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Master's thesis:

Analyzing the transition of electricity generation in the European electricity system until 2030.

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Abstract

The European Union is highly sensitive to the problematic of climate change. This is shown by the implementation of policies to foster the increase on renewable electricity production infrastructure in the region. As such, it is highly relevant to assess the effectiveness of policies packages like Fitfor55 and REPower EU in the transition of the European electricity production system by 2030.

Energy systems modeling is a useful tool to assess the impacts of policies on electricity production infrastructure. Modeling such a complex system shows to be challenging and heavily influenced by data and assumptions done during the setup.

The creation of a reliable geographical database to model the European electricity production system of 2030 through the collection of data from different sources is used to model the impacts of European policies on the transition of electricity production infrastructure under different assumptions and scenarios.

The investment on renewable energy infrastructure, especially solar installations, shows to have an important effect on the decarbonization of the electricity system. Hydrogen infrastructure for electricity production also has positive effects in the transition of the system, especially to reduce the reliance on natural gas infrastructure.

Nonetheless, the limited effect of current policies on the increase of the penetration of this type of infrastructure shows that there is still improvement potential in these packages to ensure the achievement of the 2030 objectives.

Nomenclature

AHP (Analytical Hierarchy Process)
CAPEX (Capital cost)
CECEM (Copenhagen Economics Global Climate and Energy Model)
COMBI (Calculating and Operationalizing the Multiple Benefits of Energy Efficiency in Europe)
COP21 (2015 United Nations Climate Change Conference – Conference of the Parties)
DEA (Danish Energy Agency
EGD (European Green Deal)
ENTSO-E (European Network of Transmission System Operators)
ETS (EU Emission Trading System)
EU (European Union)
EU 28 (European Union 27 + UK)
EU27 (European Union 27)
EU33 (33 analyzed countries in this study)
FINE (Framework for Integrated Energy System Assessment)
FZJ (Forschüngszentrum Jülich)
GAMS (General Algebraic Modelling System)
GEM-E3 (The General Equilibrium Model for Economy-Energy-Environment)
GHG (Greenhouse gas)
IAEA (International Atomic Energy Agency)
IEK-3 (Institute of Energy and Climate Research – Techno-Economic Systems Analysis)
IRENA (International Renewable Energy Agency)
LCOE (Levelized Cost of Electricity)
MARKAL (MARKet and ALlocation Model)
MASTR (Market master data register)
METIS (Methods and Models for Energy Transformation and Integration Systems)
MuPIA (Multi-Perspective Investment Analysis tool)
NECP (National Energy & Climate Plan)
NG (Natural gas)
NUTS (Nomenclature of Territorial Units for Statistics)
OPEX (Operational cost)
OSeMOSYS (Open Source Energy Modelling System)
PLEXOS (PLEXOS® Integrated Energy Model)
PRIMES (Price-Induced Market Equilibrium System)
PyPSA (Python for Power System Analysis)
RE (Renewable Energy)
ReEDS (Regional Energy Deployment System)
RESKit (Renewable Energy Simulation toolkit)
SAI (Supreme Audit Institutions)
TAC (Total Annual Cost)
TIMES (The Integrated Markal Efom System)
TOPSIS (Technique for Order Preference by Similarity to Ideal Solutions)
UK (United Kingdom)
VRES (Variable Renewable Energy Sources)

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1. Introduction

1.1. Forschungszentrum Jülich

Forschungszentrum Jülich (FZJ) is an internationally recognized German research institute founded in 1956 that pursues interdisciplinary research in a diversity of fields including biology, physics, materials, and energy.[1]

Inside FZJ, the Institute of Energy and Climate Research – Techno-Economic Systems Analysis (IEK-3) conducts research into how future sustainable energy systems can be achieved and what they might look like.

To this end, the IEK-3 develops a wide range of highly complex and detailed energy system models to assess local-to-global energy systems in an integrated manner. Thereby, the institute aims to provide the best possible knowledge-based support for the implementation of the clean energy transition.

1.2. Background, motivation and importance

Europe is fully embarked on the energy transition to become a climate-neutral continent by midcentury, for that, many countries have enforced policies that establish the roadmap to fulfill this objective, alongside their infrastructure plans for the investment in new power plants from conventional energy sources but especially from renewable sources.

Additionally, the recent unfortunate events in Ukraine and the subsequent sanctions imposed by most of the European countries on Russia, have increased the concern and awareness of the heavy dependency of the region on fossil fuels coming from Russia.

In this framework, analyzing the transition of electricity generation both at the country and regional level is fundamental to model possible future scenarios and obtain crucial information for the decision-makers, so that adequate policies can be implemented to achieve the European energy transition goals and to increase the geopolitical security of the European energy system.

In this context, this thesis aims to collect technical and geographical information on the power generation system in Europe, as well as the policies implemented in each country and at the European level considering the 2030 horizon. This information will be used to create a geographical database to feed an energy systems model tool called FINE (Framework for Integrated Energy System Assessment), which was developed at Forschunszentrum Jülich. This model will enable the assesment of different scenarios of a cost-optimized European electricity system in 2030, considering the targets and infrastructure of each country.

The outcomes of such scenarios will allow identifying possible gaps and infrastructure needs in the current policies and targets.

