-	-	-	-	-	-	-	-	X	X	2013	-	X		X		
DT7	OMR - Oil Market Report (pdf)	IEA	X			O	iea.org/reports/oil-market-report-	P	-	-	-	X	-	-	-	-	-	-	-	X	X	-	-	2001	-	X	X		X	AGGIORNARE TUTTI I DATI DISPONIBILI: Table:
DT8	OMR - Oil Market Report (excel)	IEA	X			O	search/analysis?q=OIL%20MARKET	E	-	-	-	X	-	-	-	-	-	-	-	X	X	-	-	2001	-	X	X	X		Dubai, 50/50 HLS/LLS
DT9	JODI OIL – Primary (all data)	JODI	X		X	O	tFolders/reportFolders.aspx?sCS_	E	-	-	-	X	-	-	-	-	-	-	-	X		-	-	2002	-	X	X	X		DA SCARICARE: [PRODUCT: crude
DT10	JODI OIL – Secondary (all data)	JODI	X		X	O	tFolders/reportFolders.aspx?sCS_	E	-	-	-	X	-	-	-	-	-	-	-	X		-	-	2002	-	X	X	X		DA SCARICARE: [PRODUCT: liquified
DT11	MOMR– Monthly Oil Market Report	OPEC	X		X	O	.opec.org/opec_web/en/publicati	P	-	-	-	X	-	-	-	-	-	-	-	X		-	-	2001	-	X	X		X	SOLO PER GLI ULTIMI 4
DT12	JODI GAS – Secondary (all data)	JODI	X		X	G	tFolders/reportFolders.aspx?sCS_	E	-	-	-	X	-	-	-	-	-	-	-	X		-	-	2009	-	X	X	X		DA SCARICARE: [PRODUCT: natural gas],
DT13	IEA Refining Margins - NET	IEA	X		X	O	s.net/assets/cbf37dfc-5fe1-4854-b	E	-	-	-	X	-	-	-	-	-	-	-	-	X	-	-	2006	-	-	X	X		
DT14	Margine EMC benchmark	SARAS	X		X	O	/it/investitori/dati-di-mercato/mar	W	-	-	X	X	-	-	-	-	-	-	-	-	X	-	-	2005	-	-	X	X	X	DATI SETTIMANALI SUL GRAFICO, DATI MENSILI
DT15	Variable Cost Margin, European refining ($/t)	TOTAL	X		X	O	/investors/results-investor-present	W	-	-	-	-	X	-	-	-	-	-	-	-	X	-	-	2007	.	-	X		X	DATI SU TABELLA WEB
DT16	Trading conditions update for oil&gas 1	LOTOS	X		X	O	estor.lotos.pl/en/1930/investors/r	E	-	-	-	X	-	-	-	-	-	-	-	-	X	-	-	2019	-	-	X	X	-	estrarre crack spread --> gasoline premium
DT17	Trading conditions update for oil&gas 2	LOTOS	X		X	O	estor.lotos.pl/en/1930/investors/r	E	-	-	-	-	-	-	X	-	-	-	-	-	X	-	-	2013	2018	-	X	X	-	estrarre crack spread --> diesel
DT18	Bollettino Petrolifero - Tav. 6: Importazioni di greggi per conto proprio (Paese/tipologia di greggio e costo medio)	MiSE	X		X	O	mise.gov.it/bollettino_petrolifero.p	E	-	-	-	X	-	-	-	-	-	-	-	X	-	-	-	2003	-	X	-	X	-	
DT19	Bollettino Petrolifero - Tav. 7: Importazioni di semilavorati e prodotti finiti (prodotto / paese)	MiSE	X		X	O	mise.gov.it/bollettino_petrolifero.p	E	-	-	-	X	-	-	-	-	-	-	-	X	-	-	-	2003	-	X	-	X	-	
DT20	Bollettino Petrolifero -Tav. 8: Esportazioni di greggio, semilavorati e prodotti finiti (prodotto / paese)	MiSE	X		X	O	mise.gov.it/bollettino_petrolifero.p	E	-	-	-	X	-	-	-	-	-	-	-	X	-	-	-	2003	-	X	-	X	-	
DT21	Bollettino Petrolifero - Tav. 12: Lavorazioni raffinerie	MiSE	X		X	O	mise.gov.it/bollettino_petrolifero.p	E	-	-	-	X	-	-	-	-	-	-	-	X	-	-	-	2003	-	X	-	X	-	
DT22	Data and statistics - Data tools - Data tables - Energy category: Balances	IEA	X		X	E/O/G/C	statistics/data-tables?country=ITAL	W	-	-	-	-	-	-	X	-	-	-	-	X	-	-	-	1990	-	X	X	X	-	per tutti i paesi europei (production, import,
DT23	Energy statistics - Gas prices for household consumers - bi-annual data (from 2007 onwards) (nrg_pc_202)	EUROSTAT	X		X	G	.ec.europa.eu/nui/show.do?datas	E	-	-	-	-	-	X	-	-	-	-	-	X	-	-	-	2007	-	X	X	X	-	CONSOM: D2; CURRENCY: euro; GEO: country EU 27 + UK; TAX:
DT24	Energy statistics - Gas prices for non-household consumers - bi-annual data (from 2007 onwards) (nrg_pc_203)	EUROSTAT	X		X	G	.ec.europa.eu/nui/show.do?datas	E	-	-	-	-	-	X	-	-	-	-	-	X	-	-	-	2007	-	X	X	X	-	CONSOM: I2,I3,I4,I5; CURRENCY: euro; GEO: country EU 27 + UK; TAX:
DT25	Energy statistics - Electricity prices for household consumers - bi-annual data (from 2007 onwards) (nrg_pc_204)	EUROSTAT	X		X	E	.ec.europa.eu/nui/show.do?datas	E	-	-	-	-	-	X	-	-	-	-	-	X	-	-	-	2007	-	X	X	X	-	CONSOM: Db,Dc; CURRENCY: euro; GEO:
DT26	Energy statistics - Electricity prices for non-household consumers - bi-annual data (from 2007 onwards) (nrg_pc_205)	EUROSTAT	X		X	E	.ec.europa.eu/nui/show.do?datas	E	-	-	-	-	-	X	-	-	-	-	-	X	-	-	-	2007	-	X	X	X	-	CONSOM: Ib, Ic, Id; Ie, If; CURRENCY: euro; GEO: country EU 27 + UK; TAX:
DT27	Gas_spot_PSV	GME	X		X	G	atoelettrico.org/It/Statistiche/Gas/	W	-	X	-	-	-	-	-	-	-	-	-	X	-	-	-	2021	-	-	X	-	X	estrarre PSV storico da dataset ENEA [DT0] e
DT28	Trend dal 2005	SNAM	X		X	G	rasporto/dati-operativi-business/2	E	-	X	-	-	-	-	-	-	X	-	-	-	-	-	-	2005	-	X	-	X	-	SCARICARE FOGLIO: Sm3 da PCS 10,57275
DT29	Consumer prices of petroleum products inclusive of duties and taxes (Weekly Oil Bulletin)	EUROPEAN COMMISSION	X		X	O	ergy/observatory/reports/Oil_Bull	E	-	-	X	-	-	-	-	-	-	-	-	X	-	-	-	2009	-	X	X	X	-	[dal 2005-2009 FONTE http://ec.europa.eu/energy/observatory/reports
DT30	Worldwide Governance Indicators (WGI)	World Bank	X		X	-	://info.worldbank.org/governance	E	-	-	-	-	-	-	X	-	-	-	-	X	-	-	-	1996	-	X	X	X	-	valore costante per tutto l'anno
DT31	Importazioni Gas Per Paese di Origine	MISE	X		X	G	gsaie.mise.gov.it/importazioni-gas	E	-	-	-	X	-	-	-	-	-	-	-	-	-	X	-	2002		X	-	X	-	aggiornamento annuale usato per la serie storica
DT31	Produzione nazionale idrocarburi	MASE	X		X	O	se.gov.it/energia/ricerca-e-produz	E	-	-	-	X	-	-	-	-	-	-	-	-	-	-	-	2004	-	X	-		X	
DT32	Web GIS UNMIG	ARCGIS	X		X	O	https://www.arcgis.com/home/w	M	-	-	-	-	-	-	-	X	-	-	-	-	-	-	-	-	-	X	-		X	
DT33	Piattaforme marine	MASE	X		X	O	t/ricerca-e-coltivazione-di-idrocar	E	-	-	-	-	-	-	-	X	-	-	-	-	-	-	-	-	-	X	-		X	
DT34	Centrali di raccolta e trattamento	MASE	X		X	O	a-e-coltivazione-di-idrocarburi/ce	E	-	-	-	-	-	-	-	X	-	-	-	-		-	-	-	-	X	-		X	
DT35	Relazione annuale situazione energetica nazionale dati	MASE	X		X	O	ia-mase-pubblica-la-relazione-sull	P	-	-	-	-	-	-	X	-	-	-	-			-	-	2018	-	X	-		X	
DT36	Petrolio	UNEM	X		X	O	.unem.it/i-numeri-dellenergia/ita	E	-	-	-	X	-	-	-	-						-	-	2019	-	X			X	
DT37	Pubblicazioni	UNEM	X		X	O	tps://www.unem.it/pubblicazioni	P	-	-	-	-	-	-	X	-						-	-	2015	-	X	X		X	
DT38	Margini di raffinazione – stime AIE	Staffetta Quotidiana	X	X	X	O	https://www.staffettaonline.com /	P	-	-	-	X	-	-	-	-						-	-	NA	-	-	X		X	
DT39	Trading conditions update for oil&gas.xls	LOTOS	X		X	O	https://inwestor.lotos.pl/en/193	E	-	-	-	-	X	-	X	-						-	-	NA	-	X	X		X	
DT40	US Crude oil production	EIA	X		X	O	https://www.eia.gov/dnav/pet/p	E/W	-	-	-	X	-	-	X	-						-	-	2005	-	-	X	X		
DT41	Weekly US Crude oil production		X		X	O	https://www.eia.gov/dnav/pet/h	E/W	-	-	X	-	-	-	-	-						-	-	1920	-	-	-	X		
DT42	Spot prices		X		X	O	https://www.eia.gov/dnav/pet/p	E/W	-	X	X	X	-	-	X	-						-	-	1983	-	-	-	X		
DT43	Commodity data Portal	IMF	X		X	O	https://www.imf.org/en/Researc	E	-	-	-	X	-	-	-	-						-	-	1986	-	-	X	X		

Figure 91: Dataset's formalisation table

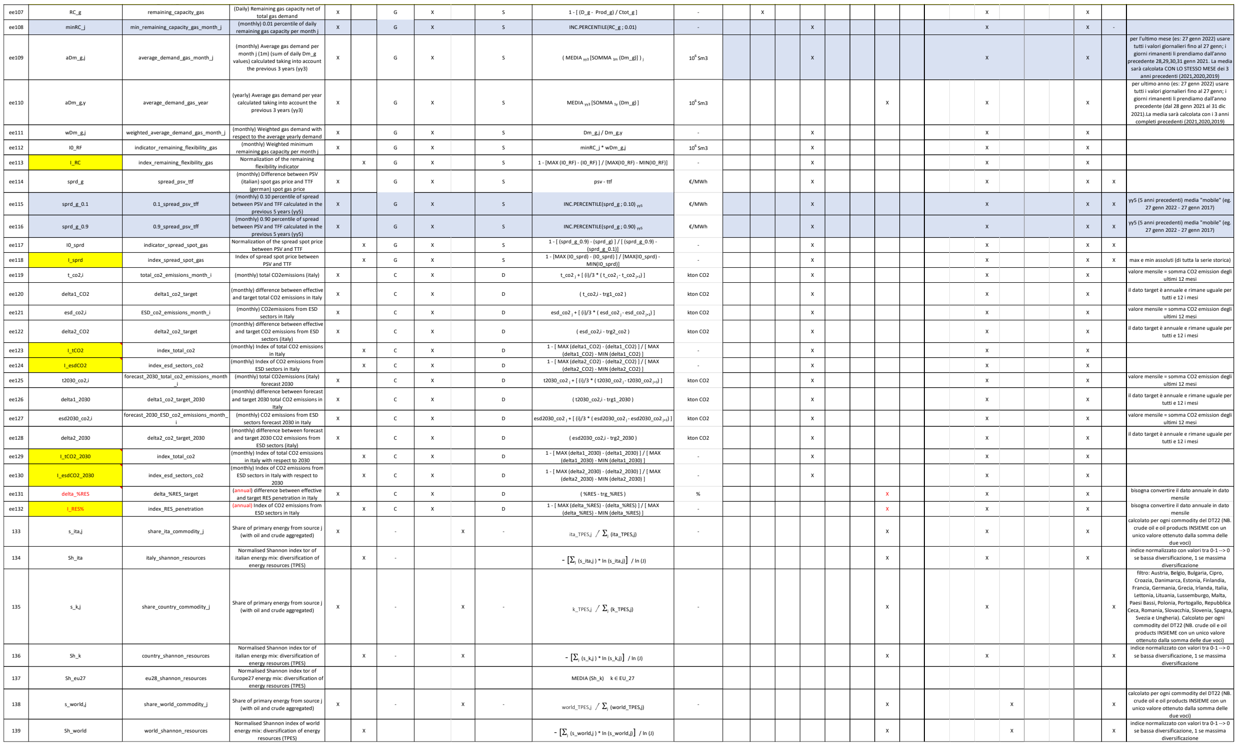
ID	General information										Specific information																	
	Symbol	Name	ID dataset	link	Category		Commodity	ISPRED		u.m.	Format	Time granularity								Spatial granularity						Spatial extent		NOTE
					d	b		YES	NO		E/P/M/W/Z	Gh	Gd	Gw	Gm	Gq	Gs	Gy	S	Ds	Zn	Ct	Rg	P	R	ITA	I	
dd1	E_w	energybalance_wind	DT1	https://www.terna.it/it/sistema-	X		E		X	GWh	E	X								-	-	X	-	-	-	X	-	
dd2	E_ph	energybalance_photov	DT1	https://www.terna.it/it/sistema-	X		E		X	GWh	E	X								-	-	X	-	-	-	X	-	
dd3	E_hy	energybalance_hydro	DT1	https://www.terna.it/it/sistema-	X		E		X	GWh	E	X								-	-	X	-	-	-	X	-	
dd4	E_geoth	energybalance_geoth	DT1	https://www.terna.it/it/sistema-	X		E		X	GWh	E	X								-	-	X	-	-	-	X	-	
dd5	E_self	energybalance_selfcons	DT1	https://www.terna.it/it/sistema-	X		E	X		GWh	E	X								-	-	X	-	-	-	X	-	
dd6	E_th	energybalance_therm	DT1	https://www.terna.it/it/sistema-	X		E		X	GWh	E	X								-	-	X	-	-	-	X	-	
dd7	E_exch	energybalance_foreignexchange	DT1	https://www.terna.it/it/sistema-	X		E	X		GWh	E	X								-	-	X	-	-	-	X	-	
dd8	E_pump	energybalance_pumpconsumption	DT1	https://www.terna.it/it/sistema-	X		E		X	GWh	E	X								-	-	X	-	-	-	X	-	
dd9	C_geo	installedcapacity_geoth	DT2	https://www.terna.it/it/sistema-	X		E		X	GW	E							X		-	-	X	-	-	-	X	-	
dd10	C_hy	installedcapacity_hydro	DT2	https://www.terna.it/it/sistema-	X		E		X	GW	E							X		-	-	X	-	-	-	X	-	
dd11	C_ph	installedcapacity_photov	DT2	https://www.terna.it/it/sistema-	X		E		X	GW	E							X		-	-	X	-	-	-	X	-	
dd12	C_th	installedcapacity_therm	DT2	https://www.terna.it/it/sistema-	X		E	X		GW	E							X		-	-	X	-	-	-	X	-	
dd13	C_w	installedcapacity_wind	DT2	https://www.terna.it/it/sistema-	X		E		X	GW	E							X		-	-	X	-	-	-	X	-	
dd14	D_n	totalload_demand_nord	DT3	https://www.terna.it/it/siste	X		E	X		MW	E	X								-	X	-	-	-	-	X	-	
dd15	D_cn	totalload_demand_cnord	DT3	https://www.terna.it/it/siste	X		E	X		MW	E	X								-	X	-	-	-	-	X	-	
dd16	D_cs	totalload_demand_csud	DT3	https://www.terna.it/it/siste	X		E	X		MW	E	X								-	X	-	-	-	-	X	-	
dd17	D_s	totalload_demand_sud	DT3	https://www.terna.it/it/siste	X		E	X		MW	E	X								-	X	-	-	-	-	X	-	
dd18	D_si	totalload_demand_sici	DT3	https://www.terna.it/it/siste	X		E	X		MW	E	X								-	X	-	-	-	-	X	-	
dd19	D_sa	totalload_demand_sard	DT3	https://www.terna.it/it/siste	X		E	X		MW	E	X								-	X	-	-	-	-	X	-	
dd20	D_cal	totalload_demand_cal	DT3	https://www.terna.it/it/siste	X		E	X		MW	E	X								-	X	-	-	-	-	X	-	
dd21	R_n	reserve_n	-	-	X		E	X		MW	E							X		-	X	-	-	-	-	X	-	
dd22	R_cn	reserve_cn	-	-	X		E	X		MW	E							X		-	X	-	-	-	-	X	-	
dd23	R_s	reserve_s	-	-	X		E	X		MW	E							X		-	X	-	-	-	-	X	-	
dd24	R_cs	reserve_cs	-	-	X		E	X		MW	E							X		-	X	-	-	-	-	X	-	
dd25	R_sa	reserve_sa	-	-	X		E	X		MW	E							X		-	X	-	-	-	-	X	-	
dd26	R_si	reserve_si	-	-	X		E	X		MW	E							X		-	X	-	-	-	-	X	-	
dd27	R_cal	reserve_cal	-	-	X		E	X		MW	E							X		-	X	-	-	-	-	X	-	
dd28	P_g	gas_price	DT6	https://my.elexys.be/Market	X		G	X		€/MWh	E				X					-	-	-	X	-	-	-	X	
dd29	EUA_d	carbon_price	DT5	https://ember-climate.org/da	X		C	X		€/ton	E		X							-	-	-	X	-	-	-	X	
dd30	PUN_h	national_elecricity_price	DT4	https://www.mercatoelettri	X		E	X		€/MWh	E	X								-	-	X	-	-	-	X	-	
dd31	Ro1	refinery_output_motor_aviation_gasoline	DT10	http://www.jodidb.org/Repo	X		O	X		kton	E				X					-	-	X	-	-	-	X	X	
dd32	Ro2	refinery_output_gas_diesel_oil	DT10	http://www.jodidb.org/Repo	X		O	X		kton	E				X					-	-	X	-	-	-	X	X	
dd33	Dm1	demand_motor_aviation_gasoline	DT10	http://www.jodidb.org/Repo	X		O	X		kton	E				X					-	-	X	-	-	-	X	X	
dd34	Dm2	demand_gas_diesel_oil	DT10	http://www.jodidb.org/Repo	X		O	X		kton	E				X					-	-	X	-	-	-	X	X	
dd35	u_iea,k	refinery_utilization_iea_country_k	DT7	eports/oil-mark	X	X	O	X		%	P				X					-	-	X	-	-	-	X	X	
dd36	u_o,k	refinery_utilization_opec_ country_k	DT11	/opec_web/en/	X	X	O	X		%	P				X					-	-	X	-	-	-	X	X	prendere solo US, UK, italy, germany,
dd37	EMC	emc_saras	DT14	https://iea.blob.core.windo	X	X	O	X		$/bl	W			X	X					-	-	-	X	-	-	-	X	dato settimanale in grafico e dato
dd38	Dub_cr	dubai_cracking	DT8,DT13	-	X	X	O	X		$/bl	E				X					-	-	-	X	-	-	-	X	dati storici su DT13, dati aggiornati su DT8
dd39	HL_cr	HLS_LLS_cracking	DT8,DT13	-	X	X	O	X		$/bl	E				X					-	-	-	X	-	-	-	X	dati storici su DT13, dati
dd40	EU_m	Variable_Cost_Margin_Eu_refining	DT15	https://www.total.com/investors/results-	X	X	O		X	$/ton	W					X				-	-	-	X	-	-	-	X	dato da convertire in $/bl moltiplicando per 0.136
dd41	sprd_go	crack_spread_unleaded_gasoline	DT16,DT17	https://investor.lotos.pl/en/1930/investo	X	X	O		X	$/bl	E				X					-	-	-	X	-	-	X	-	
dd42	sprd_d	crack_spread_diesel	DT16,DT17	https://investor.lotos.pl/en	X	X	O		X	$/bl	E				X					-	-	-	X	-	-	X	-	
dd43	k	supply_country	DT18, DT19, DT31		X			X		-	E											X					X	paesi fornitori di greggio (DT18),
dd44	c_k	crude_import_per_supplier_k	DT18	https://dgsaie.mise.gov.it/bollettino_petrolifero.php?anno=2020	X		O	X		ton	E				X					-	-	X	-	-	-	X	-	ESTRARRE il nome del paese NON dell'area geografica
dd45	API	API_degree	DT18	https://dgsaie.mise.gov.it/bollettino_petrolifero.php?anno=2020	X		O		X	°	E				X					-	-	X	-	-	-	-	-	API degree associato ad ogni quantità importata di greggio C_k
dd46	z%	sulphur_content	DT18	https://dgsaie.mise.gov.it/b	X		O		X	%	E				X					-	-	X	-	-	-	-	-	% zolfo associato ad ogni quantità
dd47	$	unit_price_crude	DT18	https://dgsaie.mise.gov.it/bollettino_petrolifero.php?anno=2020	X		O		X	$/bl	E				X					-	-	X	-	-	-	-	-	prezzo unitario associato ad ogni quantità importata di greggio C_k
dd48	o_k	oilproduct_import_per_supplier_k	DT19	https://dgsaie.mise.gov.it/b	X		O	X		ton	E				X					-	-	X	-	-	-	X	-	nuovo dato per il calcolo dell'indice di shannon dei
dd49	y	entry_point	DT28	https://www.snam.it/it/tras	X		G	X		-	E													X		X		entry point italiani per l'approvvigioname
dd50	g_k	gas_import_per_supplycountry_k	DT31	https://dgsaie.mise.gov.it/i	X		G	X		10^6 Sm3, 10^9 Sm^3	E				X					-	-	X	-	-	-	X	-	NOTA aggiornamento: dato mensile
dd51	g_y	gas_import_per_entrypoint_y	DT28	https://www.s	X		G	X		10^6 Sm3	E		X							-	-	-	-	X	-	X	-	dato real time da aggiornare quotidianamente
dd52	B_i	balance_total_imports	DT0, DT22	data-tables?cou	X		-	X		DA DEFINIRE.	E									-	-	X	-	-	-	X		dato ricavato dal bilancio
dd53	B_e	balance_total_export	DT0, DT22	data-tables?cou	X		-	X		DA DEFINIRE.	E									-	-	X	-	-	-	X		dato ricavato dal bilancio
dd54	B_mb	balance_total_marine_bunkers	DT0, DT22	data-tables?cou	X		-	X		DA DEFINIRE, TJ	E									-	-	X	-	-	-	X		dato ricavato dal bilancio energetico
dd55	B_ab	balance_total_aviation_bunkers	DT0, DT22	data-tables?cou	X		-	X		DA DEFINIRE, TJ	E									-	-	X	-	-	-	X		dato ricavato dal bilancio energetico
dd56	B_s	balance_total_stockchanges	DT0, DT22	data-tables?cou	X		-	X		DA DEFINIRE, TJ	E									-	-	X	-	-	-	X		dato ricavato dal bilancio energetico
dd57	B_i,c	balance_crude_imports	DT9	reportFolders.a	X		O	X		kton	E				X					-	-	X	-	-	-	X	X	crude=primary
dd58	B_i,p	balance_oilproduct_imports	DT10	reportFolders.a	X		O	X		kton	E				X					-	-	X	-	-	-	X	X	oilproduct=secondary
dd59	B_e,c	balance_crude_export	DT9	reportFolders.a	X		O	X		kton	E				X					-	-	X	-	-	-	X	X	
dd60	B_e,p	balance_oilproduct_export	DT10	reportFolders.a	X		O	X		kton	E				X					-	-	X	-	-	-	X	X	
dd61	B_p,c	balance_crude_production	DT9	reportFolders.a	X		O	X		kton	E				X					-	-	X	-	-	-	X	X	
dd62	B_p,p	balance_oilproduct_production	DT10	reportFolders.a	X		O	X		kton	E				X					-	-	X	-	-	-	X	X	
dd63	B_s,c	balance_crude_stockchanges	DT9	reportFolders.a	X		O	X		kton	E				X					-	-	X	-	-	-	X	X	
dd64	B_s,p	balance_oilproduct_stockchanges	DT10	reportFolders.a	X		O	X		kton	E				X					-	-	X	-	-	-	X	X	
dd65	B_TPES,c	balance_crude_TPES	DT0, DT22	https://www.iea.org/data-	X		O	X		DA DEFINIRE	E									-	-	X	-	-	-	X		dato ricavato dal bilancio
dd66	B_TPES,p	balance_oilproduct_TPES	DT0, DT22	https://www.iea.org/data-	X		O	X		DA DEFINIRE	E									-	-	X	-	-	-	X		dato ricavato dal bilancio
dd67	B_i,g	balance_naturalgas_imports	DT12	reportFolders.a	X		G	X		kton	E				X					-	-	X	-	-	-	X	X	
dd68	B_e,g	balance_naturalgas_exports	DT12	reportFolders.a	X		G	X		kton	E				X					-	-	X	-	-	-	X	X	
dd69	B_p,g	balance_naturalgas_production	DT12	reportFolders.a	X		G	X		kton	E				X					-	-	X	-	-	-	X	X	