1.3. Objectives

1.3.1. General objective

The general objective of this thesis is to compare the outcome of different scenarios of the 2030 European electricity system built with FINE, in order to assess the implications of the envisioned policies and infrastructure plans by 2030 for the electricity generation transition inside the European energy system.

1.3.2. Particular objectives

To achieve the general objective the following particular objectives are also in the scope of this thesis:

1. To assess the current landscape of electricity generation at the plant level in Europe.
2. To build a geographical database of the electricity generation plants with an expected active status in 2030 in Europe.
3. To collect and analyze the transition policies for electricity generation for 2030 at the country level.
4. To implement the database and the policies analysis into the FINE model in different proposed scenarios.
5. To compare and analyze the outcome of the different scenarios and highlight possible gaps, infrastructural needs, and recommendations to improve Europe's electricity generation transition policies.

2. Theoretical framework and background

2.1. Energy transition policies

The world faces an unprecedented challenge that threatens both the ecological equilibrium and the future well-being of humanity: climate change, which is also caused by humanity itself. As such, also humanity has the possibility to tackle the issue, limit climate change and prevent further damage to the planet.

It is widely accepted by the scientific community that this climate change has been caused by the humungous GHG (greenhouse gas) emissions that humanity has been emitting since the beginning of the industrial revolution. Most of these emissions can be linked to the energy sector through the burning of fossil fuels.

In this context, nations from all around the world have been discussing the best strategies to fight climate change and implementing energy policies with the objective to decarbonize the energy sector. The European Union is a front leader in this field, having established binding targets and objectives for their member countries through different policies in the recent years. While until 2007, most of the policy efforts to tackle the problem were isolated inside the EU to the national level, several policies independently focused on climate change, energy security, and economic growth were developed in some countries of the EU. Some regional efforts were also done, like the establishment of EU Emission Trading System (ETS) to place a price on carbon in 2003, although just covering some sectors like the power production and energy intensive industries.

It was until 2007, in the directive 2012/27/EU of the European Parliament, that common targets for 2020 for the whole EU were adopted, including -20% GHG emissions compared to 1990, 20% share of renewable energy in the EU mix, and 20% improvement on energy efficiency. [2]

Since then, and especially after the Paris agreement of COP21 (2015 United Nations Climate Change Conference – Conference of the Parties), with the goal of keeping the increase of global temperatures below 1.5°C compared to pre industrialization levels, the EU has seen a crucial increase in the coordination and development of integrated policies for energy and climate. [3]

In December 2019 the EU launched the European Green Deal (EGD), the first integral package of policies placing climate and the environment as the center of the strategy for the sustainable development of industry, innovation, and society of the European Union. With this package, the European Union has the objective of making Europe the first carbon neutral continent by 2050 and establishing clear regional objectives for both 2030 and 2050. [4]

The EGD was a first initial set of targets, providing a climate action plan for nine key policy areas that focus on delivering a clean, affordable, secure, and just transition, not only for the energy system, but also with objectives in terms of biodiversity, ecosystems restoration, and circular economy.

In terms of the energy transition, which is the main focus of the package, the EGD defines the clear objectives of a reduction of 55% of GHG emissions compared to 1990, and an increase of RE share in the energy system to at least 40% by 2030. [4]

In 2021, the EGD was furtherly detailed with the "Fit for 55" package in. This new package keeps the EGD objectives, and additional to the general action plan, it sets a clear path to achieve the targets, focusing on actions for specific topics and sector that face major challenges to achieve climate neutrality, such as aviation, the forestry sector, maritime industry and other sectors considered in the European Emissions Trading System (EU ETS). [5]

There are to components to highlight within these packages. Firstly, binding targets for each member country are set to achieve the EU goals. And secondly the packages demand the creation of National Energy & Climate Plans (NECP) in which each country sets their compromised individual targets and their strategies to achieve them.

These targets at national level are defined for renewable energy share in the electricity generation mix and for reduction in GHG. The individual targets as established in the NECPs can be consulted in Table 3 of the appendix 1.

The latest update in the energy policies of the EU came after the crisis of the Russian invasion of Ukraine in February 2022, which caused a the put in place of a package of sanctions from the EU and

member countries against Russia, the main supplier of natural gas of the EU. It boosted the realization of the urgent need to reduce the EU dependency on Russian gas.
As a result, in May 2022 the European Commission launched a new policy package called REPower EU, which has the main objective of rapidly reducing the EU dependency on Russian fossil fuels with the acceleration of the clean transition to achieve a more resilient energy system. [6]
Table 1 shows the main differences between the most relevant objectives and strategies for this thesis in the REPower EU package compared to Fit for 55.
REPower EU builds on the objectives and actions established in the Fitfor55 package, keeping the main objective of reducing GHG by 55% in 2030 and the climate neutrality of Europe by 2050. At the same time, it increases the objectives for RE share and energy efficiency by 5 p.p. and 4 p.p. respectively.
The latter results in a larger incentive to install new renewable capacity, with the objective to have 1236 GW of renewable capacity by 2030, compared to the objective of 1067 GW in the Fitfor55 package. Within this objective, there is an especial focus on solar PV, with the objective of installing 600 GW of new PV capacity by 2030.

Table 1. General EU objectives for 2030 – comparison between Fitfor55 and REPower EU.