dd70	B_s,g	balance_naturalgas_stockchanges	DT12	reportFolders.a	X		G	X		kton	E				X					-	-	X	-	-	-	X	X	
dd71	B_TPES,g	balance_naturalgas_TPES	DT0, DT22	https://www.iea.org/data-	X		O	X		DA DEFINIRE	E									-	-	X	-	-	-	X		dato ricavato dal bilancio
dd72	j	energy_commodity	DT22	https://www.iea.org/data-	X		-		X	-	W																	9 commodity --> numero colonne
dd73	ita_TPES,j	TPES_ita_commodity_j	DT22	https://www.iea.org/data-	X		-		X	TJ	W							X				X				X		filtro: Italy -->total energy supply per
dd74	k_TPES,j	TPES_country_commodity_j	DT22	https://www.iea.org/data-	X		-		X	TJ	W							X				X					X	filtro: Austria, Belgio, Bulgaria,
dd75	world_TPES,j	TPES_world_commodity_j	DT22	https://www.iea.org/data-	X		-		X	TJ	W							X					X				X	filtro: world -->total energy
dd76	Ctot_g	total_capacity_gas	DT0		X		G	X		10^6 Sm3	E								X			X				X		2010-2013 (365,8 milioni Sm3); 2014-
dd77	D_g	total_demand_gas	DT28	https://www.snam.it/it/tras	X		G	X		10^6 Sm3	E		X									X				X		estrarre "Tot. Immesso"
dd78	Prod_g	national_production_gas	DT28	https://www.snam.it/it/tras	X		G	X		10^6 Sm3	E		X									X				X		estrarre "Produz. Nazion."
dd79	ttf	ttf_spot_price	DT6	https://my.elexys.be/Market	X		G	X		€/MWh	E				X							X					X	
dd80	psv	psv_spot_price	DT27	o.org/It/Statist	X		G	X		€/MWh	E		X									X				X		
dd81	P_D2	price_gas_household_D2	DT23	https://appsso.eurostat.ec.	X		G	X		€/GJ	E						X			-	-	X	-	-	-	X	X	includere la voce
dd82	P_I2	price_gas_nonhousehold_I2	DT24	https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_pc_203&lang=en	X		G	X		€/GJ	E						X			-	-	X	-	-	-	X	X	includere la voce tasse (TAX: x_tax)
dd83	P_I3	price_gas_nonhousehold_I3	DT24	https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_pc_203&lang=en	X		G	XX		€/GJ	E						X			-	-	X	-	-	-	X	X	includere la voce tasse (TAX: x_tax)
dd84	P_I4	price_gas_nonhousehold_I4	DT24	https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_pc_203&lang=en	X		G	X		€/GJ	E						X			-	-	X	-	-	-	X	X	includere la voce tasse (TAX: x_tax)
dd85	P_I5	price_gas_nonhousehold_I5	DT24	https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_pc_203&lang=en	X		G	X		€/GJ	E						X			-	-	X	-	-	-	X	X	includere la voce tasse (TAX: x_tax)
dd86	P_Db	price_ele_household_Db	DT25	https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_pc_204&lang=en	X		E	X		€/KWh	E						X			-	-	X	-	-	-	X	X	includere la voce tasse (TAX: x_tax, x_vat, i_tax)
dd87	P_Dc	price_ele_household_Dc	DT25	https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_pc_204&lang=en	X		E	X		€/KWh	E						X			-	-	X	-	-	-	X	X	includere la voce tasse (TAX: x_tax, x_vat, i_tax)
dd88	P_Ib	price_ele_nonhousehold_Ib	DT26	https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_pc_204&lang=en	X		E	X		€/KWh	E						X			-	-	X	-	-	-	X	X	includere la voce tasse (TAX: x_tax)
dd89	P_Ic	price_ele_nonhousehold_Ib	DT26	https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_pc_204&lang=en	X		E	X		€/KWh	E						X			-	-	X	-	-	-	X	X	includere la voce tasse (TAX: x_tax)
dd90	P_Id	price_ele_nonhousehold_Ib	DT26	https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_pc_204&lang=en	X		E	X		€/KWh	E						X			-	-	X	-	-	-	X	X	includere la voce tasse (TAX: x_tax)
dd91	P_Ic	price_ele_nonhousehold_Ic	DT26	https://appsso.eurostat.ec.europa.eu/nui	X		E	X		€/KWh	E						X			-	-	X	-	-	-	X	X	includere la voce tasse (TAX: x_tax)
dd92	P_Id	price_ele_nonhousehold_Id	DT26	https://appsso.eurostat.ec.europa.eu/nui	X		E	X		€/KWh	E						X			-	-	X	-	-	-	X	X	includere la voce tasse (TAX: x_tax)
dd93	P_Ie	price_ele_nonhousehold_Ie	DT26	https://appsso.eurostat.ec.europa.eu/nui	X		E	X		€/KWh	E						X			-	-	X	-	-	-	X	X	includere la voce tasse (TAX: x_tax)
dd94	P_If	price_ele_nonhousehold_If	DT26	https://appsso.eurostat.ec.europa.eu/nui	X		E	X		€/KWh	E						X			-	-	X	-	-	-	X	X	includere la voce tasse (TAX: x_tax)
dd95	WGI	geopolitical_risk	DT30	https://info.worldbank.org/governance/w		X	-	X		-	E							X		-	-	X	-	-	-	X	X	valore costante per tutto l'anno
dd96	trg1_co2	target1_co2_italy	DT0			X	C	X		kton CO2	E							X				X				X		valore costante per tutto l'anno
dd97	trg2_co2	target2_co2_italy	DT0			X	C	X		kton CO2	E							X				X				X		valore costante per tutto l'anno
dd98	t_co2,j	total_co2_emission_quarter_j	DT0		X		C	X		kton CO2	E					X						X				X		il valore trimestrale è ottenuto dalla
dd99	esd_co2,j	ESD_sectors_co2_emission_quarter_j	DT0		X		C	X		kton CO2	E					X						X				X		il valore trimestrale è ottenuto dalla
dd96	trg1_2030	target1_co2_italy_2030	DT0			X	C	X		kton CO2	E							X				X				X		valore costante per tutto l'anno
dd97	trg2_2030	target2_co2_italy_2030	DT0			X	C	X		kton CO2	E							X				X				X		valore costante per tutto l'anno
dd98	t2030_co2,j	total_co2_emission_quarter_j	DT0		X		C	X		kton CO2	E					X						X				X		il valore trimestrale è ottenuto dalla
dd99	esd2030_co2,j	ESD_sectors_co2_emission_quarter_j	DT0		X		C	X		kton CO2	E					X						X				X		il valore trimestrale è ottenuto dalla
dd100	%RES	RES_penetration_%	DT0			X	C	X		%	E							X				X				X		il valore ANNUALE è costante
dd101	trg_%RES	target_RES_penetration_%	DT0			X	C	X		%	E							X				X				X		il valore ANNUALE è costante

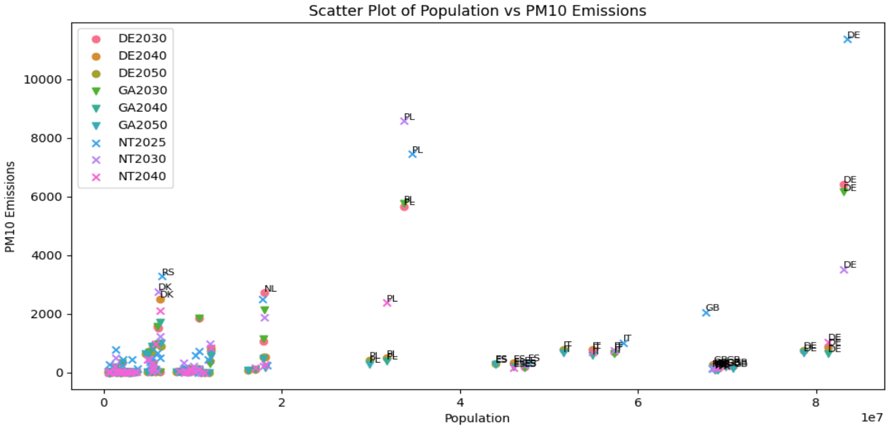
Figure 92: Raw data's formalisation table