Objective	Fit for 55	REPower EU
GHG emissions reduction	55%	55%
RE share in EU energy mix	40%	45% (69% in electricity)
RE installed capacity	1067 GW	1236 GW
New PV installed capacity	Not especified	600 GW
Energy efficiency (reduction in energy consumption)	9%	13%
Natural gas consumption reduction with respect to 2019 levels	30% (116 bcm)	Additional 140 bcm
Green H_2 production	-	10 Mt
Green H_2 imports	-	10 Mt

To achieve this, the REPower EU package includes a specific strategy for solar: the EU solar strategy. This strategy presents the European Solar Rooftop Initiative, which introduces new regulations and binding obligations for the implementation of solar rooftop infrastructure on certain categories of buildings. Additionally, the EU solar strategy presents the guidelines and enabling measures for the promotion of utility scale solar deployment, and the preparation of the network for an efficient absorption of solar electricity.
The main objective of REPower EU is to reduce the fuel dependency of the EU on Russia to zero by 2027. For this, REPower EU defines additional actions to the already established in the Fitfor55 package to save energy, diversify suppliers, substitute fossil fuels by accelerating the clean energy transition, and smartly combine investment and reforms.
These actions show a potential increase of the natural gas consumption reduction of 140 bcm additional to the 116 bcm target in Fitfor55. Many of these actions turn around an increase of the use of renewable energies, especially PV, and the role of green hydrogen for the total substitution of 155 bcm of natural gas, the equivalent to Russian imports, by 2027.

2.2. Energy policies assessment and implementation

Energy policies like the ones previously discussed, are usually defined based on a prior assessment of the potential effects of their implementation in the energy systems. For this, several different approaches can be applied.
One of the most common tools to assess energy policies is computational modeling, a quantitative approach towards the analysis of the implementation and assessment of their results. Energy systems

modeling is particularly relevant because governments and organizations extensively use it to obtain the information that sustains their policy initiatives. For example, the EU used the energy systems model PRIME (Price-Induced Market Equilibrium System) as a tool to define scenarios, like the reference scenario (EU Reference Scenario 2020), in the elaboration process of the EGD package.

However, and as discussed in the following section, this quantitative approach has some limitations at the social and political level, especially with energy efficiency-oriented policies. Hence, it is important to review other tools that exist in the literature as techniques to assess the implementation and effectiveness of energy policies. These tools have a more qualitative approach, which complement the quantitative assessment done with energy systems modeling.

From the different studies analyzed, it can be observed that there are two main categories of approaches for assessing energy policies without using energy models.

The first is the use of other mathematical models, like Gkonis et al. [2] that use a Multi-Perspective Investment Analysis tool (MuPIA) solved in the General Algebraic Modelling System (GAMS) to study a cost-optimal energy efficiency portfolio of measures and policies in the framework of the "energy efficiency first" principle of the EU. Another example is the study made by Thema et al. [7] of the COMBI project (Calculating and Operationalizing the Multiple Benefits of Energy Efficiency in Europe) impact indicators through different quantification methodologies, including modelling tools like the Copenhagen Economics Global Climate and Energy Model (CECEM).

The second approach is through statistical or economic multi-criteria analysis, like the Technique for Order Preference by Similarity to Ideal Solutions (TOPSIS), and the Analytical Hierarchy Process (AHP), used for instance by Balode et al. [8] to assess the policy impacts on National Energy and Climate Plans (NECP). Another example of this approach is the study made by Wach et al. [9] to evaluate the level of "Europeanization" of climate and energy policies in the Visegrad countries, using multivariate comparative analysis methods. Finally, there is the case of Kilinc-Ata [3] that applies an econometric framework to assess the effectiveness of four policy instruments (feed-in tariffs, quotas, tenders and tax incentives) in different countries of the EU and states of the USA.

Although these approaches are of great interest and are crucial for the evaluation of effectiveness of policies, they face some limitations, for example they might be subject of some biases, since, for instance they sometimes determine the weight of indicators based on the criteria of experts through surveys that might not always be fully objective.

Finally, in the context of different ways to assess energy policies, the study of Sulkowski & Dobrowolski [10] states the importance of Supreme Audit Institutions (SAIs), since they play a vital role as the primary external and independent evaluator of the realization of government policies. However, in the field of energy policies, they still flaw in terms of energy accountability, more at the supranational level of the European Union.

2.3. Modeling as a qualitative approach to assess energy policies

In the framework of the energy transition, the creation and implementation of policies is not trivial, and it requires a lot of information and knowledge, hence the importance of energy planning and energy systems modeling.

As mentioned by Pfenninger et al. [11], the oil crisis of the seventies enhanced the attention of the world towards energy, and more specifically, energy scenarios planning through modeling. Since then, this field has helped to increase the understanding of the complex energy sector. Energy systems modelling has also allowed decision-makers to have more detailed information to envision the growth and evolution of the energy system, and to test the effect of various policies to accomplish their energy goals. [12]

Models have shown their great importance and influence on energy policies, and at the same time they have evolved in their complexity and efficiency to reflect the different components of the energy system. Nowadays, energy modeling has become a crucial discipline for the evaluation of the future energy system and is key for the development of the knowledge that sustains the decarbonization and transition targets and strategies. As such, they have become an important foundation for energy planning and energy policy development.

As mentioned by Prina et al. [13], energy planning has two main objectives: provide the information and knowledge for the discussion about future energy system and support decision-makers in developing energy strategies.