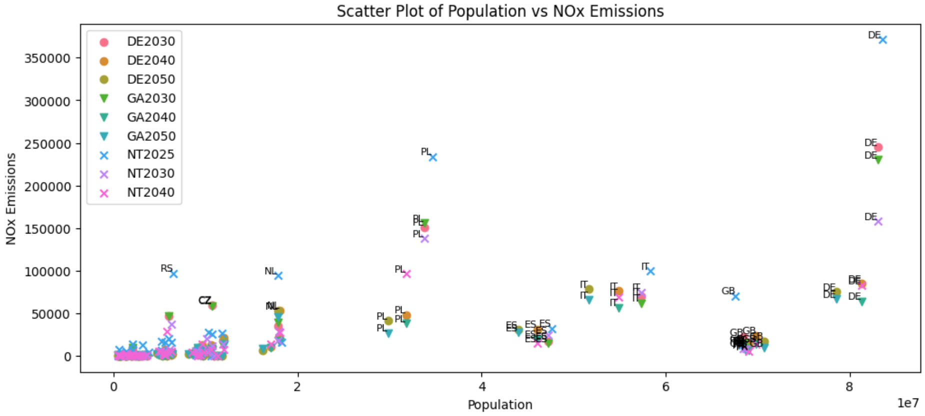
ID	Symbol	Name	Description	Category		Commodity	ISPRED		Trilemma Dimension	Formula	u.m.	Time granularity								Spatial granularity						Spatial extent		NOTE
				i	I	E/O/G/C	YES	NO	S/P/D			Gh	Gd	Gw	Gm	Gq	Gs	Gy	S	Ds	Zn	Ct	Rg	P	R	ITA	I	
ee1	D	totalload	Italian total load (included selfconsumption)	X		E	X		S	D_n + D_cn + D_s + D_cs + D_sa + D_si + D_cal	MW	X										X				X	-	
ee2	nD	net_totalload	Italian total load (excluded selfconsumption)	X		E	X		S	D - (E_self * 1000)	MW	X										X				X	-	
ee3	R_min	min_reserve	Italian minimum operative reserve	X		E	X		S	R_n + R_cn + R_s + R_cs + R_sa + R_si + R_cal	MW							X				X				X	-	costante per tutto l'anno --> non critico conversione in granularità mensile
ee4	UnC_th	unavailable_thermal	Annual thermal unavailability	X		E	X		S	0.15 * C_th*1000	MW							X				X				X	-	costante per tutto l'anno --> non critico conversione in granularità mensile
ee5	Cm_h	capacity_margin	Effective capacity margin (excluded RES generation)	X		E	X		S	[C_th - UnC_th + (E_exch *1000)] - (nD + R_min)	MW	X										X				X	-	C_th, UnC_th, R_min valori COSTANTI nella conversione alla **granularità unica uniforme**
ee6	Cm%_h	%capacity_margin	Share of effective capacity margin (excluded RES generation)	X		E	X		S	Cm_h / (nD + R_min)	%	X										X				X	-	R_min valori COSTANTI nella conversione alla granularità unica uniforme
ee9	Cm%_m_0.01	0.01_%capacity_margin	(monthly) 0.01 percentile of the Cm%_h	X		E	X		S	INC.PERCENTILE(Cm%_h ; 0.01)	%					X						X				X	-	si calcola l'inc. percentile allo 0.01 per ottenere, a partire dai C_m% ORARI, un unico valore di C_m% MENSILE (from hourly --> MONTHLY data)
ee13	I_CM	capacity_margin_index	Index of the effective capacity margin		X	E	X		S	1 - [(C_m%_0.25_max) - (C_m%_0.25)] / [(C_m%_0.25:max) - (C_m%_0.25_min)]	-				X							X				X	-	
ee14	FRNPh_i	FRNP_production	Wind and photovoltaic power production during the hour i	X		E	X		S	1000 * (E_w + E_ph)$_{i}$	MWh	X										X				X	-	
ee15	FRNPh_i-1	FRNP_production	Wind and photovoltaic power production during the hour i-1	X		E	X		S	1000 * (E_w + E_ph)$_{i-1}$	MWh	X										X				X	-	
ee16	var_FRNP%_h	var_FRNP_%	Hourly variation of wind and photovoltaic over the demand of hour i-1	X		E	X		S	(FRNP$_{i}$ - FRNP$_{i-1}$) / nD$_{i-1}$	%	X										X				X	-	
ee17	FRNP%_0.975_m	0.975_var_FRNP_%	(monthly) 0.975 percentile of hourly variation of wind and photovoltaic over the demand of hour i-1	X		E	X		S	INC.PERCENTILE(FRNP% ; 0.975)	%				X							X				X	-	
ee18	FRNP%_0.025_m	0.025_var_FRNP_%	(monthly) 0.025 percentile of hourly variation of wind and photovoltaic over the demand of hour i-1	X		E	X		S	INC.PERCENTILE(FRNP% ; 0.025)	%				X							X				X	-	
ee19	i0_FRNP_m%	var_FRNP_%_indicator	(monthly) Indicator of the of hourly variation of wind and photovoltaic over demand	X		E	X		S	MAX (FRNP%_0.975; ASS (FRNP%_0.025))	%				X							X				X	-	Valore mensile
ee21	I_FRNP%	var_FRNP_%_index	Index of the of hourly variation of wind and photovoltaic over demand		X	E	X		S	1 - [MAX(i0_FRNP_m%) - (i0_FRNP_m%)] / [MAX(i0_FRNP_m%) - MIN(i0_FRNP_m%)]	-				X							X				X	-	
ee22	PUN_m	PUN_monthly_average	(monthly) Average electricity price	X		E	X		S	MEDIA$_{m}$ (PUN_h)	€/MWh				X							X				X	-	
ee23	SS_m	spark_spread	(monthly) Difference between the price received by a generator for electricity produced and the cost of the natural gas needed to produce that electricity	X		G	X		S	PUN_m - (P_g / 0.54)	€/MWh				X							X				X	-	
ee24	EUA_m	EUA_monthly_average	(monthly)Average Carbon Prices	X		C	X		S	MEDIA$_{m}$ (EUA_d)	€/ton				X								X			X	-	
ee25	CSS_m	clean_spark_spread	(monthly) Net revenue a generator makes from selling power, having bought gas and the required number of carbon allowances	X		E	X		S	SS_m – (EUA_m * 0.411)	€/MWh				X							X				X	-	
ee26	CSS_mm6	6month_clean_spark_spread	Average Clean Spark Spread in the last 6 months	X		E	X		S	MEDIA $_{mm6}$ (CSS_m)	€/MWh						X					X				X	-	
ee27	I_CSS	CSS_index	(monthly) Normalised average Clean Spark Spread in the last 6 months		X	E	X		S	1 - [MAX(CSS_mm6) - (CSS_mm6)] / [MAX(CSS_mm6) - MIN(CSS_mm6)]	-				X							X				X	-	
ee31	Ro1/Dm1	prod_over_demand_gasoline	Local producion over demand of gasoline	X		O	X		S	(Ro1/Dm1)	-				X							X				X	X	per tutti i paesi disponibili
ee32	Ro2/Dm2	prod_over_demand_diesel	Local producion over demand of diesel oil	X		O	X		S	(Ro2/Dm2)	-				X							X				X	X	per tutti i paesi disponibili
ee33	Ro1/Dm1_ita	ita_prod_over_demand_gasoline_mm4	Season average of the of local producion over demand of gasoline (only Italy)	X		O	X		S	MEDIAmm4 (Ro1/Dm1)	-					X						X				X		solo italia
ee34	Ro2/Dm2_ita	ita_prod_over_demand_diesel_mm4	Season average of the of local producion over demand of diesel oil (only Italy)	X		O	X		S	MEDIAmm4 (Ro2/Dm2)	-					X						X				X		
ee35	I0_Ro1/Dm1	prod_over_demand_gasoline_normalised	Normalised local production over demand of gasoline		X	O	X		S	1 - [MAX(Ro1/Dm1) - (Ro1/Dm1)] / [MAX(Ro1/Dm1) - MIN(Ro1/Dm1)]	-				X							X					X	
ee36	I0_Ro2/Dm2	prod_over_demand_diesel_normalised	Normalised local production over demand of diesel oil		X	O	X		S	1 - [MAX(Ro2/Dm2) - (Ro2/Dm2)] / [MAX(Ro2/Dm2) - MIN(Ro2/Dm2)]	-				X							X					X	
ee37	I_Ro1/Dm1	prod_over_demand_gasoline_index	Index of local production over demand of gasoline		X	O	X		S	1 - [MAX(I0_Ro1/Dm1) - (I0_Ro1/Dm1)] / [MAX(I0_Ro1/Dm1) - MIN(I0_Ro1/Dm1)]	-				X							X					X	
ee38	I_Ro2/Dm2	prod_over_demand_diesel_index	Index of local production over demand of diesel oil		X	O	X		S	1 - [MAX(I0_Ro2/Dm2) - (I0_Ro2/Dm2)] / [MAX(I0_Ro2/Dm2) - MIN(I0_Ro2/Dm2)]	-				X							X					X	
ee39	u_ j,k	refinery_utilization_country_k	(monthly) Refinieries utilization rate per month estimated through OPEC data	X		O	X		S	u$_{(j-1),k}$ * (u$_{o,j}$ / u$_{o,(j-1)}$)$_{k}$ or u_iea,k	%				X							X				X	X	(per tutti i paesi disponibili) u_j=u_iea (DT11); versione aggiornata (provvisoria) è calcolata con i dati OPEC u_o (DT11); il dato definitivo (u_iea) viene preso direttamente da IEA (DT7)
ee42	deltaU_EU_k	delta_utilization_EU_country_k	Difference between country (k) rifinery utilization and average EU refinery utilization	X		O	X		S	(u_j,k)- (u_j)$_{EU}$	%				X							X				X	X	fino a che c'è disponibile prendo dal DT 7 e calcolo EU = AVERAGE (spain, italy, france, uk, netherlands, germany); per i mesi successivi prendo dal DT11 il dato EU14 (senza fare calcoli)
ee43	I0_U_EU	delta_utilization_EU_normalized	Normalization of the difference between country rifinery utilization and average EU refinery utilization		X	O	X		S	1 - [MAX(deltaU_EU_k) - (deltaU_EU_k)] / [MAX(deltaU_EU_k) - MIN(deltaU_EU_k)]	-				X							X				X	X	ISPRED needs only Udelta$_{EU-ITA}$
ee44	I0_U_ITA	utilization_ITA_normalised	Normalised italian refinery utilization		X	O	X		S	1 - [MAX(u_j,ita) - (u_j,ita)] / [MAX(u_j,ita) - MIN(u_j,ita)]	-				X							X				X		only ITALY
ee45	I0_U	utilization_EU_ITA_combination	Combination of refinery utilization indices (EU and ITA)		X	O	X		S	[I0_U_EU * 0,3] + [I0_U_ITA * 0,7]	-				X							X				X	X	ISPRED needs only Udelta$_{EU-ITA}$
ee46	I_U	refinery_utilization_index	Refinery utilization index		X	O	X		S	1 - [MAX(I0_U) - (I0_U)] / [MAX(I0_U) - MIN(I0_U)]	-				X							X				X		ISPRED needs only Udelta$_{EU-ITA}$
ee47	Sprd_D	Spread_EMC_Dubai_cracking	Difference between EMC margin and Dubai cracking margin	X		O	X		S	EMC - Dub_crack	$/bl				X								X				X	
ee48	Sprd_HL	Spread_EMC_HLS_LSS_cracking	Difference between EMC margin and HLS/LSS cracking margin	X		O	X		S	EMC - HLS_LSS_crack	$/bl				X								X				X	
ee49	EMC_mm2	EMC_average_2month	Average EMC in the last 2 months	X		O	X		S	MEDIA mm2 (EMC)	$/bl					X							X				X	
ee50	Sprd_D_mm2	Spread_Dubai_cracking_average_2month	Average spread EMC - (Dubai margin) in the last 2 months	X		O	X		S	MEDIA mm2 (Sprd_D)	$/bl					X							X				X	
ee51	Sprd_HL_mm2	Spread_HLS_LLS_cracking_average_2month	Average spread EMC - (HLS/LSS margin) in the last 2 months	X		O	X		S	MEDIA mm2 (Sprd_HL)	$/bl					X							X				X	
ee52	sprd_DHL	average_spread_Dub_HLS_LSS	Monthly Average of spread Dubai and spread HLS/LSS (with respect to EMC)	X		O	X		S	MEDIA (Sprd_D ; Sprd_HL_)	$/bl					X							X				X	
ee53	I0_EMC	EMC_margin_normalised	Normalised EMC margin		X	O	X		S	1 - [MAX(EMC) - (EMC)] / [MAX(EMC) - MIN(EMC)]	-					X							X				X	
ee54	I0_DHL	average_spread_HL_Dub_normalised	Normalised average spread Dubai and HLS/LSS margins		X	O	X		S	1 - [MAX(DHL) - (DHL)] / [MAX(DHL) - MIN(DHL)]	-					X							X				X	
ee55	I0_marg	weighted_average_margin	Weighted average of refinery margin (EMC,Dubai, HLS/LSS)		X	O	X		S	I0_EMC * 0,75 + I0_DHL * 0,25	-					X							X				X	
ee56	I_marg	refinery_margin_index	Index of refinery margin		X	O	X		S	1 - MAX [I0_marg) - (I0_marg)] / [MAX(I0_marg) - MIN(I0_marg)]	-					X							X				X	
ee59	sC_k	share_crude_supplier_k	Share of crude oil imported by the country k (supplier)	X		O	X		S	c_k / Σ_{k} (c_k)	-					X						X				X		
ee60	sO_k	share_oilproduct_supplier_k	Share of oil product imported by the country k (supplier)	X		O		X	S	o_k / Σ_{k} (o_k)	-					X						X				X		
ee67	Sh_c	crude_shannon_indicator	Normalised Shannon index (only crude)	X		O		X	S	- [Σ_{k} (sC_k) * ln (sC_k)] / ln (K)	-				X							-				X		
ee68	Sh_o	oilproduct_shannon_indicator	Normalised Shannon index (only oil product)	X		O		X	S	- [Σ_{k} [(sO_k) * ln (sO_k)] / ln (K)	-				X							-				X		
ee71	B_TPES	total_TPES_indicator	Total Primary Energy Supply (all energy commodities)	X		-		X	S	B_p + B_i + B_e + B_s + B_mb + B_ab	DA DEFINIRE, TJ											X				X	X	for all EU countries
ee72	B_GIC	total_GIC_indicator	Total Primary Energy Supply (all energy commodities)	X		-		X	S	B_p + B_i + B_e + B_s + B_mb	DA DEFINIRE, TJ											X				X	X	for all EU countries
ee73	B_GAE	total_GAE_indicator	Gross Available Energy (all energy commodities)	X		-	X		S	B_p + B_i + B_e + B_s	DA DEFINIRE, TJ											X				X	X	for all EU countries
ee74	B_GAE,c	crude_GAE_indicator	Gross Available Energy (only crude)	X		O	X		S	B_p,c + B_i,c + B_e,c + B_s,c	kton				X							X				X	X	for all EU countries
ee75	B_GAE,p	oilproduct_GAE_indicator	Gross Available Energy (only oil products)	X		O	X		S	B_p,p + B_i,p + B_e,p+ B_s,p	kton				X							X				X	X	for all EU countries
ee76	B_n,c	net_import_crude	Net crude oil import	X		O	X		S	B_i,c - B_e,c	kton				X							X				X	X	
ee77	B_n,p	net_import_oilproduct	Net oil products import	X		O	X		S	B_i,p - B_e,p	kton				X							X				X	X	
ee78	i_Do,k	oil_dependency_indicator_country	Indicator of the dependency of national mix on oil sources (crude and	X		O	X		S	(B_n,c + B_n,p) / (B_GAE,c + B_GAE,p) * (B_GAE,c + B_GAE,p) / (B_GAE)	-				X							X					X	all EU countries
ee79	i_Do,ita	oil_dependency_indicator_italy	Indicator of the dependency of italian mix on oil sources (crude and oil	X		O	X		S	[(B_n,c + B_n,p) / (B_GAE,c + B_GAE,p) * (B_GAE,c + B_GAE,p) / (B_GAE)]$_{ITALY}$	-				X							X				X		only ITALY
ee80	I0_Do_1	oil_dependency_normalised_1	Normalisation 1 of the indicator of oil dependency (crude and oil products, **excluded biofuels**)		X	O	X		S	1 - [MAX (i_Do,k) - (i_Do,ita)] / [MAX(i_Do,k) - MIN(i_Do,k)]	-				X							X				X	X	
ee81	I0_Do_2	oil_dependency_normalised_2	Normalisation 2 of the indicator of oil dependency (crude and oil products, **excluded biofuels**)		X	O	X		S	1 - [MAX (i_Do,ita) - (i_Do,ita)] / [MAX(i_Do,ita) - MIN(i_Do,ita)]	-				X							X				X	X	
ee82	I0_Do	oil_dependency_normalised_combination	Combination of normalisation 1 and 2 of the indicator of oil dependency		X	O	X		S	(I0_Do_1 * 0,5) + (I0_Do_2 * 0,5)	-				X							X				X	X	
ee83	I_Do	oil_dependency_index	Index of oil dependency (crude and oil products, excluded biofuels)		X	O	X		S	1 - [MAX (I0_Do) - (I0_Do)] / [MAX(I0_Do) - MIN(I0_Do)]	-				X							X				X	X	
ee84	B_GAE,g	gas_GAE_indicator	Gross Available Energy (only natural gas)	X		G	X		S	B_p,g + B_i,g + B_e,g + B_s,g	kton				X							X				X	X	for all EU countries
ee85	B_n,g	net_import_naturalgas	Net natural gas import	X		G	X		S	B_i,g - B_e,g	kton				X							X				X	X	
ee86	i_Dg,k	gas_dependency_indicator_country	Indicator of the dependency of national mix on natural gas for country	X		G	X		S	(B_n,g) / (B_GAE,g) * (B_GAE,g) / (B_GAE)	-				X							X					X	all EU countries
ee87	i_Dg,ita	gas_dependency_indicator_italy	Indicator of the dependency of italian mix on natural gas (only italy historical	X		G	X		S	[(B_n,g) / (B_GAE,g) * (B_GAE,g) / (B_GAE)]$_{ITALY}$	-				X							X				X		only ITALY
ee88	I0_Dg_1	gas_dependency_normalised_1	Normalisation 1 of the indicator of natural gas dependency		X	G	X		S	1 - [MAX (i_Dg,k) - (i_Dg,ita)] / [MAX(i_Dg,k) - MIN(i_Dg,k)]	-				X							X				X	X	
ee89	I0_Dg_2	gas_dependency_normalised_2	Normalisation 2 of the indicator of natural gas dependency		X	G	X		S	1 - [MAX (i_Dg,ita) - (i_Dg,ita)] / [MAX(i_Dg,ita) - MIN(i_Dg,ita)]	-				X							X				X	X	
ee90	I0_Dg	gas_dependency_normalised_combination	Combination of normalisation 1 and 2 of the indicator of natural gas		X	G	X		S	(I0_Dg_1 * 0,5) + (I0_Dg_2 * 0,5)	-				X							X				X	X	
ee91	I_Dg	gas_dependency_index	Index of natural gas dependency		X	G	X		S	1 - [MAX (I0_Dg) - (I0_Dg)] / [MAX(I0_Dg) - MIN(I0_Dg)]	-				X							X				X	X	
ee92	G_y	monthly_gas_import_perentrypoint	Monthly natural gas import per entry point y	X		G	X		S	SOMMA 1$_{month}$ (g_y)	10^{6} Sm3				X									X		X		disponibile real time (quotidianamente)
ee93	sG_k	share_gas_supplier_k	Share of natural gas imported by the country k (suppliers)	X		G	X		S	g_k / Σ_{k} (g_k)	-				X							X				X	X	disponibile con ritardo di un anno
ee94	sG_y	share_gas_supplypoint_y	Share of natural as imported by entry point y (supply points)	X		G	X		S	G_y / Σ_{k} (G_y)	-				X									X		X		disponibile real time (quotidianamente)
ee95	rG_k	gas_supplier_risk	Energy risk related to all Italian suppliers of natural gas	X		G	DA VERIFICARE		S	sG_k * WGI	-					X						X				X	X	disponibile con ritardo di un anno
ee96	rG_y	gas_supplypoint_risk	Energy risk related to the major Italian suppliers of natural gas (LNG considered as an entry point)	X		G	DA VERIFICARE		S	sG_y * WGI	-					X								X		X		disponibile real time (quotidianamente)
ee97	i0_rG	gas_supply_risk	Energy risk of gas supply	X		G	X		S	SOMMA (rG_y)	-					X						X				X		si usa rG_k (MISE) per il dato storico e rG_y (SNAM) per il dato real time (provvisorio)
ee98	i_rG_mm4	mm4_gas_supply_risk	Season Average of Energy risk of gas supply	X		G	X		S	MEDIA$_{mm4}$ (i_rG)	-					X						X				X		
ee99	I_rG	gas_supply_risk_index	Index of risk related to gas supply		X	G	X		S	1 - [MAX (i_rG_mm4) - (i_rG_mm4)] / [MAX(i_rG_mm4) - MIN(i_rG_mm4)]	-					X						X				X		
ee100	hhi_g	gas_HHI	Herfindahl Hirschman indicator of gas	X		G	X		S	SOMMA.Q (sG_y)	-		X									X				X		si usa sG_k (MISE) per il dato storico e sG_y (SNAM) per il dato real time (provvisorio)
ee101	hhi_g,max	gas_HHI_max	Herfindahl Hirschman indicator of gas	X		G	X		S	SOMMA.Q (sG_y)	-					X						X				X		si usa sG_k (MISE) per il dato storico e sG_y (SNAM) per il dato real time (provvisorio)
ee102	Y	total_entry_points	Number of italian entry points for gas supply	X		G				CONTA.VAL (y)	-															X		numero degli entry point italiani
ee103	K	total_supply_countries	Number of supply countries	X		G/O	X		S	CONTA.VAL (k)	-																X	numero dei paesi fornitori
ee104	Sh_g,y	gas_shannon_indicator_y	Normalised Shannon index (only gas) of y entry points	X		O		X	S	- [Σ_{y} (sG_y) * ln (sG_y)] / ln (Y)	-				X							-				X		si ottiene un valore normalizzato tra 0-1 grazie al rapporto con SWImax che coincide con il logaritmo naturale del numero degli entry points
ee105	Sh_g,k	gas_shannon_indicator_k	Normalised Shannon index (only gas) of k supply countries	X		O		X	S	- [Σ_{k} (sG_k) * ln (sG_k)] / ln (K)	-				X							-				X		si ottiene un valore normalizzato tra 0-1 grazie al rapporto con SWImax che coincide con il logaritmo naturale del numero dei paesi fornitori
ee106	J	total_energy_commodity	Number of energy resources in TPES	X		G				CONTA.VAL (j)	-															X		numero degli entry point italiani



ee107	RC_g	remaining_capacity_gas	(Daily) Remaining gas capacity net of total gas demand	X		G	X		S	1 - [(D_g - Prod_g) / Ctot_g]	-		X									X				X		
ee108	minRC_j	min_remaining_capacity_gas_month_j	(monthly) 0.01 percentile of daily remaining gas capacity per month j	X		G	X		S	INC.PERCENTILE(RC_g ; 0.01)	-				X							X				X	-	
ee109	aDm_g,j	average_demand_gas_month_j	(monthly) Average gas demand per month j (1m) (sum of daily Dm_g values) calculated taking into account the previous 3 years (yy3)	X		G	X		S	(MEDIA $_{yy3}$ [SOMMA $_{1m}$ (Dm_g)]) $_j$	10^6 Sm3				X							X				X		per l'ultimo mese (es: 27 genn 2022) usare tutti i valori giornalieri fino al 27 genn; i giorni rimanenti li prendiamo dall'anno precedente 28,29,30,31 genn 2021. La media sarà calcolata CON LO STESSO MESE dei 3 anni precedenti (2021,2020,2019)
ee110	aDm_g,y	average_demand_gas_year	(yearly) Average gas demand per year calculated taking into account the previous 3 years (yy3)	X		G	X		S	MEDIA $_{yy3}$ [SOMMA $_{1y}$ (Dm_g)]	10^6 Sm3							X				X				X		per ultimo anno (es: 27 genn 2022) usare tutti i valori giornalieri fino al 27 genn; i giorni rimanenti li prendiamo dall'anno precedente (dal 28 genn 2021 al 31 dic 2021).La media sarà calcolata con i 3 anni completi precedenti (2021,2020,2019)
ee111	wDm_g,j	weighted_average_demand_gas_month_j	(monthly) Weighted gas demand with respect to the average yearly demand	X		G	X		S	Dm_g,j / Dm_g,y	-				X							X				X		
ee112	I0_RF	indicator_remaining_flexibility_gas	(monthly) Weighted minimum remaining gas capacity per month j	X		G	X		S	minRC_j * wDm_g,j	10^6 Sm3				X							X				X		
ee113	I_RC	index_remaining_flexibility_gas	Normalization of the remaining flexibility indicator		X	G	X		S	1 - [MAX (I0_RF) - (I0_RF)] / [MAX(I0_RF) - MIN(I0_RF)]	-				X							X				X		
ee114	sprd_g	spread_psv_ttf	(monthly) Difference between PSV (italian) spot gas price and TTF (german) spot gas price	X		G	X		S	psv - ttf	€/MWh				X							X				X	X	
ee115	sprd_g_0.1	0.1_spread_psv_tff	(monthly) 0.10 percentile of spread between PSV and TFF calculated in the previous 5 years (yy5)	X		G	X		S	INC.PERCENTILE(sprd_g ; 0.10) $_{yy5}$	€/MWh				X							X				X	X	yy5 (5 anni precedenti) media "mobile" (eg. 27 genn 2022 - 27 genn 2017)
ee116	sprd_g_0.9	0.9_spread_psv_tff	(monthly) 0.90 percentile of spread between PSV and TFF calculated in the previous 5 years (yy5)	X		G	X		S	INC.PERCENTILE(sprd_g ; 0.90) $_{yy5}$	€/MWh				X							X				X	X	yy5 (5 anni precedenti) media "mobile" (eg. 27 genn 2022 - 27 genn 2017)
ee117	I0_sprd	indicator_spread_spot_gas	Normalization of the spread spot price between PSV and TTF		X	G	X		S	1 - [(sprd_g_0.9) - (sprd_g)] / [(sprd_g_0.9) - (sprd_g_0.1)]	-				X							X				X	X	
ee118	I_sprd	index_spread_spot_gas	Index of spread spot price between PSV and TTF		X	G	X		S	1 - [MAX (I0_sprd) - (I0_sprd)] / [MAX(I0_sprd) - MIN(I0_sprd)]	-				X							X				X	X	max e min assoluti (di tutta la serie storica)
ee119	t_co2,i	total_co2_emissions_month_i	(monthly) total CO2emissions (italy)	X		C	X		D	t_co2 $_j$ + [(i)/3 * (t_co2 $_j$ - t_co2 $_{j+1}$)]	kton CO2				X							X				X		valore mensile = somma CO2 emission degli ultimi 12 mesi
ee120	delta1_CO2	delta1_co2_target	(monthly) difference between effective and target total CO2 emissions in Italy	X		C	X		D	(t_co2,i - trg1_co2)	kton CO2				X							X				X		il dato target è annuale e rimane uguale per tutti e 12 i mesi
ee121	esd_co2,i	ESD_co2_emissions_month_i	(monthly) CO2emissions from ESD sectors in Italy	X		C	X		D	esd_co2 $_j$ + [(i)/3 * (esd_co2 $_j$ - esd_co2 $_{j+1}$)]	kton CO2				X							X				X		valore mensile = somma CO2 emission degli ultimi 12 mesi
ee122	delta2_CO2	delta2_co2_target	(monthly) difference between effective and target CO2 emissions from ESD sectors (italy)	X		C	X		D	(esd_co2,i - trg2_co2)	kton CO2				X							X				X		il dato target è annuale e rimane uguale per tutti e 12 i mesi
ee123	I_tCO2	index_total_co2	(monthly) Index of total CO2 emissions in Italy		X	C	X		D	1 - [MAX (delta1_CO2) - (delta1_CO2)] / [MAX (delta1_CO2) - MIN (delta1_CO2)]	-				X							X				X		
ee124	I_esdCO2	index_esd_sectors_co2	(monthly) Index of CO2 emissions from ESD sectors in Italy		X	C	X		D	1 - [MAX (delta2_CO2) - (delta2_CO2)] / [MAX (delta2_CO2) - MIN (delta2_CO2)]	-				X							X				X		
ee125	t2030_co2,i	forecast_2030_total_co2_emissions_month_i	(monthly) total CO2emissions (italy) forecast 2030	X		C	X		D	t2030_co2 $_j$ + [(i)/3 * (t2030_co2 $_j$ - t2030_co2 $_{j+1}$)]	kton CO2				X							X				X		valore mensile = somma CO2 emission degli ultimi 12 mesi
ee126	delta1_2030	delta1_co2_target_2030	(monthly) difference between forecast and target 2030 total CO2 emissions in Italy	X		C	X		D	(t2030_co2,i - trg1_2030)	kton CO2				X							X				X		il dato target è annuale e rimane uguale per tutti e 12 i mesi
ee127	esd2030_co2,i	forecast_2030_ESD_co2_emissions_month_i	(monthly) CO2 emissions from ESD sectors forecast 2030 in Italy	X		C	X		D	esd2030_co2 $_j$ + [(i)/3 * (esd2030_co2 $_j$ - esd2030_co2 $_{j+1}$)]	kton CO2				X							X				X		valore mensile = somma CO2 emission degli ultimi 12 mesi
ee128	delta2_2030	delta2_co2_target_2030	(monthly) difference between forecast and target 2030 CO2 emissions from ESD sectors (italy)	X		C	X		D	(esd2030_co2,i - trg2_2030)	kton CO2				X							X				X		il dato target è annuale e rimane uguale per tutti e 12 i mesi
ee129	I_tCO2_2030	index_total_co2	(monthly) Index of total CO2 emissions in Italy with respect to 2030		X	C	X		D	1 - [MAX (delta1_2030) - (delta1_2030)] / [MAX (delta1_2030) - MIN (delta1_2030)]	-				X							X				X		
ee130	I_esdCO2_2030	index_esd_sectors_co2	(monthly) Index of CO2 emissions from ESD sectors in Italy with respect to 2030		X	C	X		D	1 - [MAX (delta2_2030) - (delta2_2030)] / [MAX (delta2_2030) - MIN (delta2_2030)]	-				X							X				X		
ee131	delta_%RES	delta_%RES_target	(annual) difference between effective and target RES penetration in Italy	X		C	X		D	(%RES - trg_%RES)	%							X				X				X		bisogna convertire il dato annuale in dato mensile
ee132	I_RES%	index_RES_penetration	(annual) Index of CO2 emissions from ESD sectors in Italy		X	C	X		D	1 - [MAX (delta_%RES) - (delta_%RES)] / [MAX (delta_%RES) - MIN (delta_%RES)]	-							X				X				X		bisogna convertire il dato annuale in dato mensile
133	s_ita,j	share_ita_commodity_j	Share of primary energy from source j (with oil and crude aggregated)	X		-		X	-	ita_TPES,j / Σ_j (ita_TPES,j)	-							X				X				X		calcolato per ogni commodity del DT22 (NB. crude oil e oil products INSIEME con un unico valore ottenuto dalla somma delle due voci)
134	Sh_ita	italy_shannon_resources	Normalised Shannon index tor of italian energy mix: diversification of energy resources (TPES)		X	-				- [Σ_j (s_ita,j) * ln (s_ita,j)] / ln (J)								X				X				X		indice normalizzato con valori tra 0-1 --> 0 se bassa diversificazione, 1 se massima diversificazione
135	s_k,j	share_country_commodity_j	Share of primary energy from source j (with oil and crude aggregated)	X		-		X	-	k_TPES,j / Σ_j (k_TPES,j)	-							X				X					X	filtro: Austria, Belgio, Bulgaria, Cipro, Croazia, Danimarca, Estonia, Finlandia, Francia, Germania, Grecia, Irlanda, Italia, Lettonia, Lituania, Lussemburgo, Malta, Paesi Bassi, Polonia, Portogallo, Repubblica Ceca, Romania, Slovacchia, Slovenia, Spagna, Svezia e Ungheria). Calcolato per ogni commodity del DT22 (NB. crude oil e oil products INSIEME con un unico valore ottenuto dalla somma delle due voci)
136	Sh_k	country_shannon_resources	Normalised Shannon index tor of italian energy mix: diversification of energy resources (TPES)		X	-		X		- [Σ_j (s_k,j) * ln (s_k,j)] / ln (J)								X				X					X	indice normalizzato con valori tra 0-1 --> 0 se bassa diversificazione, 1 se massima diversificazione
137	Sh_eu27	eu28_shannon_resources	Normalised Shannon index tor of Europe27 energy mix: diversification of energy resources (TPES)							MEDIA (Sh_k) k ∈ EU_27																		
138	s_world,j	share_world_commodity_j	Share of primary energy from source j (with oil and crude aggregated)	X		-		X	-	world_TPES,j / Σ_j (world_TPES,j)	-							X					X				X	calcolato per ogni commodity del DT22 (NB. crude oil e oil products INSIEME con un unico valore ottenuto dalla somma delle due voci)
139	Sh_world	world_shannon_resources	Normalised Shannon index of world energy mix: diversification of energy resources (TPES)		X					- [Σ_j (s_world,j) * ln (s_world,j)] / ln (J)								X					X				X	indice normalizzato con valori tra 0-1 --> 0 se bassa diversificazione, 1 se massima diversificazione