While there is no official consensus on the classification of energy models, there have been several efforts to identify the characteristics that differentiate them. Most of these efforts agree in two main approaches towards the classification of models: the approach of study and the methodology used to solve the problem.

Regarding the approach of study, the main classification is between bottom-up models, which work based on a detailed description of the technical components of the system, and top-down models that focus on the role of energy systems inside the whole economic system. In this sense, bottom-up models have a central focus on the energy system, affected mainly by its own components. Top-down models focus more on the effect that macroeconomic parameters have on the energy systems.

With respect to the methodology used to solve the model, Ringkjob et al. [14] propose a classification on three types: simulation, optimization (most of these models apply linear programming or mixed-integer linear programming methodologies), and equilibrium models (with considerations of the whole economic system). However, most of the extensively used models used nowadays are either simulation or optimization based.

Considering the latter, Pfenninger et al. [11] propose a classification just on simulation models, which have a more predictive oriented application, and optimization models with a normative oriented approach.

Besides the aforementioned approaches for the classification of models, several authors propose other categories like the geographical coverage, the time resolution, or the energy sectors covered [13]. However, the most widely extended approach is the top-down/bottom-up & simulation/optimization classification.

An important remark is that, as mentioned by Pfenninger et al. [11], the boundaries defined by the different types of models are not rigid, and a particular model can fit between a continuous scale between the different categories of classification.

2.4. Challenges for energy systems modeling

The key aspect of energy planning is well-sustained information coming from energy systems modeling. Traditionally, energy systems models have been able to produce this information. However, they still face several challenges to address the increasing complexity of energy systems with a higher penetration of VRES (variable renewable energy sources) and with a more relevant role of consumers and prosumers. The latter has pushed the improvement and innovation in the energy models. [13]

Pfenninger et al. [11] do an intensive analysis of them and classify them based on four categories: resolving details in time & space (focusing on the resolution), uncertainty and transparency, complexity and optimization across scales, and capturing the human dimension. Following, there is an overview of the main challenges of energy systems modeling based on the classification of Pfenninger et al.

2.4.1. Resolution

The issue of balancing model resolution and data availability, along their relation to computational power to solve the model is a key challenge for modern energy systems models, especially because the insertion of variable renewables, storage systems, and interactions of electricity markets adds an extra importance to the level of spatial detail and time resolution of models. However, due to the computational limitations on solving time, the desired level of detail cannot be applied to modern models.

Even though, several models can handle high resolution in either time, space, techno-economic detail, and sector-coupling resolution or in a combination of them, achieving high resolution in all these categories keeps being the main challenge in terms of resolution.
The literature presents some alternatives to try to assess this problematic, for instance, by using long duration curves or capacity factors (like MARKAL- MARKet and ALlocation model), by using time slices with representative days and seasons (like TIMES - The Integrated Markal Efom System), or by applying real time series of solar and wind production potential (like ReEDS- Regional Energy Deployment System). However, increasing the resolution with these strategies must be approached carefully, because it might demand a higher and unfeasible computational power. For instance, Calliope (a multi-scale, open-source framework to build energy system models [14]) can theoretically be run with high resolution in time, space, and sector-coupling, and medium resolution in techno-economic aspects. However, it would require a heavy computation burden and it is unlikely that it could be solved under this level of detail.[13]

2.4.2. Uncertainty and transparency

In the field of energy modeling, two main types of uncertainties are identified: epistemic, when the modeler thinks that more or better, but inaccessible data might be available, and aleatory uncertainty, when this uncertainty cannot be further reduced. Although the latter cannot be addressed, epistemic uncertainties can be addressed by deterministic or stochastic approaches. These uncertainties are even more evident considering that energy system models cannot be compared or verified against observable physical phenomena. This issue with the uncertainty highlights the key importance and reliance on assumptions when energy systems are modeled.
As the challenge of uncertainty is related to the approach towards the lack of quality of information used in the models, this is linked to the issue of transparency in the field.
Sometimes models can become untransparent or inaccessible to other researchers, decision-makers and the general public. Pfenninger et al. [15] state that most models work as “black boxes” where the access to data and code is almost impossible, and shows that there are several reasons that partially explains and justifies why models are mostly not open. They highlight the issues related to sensitive commercial data and personal information, unwanted exposure, the time-consumption of sharing code and information, and institutional and personal inertia.
On the other hand, open models imply that anyone can access, use, modify, and share both model code and data for any purpose; an example of this is OSeMOSYS (Open Source Energy Modelling System). Pfenninger et al. [15] also state that open models can bring several benefits to the field: improving the quality of studies, bringing more effective collaboration across the science-policy boundary, increasing the productivity through collaboration of researchers, and bringing profound relevance to societal debates.