Figure 93: Elaborated data's formalisation table





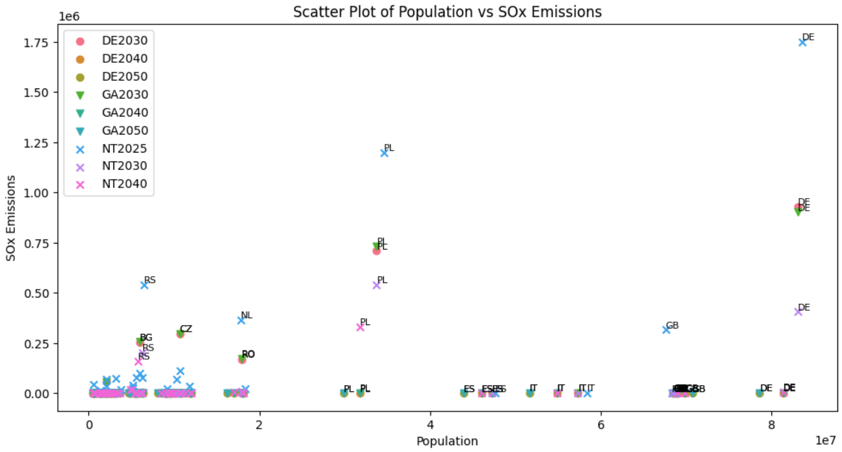
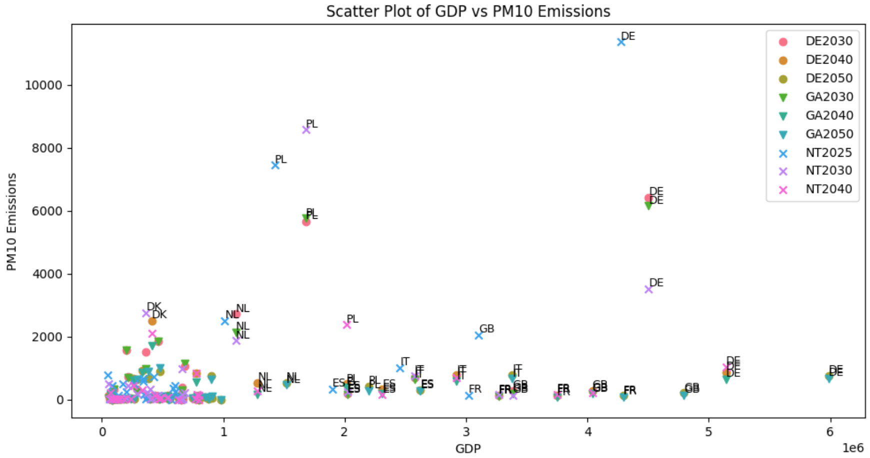
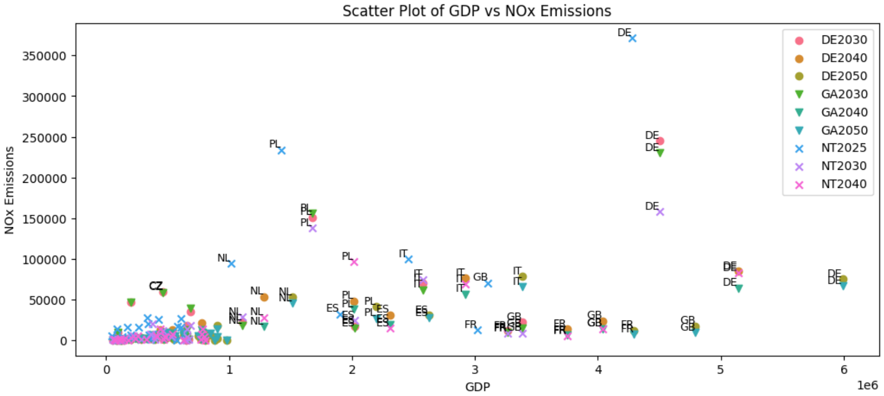


Figure 94: Scatter plot between country's air pollutant emissions and population





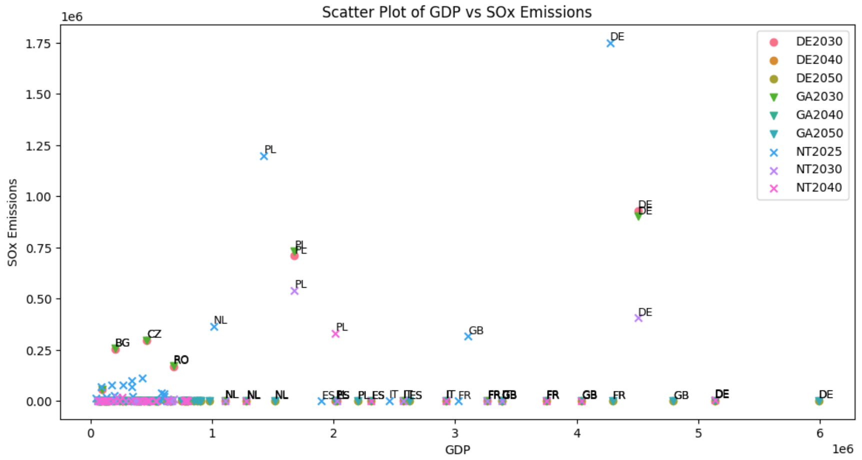


Figure 95: Scatter plot between country's air pollutant emissions and GDP

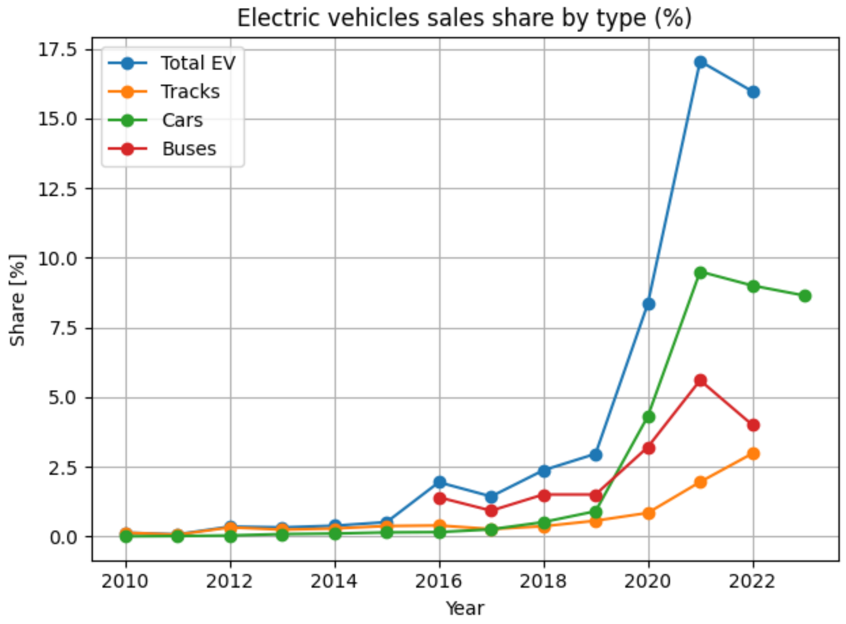


Figure 96: Evolution of electric vehicles sales (share over total vehicles sales %) by type