2.4.3. Complexity

Another important challenge is the lack of connection and integration across different scales of analysis with their appropriate resolution. Current models might be missing important information when applying trade-offs in resolution or by using simplified assumptions; and as energy systems become more complex and interconnected, their modeling gets linked to the issue of scale, where scale is the relative size of the boundary of an analyzed or modeled system. Most large-scale models (continent level) work with a reduced level of resolution, while small-scale models (single location) have usually a high resolution. However, Pfenninger et al. [11] mention that high resolution phenomena, like demand fluctuation, can also be of great importance for large-scale modeling.
To address this challenge, and as an alternative to simply increase the level of resolution of large-scale models, which could make the model unfeasible due to computational limitations, there are several alternatives.
The so called two-scale models consider different time scales with different levels of detail, agent-level models allow the decoupling of processes happening at different scales, allowing the interaction

between simple models, and the combination of different models to capture different dimensions. [16]

2.4.4. Human dimension

Current models focus basically just in the technical and economic aspects of the energy systems. However, this neglects the importance and the impacts of key factors like political will, public acceptance, human behaviors, indirect cost, sociopolitical and non-financial barriers to deploying technologies, among others. More specifically at the policy level, policy baseline assumptions should also include assessments of how likely it is that those policies will be implemented. [11]
Another important bias that models have related to this aspect, is that they assume individuals as rational and active economic agents, while in the reality they are strongly influenced by biases and preferences. [13]
The bias of energy models on the human dimension can also overlook some important behavioral aspects, for instance some studies show that people are willing to pay more than what would be cost-optimal, having a great impact on the economics of models.
All the aforementioned aspects heavily contribute to a higher level of uncertainty and should not be dismissed.

2.5. FINE – Framework for Integrated Energy System Assessment

As part of the academic effort to tackle these challenges, several open-source frameworks have been developed in recent years. FINE (Framework for Integrated Energy System Assessment) is one of these modeling frameworks, that aims to tackle especially the issues of resolution, complexity, and transparency.
FINE is an open source, bottom-up, object-oriented optimization modelling framework for energy systems. As an open source framework, it aims to allow the assessment of energy systems to any scientist, programmer or interest person in the matter.
It was jointly developed under the funding of METIS (Methods and Models for Energy Transformation and Integration Systems) project by the Forschunszentrum Jülich, RWTH-Aachen University, and the Friedrich-Alexander University. [17]
In technical aspects, FINE is built on Python, with Pyomo as the mathematical modeling language and can use different Linear or Mixed Integer Liner Programming solvers, such as Gurobi. As an optimization model, FINE is solved considering the objective of minimizing the total annual cost of the system.
The structure of FINE is based on five core components: Source, Conversion, Storage, Transmission, and Sink, which cover all the elements of an energy system. Source components are the ones that provide or consume any defined commodity, for instance, wind and solar power plants that generate electricity as a commodity.
Conversion components are the components that transform energy vectors or commodities, like traditional power plants that convert fuels into electricity.
Storage components store the surplus of a commodity to be used in a different time period of the analysis. Transmission components allow the exchange of commodities between the analyzed regions.
Finally, sink components absorb elements of the energy system that cannot be used by any of the other components, such as GHG emissions.
One of the main features of FINE is its high space-time resolution, with the advantage that since regions are represented as nodes, it can cover several regions and its interactions. This allows to consider the exchange of energy vectors and commodities throughout the analyzed regions, which increases the accuracy of the model. These regions can be defined both at country-level or at the level of subnational entities.
This exchange is done with the balance of generation and demand of commodities at the nodes (regions) and allowing the flow of commodities between the nodes.

Another remarkable feature of FINE is that it allows the use different levels for time resolution, being one hour the highest level of resolution. Regarding time-related features. It also allows the possibility of using time series aggregation on typical periods to reduce the computing time. [18]
Both the high level of spatial and temporal resolution previously described allows to tackle the resolution and complexity challenges discussed in chapter 2.4.
Considering that FINE aims to minimize the total annual cost of the energy system, techno-economic parameters, such as cost of investment (CAPEX), operational cost (OPEX), economic lifetime, commodities prices, among others, are assigned to each component of the system. This allows the model to compute the optimal capacities of the components, as well as the optimal exchange of energy and commodities between regions, in order to obtain a system with the minimal total annual cost.

2.6. Models currently used in the analysis of the European energy system

In the context of this thesis and trying to assess the level at which FINE addresses the aforementioned challenges, it can be compared to other frameworks and models that have been used to evaluate the evolution of electricity generation in the European energy system.
Following are some examples of these frameworks consulted for the development of this literature review:
Capros et al. [19] use the EU model PRIMES to create an outlook of the EU energy systems up to 2050. Deane et al. [20] evaluate the effect of electricity and gas interruptions on the EU energy system using PRIMES and PLEXOS (PLEXOS® Integrated Energy Model). Collins et al. [21] apply PRIMES and PLEXOS to show the impact of VRES on the operation of the European power system in 2030. Fragkos et al. [22] apply PRIMES and GEM-E3 (The General Equilibrium Model for Economy-Energy-Environment) to assess the impact of European Intended National Determined Contributions (INDC) on the energy system for 2050.
Henke et al. [23] use OSeMOSYS to evaluate the dynamic expansion of the power sector in Europe until 2050. Coppens et al. [24] evaluate if under the current policies the region of Wallonia in Belgium might achieve its GHG reduction target with the use of TIMES. Blesl et al. [25] uses TIMES to evaluate the effects of policies on the structure of European energy systems in 2020 and beyond.
Finally, Tröndle et al. [26] applies a model based on Calliope to evaluate the trade-offs between geographical scale, cost, and infrastructure requirements for a fully renewable energy system in Europe until 2050.
Table 2 shows a comparison between the main studies analyzed in this thesis, regarding the applied modeling framework, geographical scope and time resolution used for the analysis of energy systems. It can be seen that the different studies use a diversity of energy systems modeling frameworks, some of them focusing on partial equilibrium models like PRIME, or optimization models like TIMES; this difference arises mainly for the objective of each study, and it carries their respective limitations, as discussed before.
Considering the latter, they approach the application of policies differently, also, depending on their objective, having diverse cases like Tröndle et al. [26] where an ideal fully renewable energy system is studied, Capros et al. [19] which was the base study for the creation of the "clean energy for all Europeans" package, or Deane et al. [20] which mainly focuses on the distribution of electricity and gas.
Although all these models aim to analyze the evolution of the European electricity system under the energy policies established by the European Union, Table 2 shows that they diverge in terms of the model used geographical and temporal scope.
Geographically wise, most of the studies have a broad geographical scope, considering the entirety of the member countries of the EU, and some neighboring countries, which is a similar scope to the one considered in this thesis. The only remarkable exception is the study of Coppens et al. which has a focus on a single region inside Belgium.

Table 2. Comparison of selected models used for studies in the evolution of the European energy system.

Study	Model used	Type of model	Time resolution	Geographical scope
Capros et al.	PRIMES	Partial equilibrium	2015-2050 in 5-year steps	EU27
Deane et al.	PRIMES & PLEXOS	Partial equilibrium & optimization	2015-2050 in 5-year steps & 5 min-1 hour resolution	EU28
Collins et al.	PRIMES & PLEXOS	Partial equilibrium & optimization	2015-2050 in 5-year steps & 5 min-1 hour resolution	EU28
Fragkos et al.	PRIMES & GEM-E3	Partial equilibrium & general equilibrium	2015-2050 in 5-year steps	EU28
Henke et al.	OSeMOSYS	Bottom-up optimization	2015-2050 with 5 seasons per year, and one typical day per season	EU27, Switzerland, Norway & the UK
Coppens et al.	TIMES	Bottom-up optimization	1 year divided in 24 typical periods.	Wallonia, Belgium
Blesl et al.	TIMES	Bottom-up optimization	1 year divided in 12 time slices.	EU27, Norway, Switzerland & Iceland
Tröndle et al.	Calliope	Bottom-up optimization	1 year in 4 hours resolution	EU28, Norway, Switzerland & Western Balkans divided in 497 subnational regions
This thesis	FINE	Bottom-up optimization	1 year in 1 hour resolution, 40 typical periods.	EU28, Norway, Switzerland & Western Balkans divided in 108 regions

In terms of time resolution, Table 2 shows that partial equilibrium models have a longer time scope (several years) with different levels of resolution in terms of typical periods. On the other hand, most optimization models focus on a single year, in a similar way to the approach considered for this thesis, with different levels of resolution and considered typical periods.

In this sense, the settings used in this thesis are comparable to the others, having the highest resolution (one hour), but not the most detailed number of typical periods. However, since it applies the time series aggregation method, these settings provide a high level of resolution with a lower computing complexity compared to other studies.

2.7. Considerations for existing power plants in European energy systems models

Data is key for any energy systems modeling analysis. As such, the level of detail of data is the backbone for this thesis. Power plant location and capacity are the main data considered in this study, hence, they are the priority in terms of level of detail, as will be furtherly explained in chapter 3. Techno-economic parameters of the power plants, commodities price, and historic electricity generation are also important parameters considered for the optimization and analysis of results.

Analogously to the comparison done in section 2.6, it is relevant to compare the approach used for the data used between the different analyzed studies and the one used in this thesis.

Table 1 of the appendix 1 shows the comparison between the gathering approach given to the power plants data and an overview of the data sources used by the different studies. Regarding the approach, there are two categories of classification: brownfield in which the study considers the data of existing power plants, and greenfield in which the study does not consider existing power plants and uses technoeconomic parameters and generation data to perform the analysis.

Table 1 in the appendix 1 shows that most of the analyzed studies consider a brownfield approach, in a comparable way to this thesis, with just three studies considering the greenfield approach. It can be seen that as a general trend the studies that consider the brownfield approach tend to gather data from a wider variety and number of sources than the ones considering the greenfield approach.
Regarding the level of detail for the collected data, as shown in Table 1 in the appendix 1, varies between the different studies, in terms of number of data sources and the level of open-access data used.
For instance, Deane et al. [20] only considers the power plant inventory from ESAP SA and Platts, Henke et al. [23] gathers data from regional studies that are only partially public, and Tröndle et al. [26] obtains the data for hydropower exclusively from the JRC Hydro Power Database.
In contrast, and as further explained in the following chapter, the database of this thesis gathers information from a large number of sources, assuring a high level of reliability, which was additionally validated by the comparison with the officially reported capacities at country level.

3. Methodology

The structure of this thesis is composed of three parts related to the main tasks performed. In a first step, a geographical database of the power plants in Europe is created, validated with reference data, and contrasted with the reference information on electricity generation.
Secondly, an analysis of the European policies for the transition of the electricity generation sector for 2030 is conducted and different scenarios for the 2030 energy system are defined on this basis.
The final step is the setup of the model FINE in a European context, considering the outcomes of the first two steps into the settings of the model. As a result, the built model allows the simulation of the different scenarios making use of the created database.
In this section of the thesis an explanation of the methodology followed at each of the previously mentioned step is described.