Table 35: Temporal coverage of datasets: "from" refers to the first earliest data available and "to" refers the last update (Source: [117]*)*

Dataset ID	**Dataset Name**	**From**	**To**
DT1	Dati di produzione e raccolta differenziata	2010	2022
DT2	Dati sui costi di gestione dei rifiuti urbani (pro capite o per chilogrammo di rifiuto)	2011	2022
DT3	Rifiuti_Produzione rifiuti speciali	2011	2020
DT4	Aria - la qualità dell'aria in Piemonte (Misure)	2000	2024
DT5	Bilancio di sostenibilità SMAT	2007	2022
DT6	Ambiente urbano - Verde Urbano	2000	2023
DT7	Consumo del suolo	2006	2022
DT8	Istat_Tavole_Censimento_acque_per_uso_civile	1999	2020
DT9	Catasto Impianti Termici	-	2024

DT10	Iren - Bilancio di sostenibilità	2016	2021
DT11	Ambiente urbano - Energia	2000	2022
DT12	Dichiarazione non finanziaria	2019	2022
DT13	Autoritratto_2021 - Circolante_Copert_2021	2002	2023
DT14	Open Parco Veicoli	2015	2022
DT15	Ambiente urbano - Mobilità	2000	2022
DT16	Ambiente urbano - Eco management (dati su illuminazione pubblica)	2000	2022
DT17	Consumi energetici, Impianti e Attestazione di Prestazione Energetica	-	-
DT18	Popolazione residente ricostruita - Anni 2002-2019	2002	2019
DT19	Reddito e principali variabili IRPEF su base subcomunale/comunale	2012	2021
DT20	Mortalità per cause	1980	2019
DT21	Mortalità per territorio di evento	2003	2021
DT22	AAEP - Anagrafe delle Attività Economiche Produttive - Consultazione	2020	2024
DT23	Principali aggregati territoriali di Contabilità Nazionale - Valore aggiunto per branca di attività	2005	2021
DT24	Imprese e addetti	2012	2021
DT25	Principali aggregati territoriali di Contabilità Nazionale - Investimenti fissi,lordi,interni e Spesa per consumi finali delle amministrazioni pubbliche	2005	2021
DT26	TAPE - Turin Action Plan for Energy	2010	2019
DT27	Torino - Informacasa	2009	2020
DT28	Analisi del potenziale solare per i comuni dell'area metropolitana torinese	2010	2010
DT29	Relazione annuale relativa al funzionamento e alla sorveglianza dell'impianto - Termovalorizzatore Gerbido	2017	2022
DT30	Dichiarazione ambientale - Centrale di cogenerazione Torino Nord	2014	2021
DT31	Dichiarazione ambientale - Centrale di cogenerazione Moncalieri	2006	2022
DT32	Stato d'avanzamento attività discarica e attività di gestione del biogas	2020	2021
DT33	Annuario Statistico - Settore toponomastica ed edilizia	2001	2021
DT34	Indagine sulle spese delle famiglie: microdati ad uso pubblico	2014	2022

Table 36: Selected indicators to assess the UETI in Amsterdam, Eindhoven, Rotterdam and Utrecht

Indicator	**Unit**	**Sub-domain**	**Domain**
Homes with valid energy label greater than A	n	Energy intensity	Energy
Residential energy consumption	TJ	Energy intensity	Energy
Transport energy consumption	TJ	Energy intensity	Energy
Efficiency of cycle lines network	Score	Green mobility	Energy
H2 refuelling stations	n	Green mobility	Energy
Maintenance status of cycle lines	Score	Green mobility	Energy
Percentage of electric and plug in passengers cars	%	Green mobility	Energy
Total number of public charging points for electric cars	n	Green mobility	Energy
Electricity outage duration	min	Power grid quality	Energy
Geothermal installed capacity	MW	RES penetration	Energy
Hydropower operational capacity	MW	RES penetration	Energy
Number of local energy cooperatives	n	RES penetration	Energy
Onshore wind installed capacity	MW	RES penetration	Energy
PV installed capacity	kW	RES penetration	Energy
Share of RES in energy mix	%	RES penetration	Energy
Exposure NO2	µg/m3	Air pollutants	Environment

Exposure PM10	µg/m3	Air pollutants	Environment
Avoided CO2 emissions by renewable energy	kton CO2	GHGs	Environment
CO2 emission Agriculture, forestry and fisheries	kton CO2	GHGs	Environment
CO2 emission Energy sector	kton CO2	GHGs	Environment
CO2 emission Industry	kton CO2	GHGs	Environment
CO2 emission Residential	kton CO2	GHGs	Environment
CO2 emission Transport	kton CO2	GHGs	Environment
CO2 emissions Water and Waste management	kton CO2	GHGs	Environment
Total known CO2 emissions	kton CO2	GHGs	Environment
Area of greenery per neighbourhood	%	Land use	Environment
Woodland and nature	ha	Land use	Environment
Total household waste	kg/inhab	Waste	Environment
Residual waste of households	kg/inhab	Waste	Environment
Total water consumption	Pm3/year	Water	Environment
Financial prosperity	Score	Economic impact	Socio-economy
Local sustainability loan	€	Economic impact	Socio-economy
Socio-economy status	Score	Economic impact	Socio-economy
Unemployment rate	%	Economic impact	Socio-economy
Chronic lower respiratory diseases	n deaths	Health	Socio-economy
Life expectancy	years	Health	Socio-economy
Median disposable income per household	k€	Well-being	Socio-economy
Share of energy costs in average households income	%	Well-being	Socio-economy

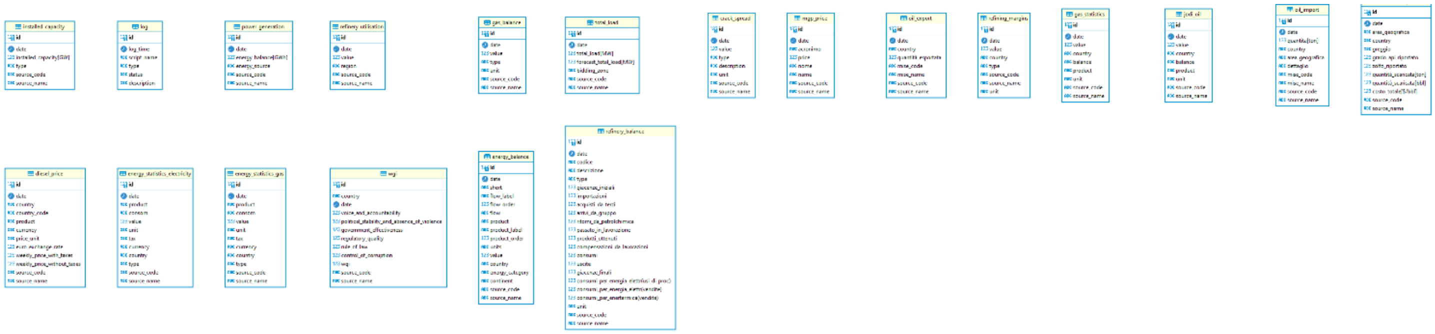


Figure 97: Scheme of indipendent tables (ER Databse Structure of ET@IT platform)

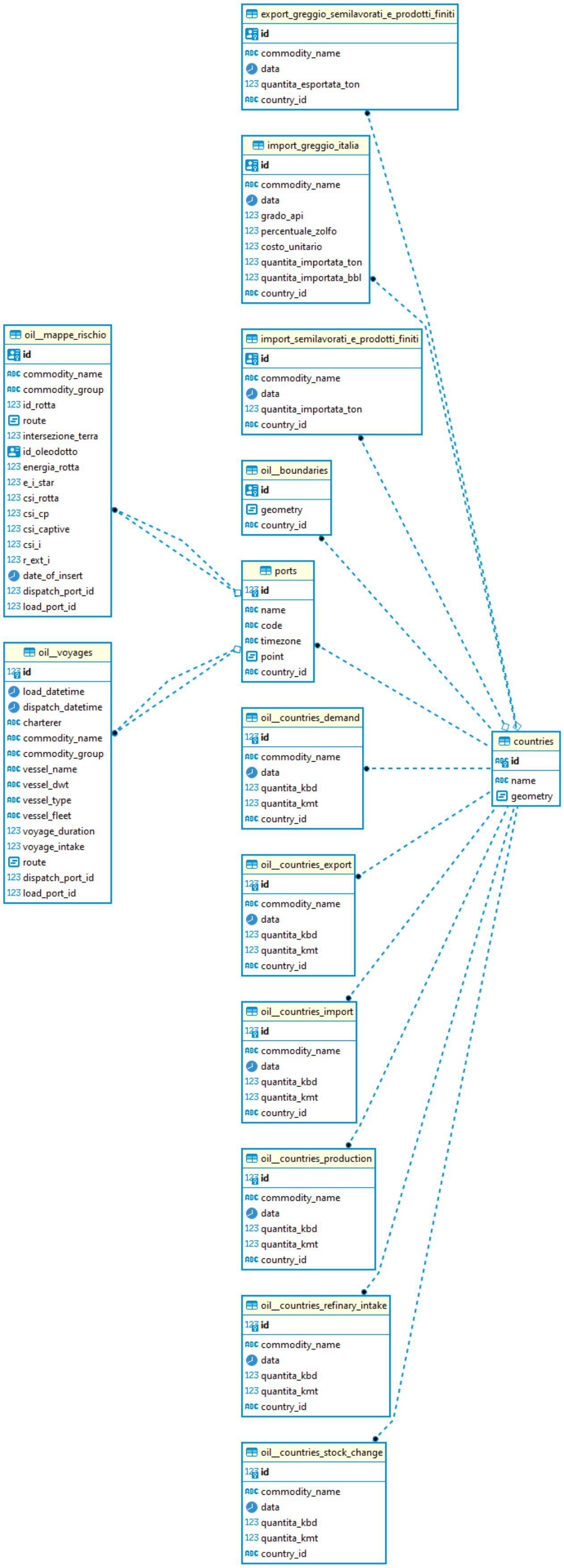


Figure 98: Scheme of interlinked tables (ER Databse Structure of SERT platform)