3.1. Creation of the database

3.1.1. Geographical scope

The first step in the creation of the database is the delimitation of the scope to define the technical and geographical characteristics of the data to gather. Since the objective of the thesis is to analyze the transition of electricity production in Europe, it is crucial to first define which countries of Europe are considered in the study, since the boundaries of Europe are not always clearly defined.
The main reference for the definition of which countries to consider in the study are the Nomenclature of Territorial Units for Statistics (NUTS) of the European Union, with some specific exceptions. [27]
While Turkey is part of the NUTS, it is not considered in this thesis since most of its territory is in Asia and due to the increasing distancing between the policy agenda of Turkey and the European Union.
Lichtenstein also falls under the NUTS; however, it is not considered for this study because it does not have electricity generation plants. Finally, even though Iceland, and Cyprus are also considered in the NUTS classification, they were not considered in the study due to the level of isolation of the islands from the rest of Europe. Aside from Turkey and Lichtenstein, the overseas territories of France that fall under the NUTS are not considered either, since they are not connected to the European energy system.
As a result of these considerations, Table 2 of the appendix 1 shows all the countries considered in this study, alongside the abbreviation codes defined in the NUTS, which will be used in this thesis to refer to each country.
This selection allows a study of a continuous geographical extension, except from Monaco, Andorra, San Marino, The Vatican City, Bosnia & Herzegovina, and Kosovo, which are not considered under the NUTS.

An important consideration regarding the NUTS is that this nomenclature has different levels based on the number of regions in which each country is subdivided. There are four levels in total, NUTS 0 (28 regions – country level), NUTS 1 (108 regions – major socio-economic regions), NUTS 2 (242 regions – basic regions for the application of regional policies), and NUTS 3 (1166 regions – small regions for specific diagnoses).
For this study, the level considered is NUTS 1 since it is considered a sufficient level of detail and to minimize the computing time for the optimization.

3.1.2. Information contained in the database

The second step is defining the type of data to include in creating the database. The database aims to contain detailed information on power plants in Europe. As such, for this study a power plant is considered to be any infrastructure able to produce electricity and inject it into the European electricity network, that in turn falls into any of the territories of the countries described in the previous section. No threshold on minimum installed capacity was defined.
For each powerplant the following information is collected: identification (name of the plant), coordinates in the WGS84 format, type of plant (source of energy), and installed capacity in MW.
Since the category of type of plant depending on the source of energy is highly relevant for the subsequent analysis of the results of this thesis, it is worth to clarify these categories. The definition of the type of plant is subdivided in two categories: non-renewable sources, including hard coal, lignite, oil, natural gas, and nuclear power plants; and renewable sources including solar (PV), wind onshore, wind offshore, hydropower, and bioenergy power plants.
In order to perform the optimization, FINE considers the historical generation profile for solar and wind power plants. For that, an extra step must be added before setting up the model: the simulation of these profiles for each power plant in a simulation tool called RESKit (Renewable Energy Simulation toolkit). [28]
RESKit produces a time series with the information of solar and wind generation based on the technical features of the individual power plants, their location, and weather data for a particular year. Considering the latter, an extra set of information is gathered for solar and wind power plants to perform such simulation. For solar power plants, the extra data collected are the tilt angle and orientation of the panel; while for wind power plants are the height of the hub, the diameter of the rotor and the model of the turbine (when available).
The results from the RESKit simulation are subsequently used by the model, alongside land-eligibility analyses to create new renewable power plants for wind and solar energy. However, it is important to notice that this study does not make an exclusion the land that is already used by existing renewable power plants, hence there is the possibility that these new renewable power plants are built at the same location as existing power plants.
Finally, it is important to clarify that, since the objective of this study is to analyze the transition of the electricity production system by 2030, two databases are built with the previously mentioned information. A first database with the power plants with an active status by the end of 2021 (2021 study database), and a second database with the power plants with an expected active status in 2030 (2030 study database).

3.1.3. Database creation

Additional to the study database, a reference database is created with the objective of contrasting the data in the study database in order to achieve the greatest accuracy possible. The reference database contains the officially reported installed capacity by energy source for each of the 33 countries analyzed in this study. This information is firstly collected from IRENA's online data query tool IRENASTAT, and their Renewable Capacity Statistics 2022 report. [29] [30]
The latter is then contrasted with the information published by the European Union, the national governments of each country, the transparency platform of ENTSO-E, and the Power Reactor Information System from IAEA. [31]

On the other hand, the study database is built based on a structure that considers the information stated in section 3.1.2. The process of creation is roughly divided into four main tasks: collection, clean up, validation, and complementation. These tasks are performed in an iterative manner as shown in Figure 1, using Excel, SQL, and Python as data analysis tools. These tasks were performed several times, using different sources to complement the database.

These iterations can be classified into four consecutive levels: the first one coming directly from the sources of powerplantmatching (furtherly explained later in this section); the second level with sources from national statistics offices; the third level considers the information coming directly from Transmission System Operators (TSOs) and energy companies; and finally in the fourth level, information coming from other data projects or databases, especially the ones from the Global Energy Monitor and the detailed data on wind power plants from a commercial database called "The Wind Power".

Appendix 2 shows a more detailed description of the sources used for the creation of both the reference and the study databases. Additionally, appendix 3 shows a more detailed workflow on the process of the creation of the database.

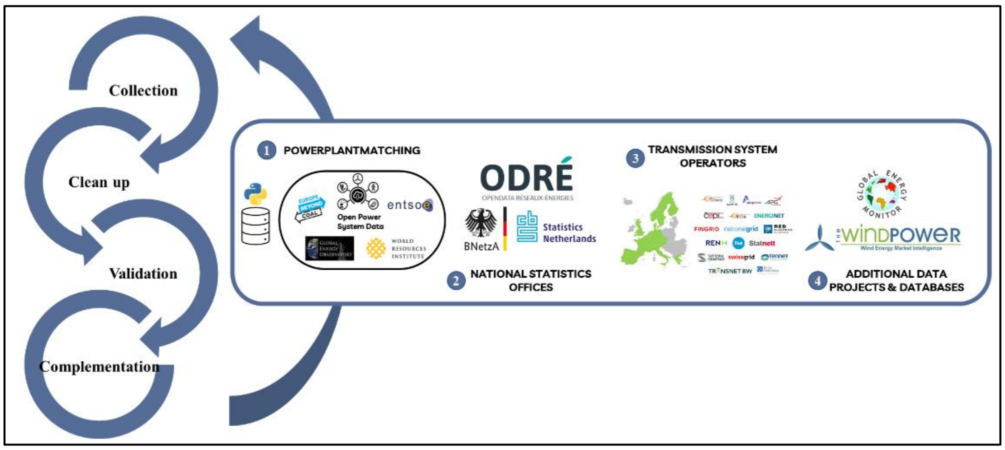


Figure 1. Summarized task flow followed for the creation of the study database.

The creation of such a detailed database does not come without major challenges. While member countries of the European Union share electricity generation data in line with the regulation on transparency of the electricity markets through the European Network of Transmission System Operators for Electricity (ENTSO-E), sometimes this data does not represent the total installed capacity officially reported by the country or lacks geographical accuracy.

Hence, gathering data from other sources, like private companies' reports, official government reports, or previous database open-source projects, is imperative. However, compiling and harmonizing a large dataset from various sources becomes a very manual and time-consuming task.

Fortunately, this is not the first study facing such problems, and there have been already several efforts to facilitate the process of collecting power plant data. One of the most relevant is the set of tools contained in the powerplantmatching library.

Powerplantmatching is a PyPSA (Python for Power System Analysis) based toolset for cleaning, standardizing, and combining power plant databases from the following sources: Europe Beyond Coal, ENTSO-E, Open Power System Data, Global Energy Observatory, and the World Resources Institute.[32]

Considering the latter, the first set of information used as a source in the creation of the database comes from using powerplantmatching. For that, the tool was run in Python considering the geographical scope and the information of interest for the study to create a first version of the database. It is important to clarify that in this step, the extra information for the simulation of solar and wind generation in RESKit is not included.

Following the task flow shown in Figure 1, this first version of the database was explored to clean it. This clean-up was done removing duplicates based on the exploration of the data looking for similarities in names, location, installed capacity, and the ENTSO-E code that is assigned to each power plant and that comes in the powerplantmatching database.
For the third step, the total installed capacity by source is contrasted with the reference database. With the first detailed version of the study database coming from powerplantmatching, this comparison against the reference database shows several differences in the total installed capacity as shown in Figure 2.
This first validation shown in Figure 2 was performed before the removal of duplicates, in order to have an initial idea of the differences with the data coming directly from powerplantmatching, and as such, still shows the excess capacity coming from these duplicates in fossil sources (hard coal, lignite, oil, and natural gas). For the following iterations the removal step is always done after the validation step.

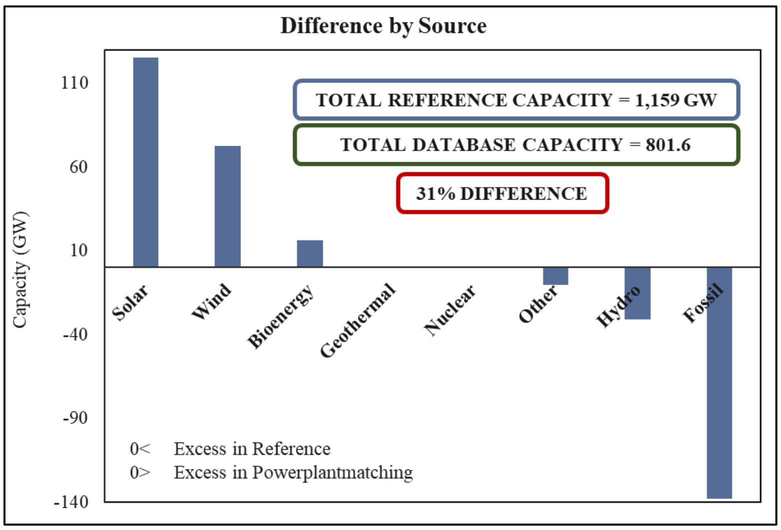


Figure 2. Difference in total capacity by source between the first version of the database coming from powerplantmatching and the reference capacities.

Figure 2 shows that this first version of the database, which just considers the information from powerplantmatching still has a large lack of information for renewable energy power plants. In total, these account for 31% of difference between the total installed capacity of the databases. This evidences the need to complement the powerplantmatching with information from other sources.
The final step of complementation aims to reduce this total difference, adding data from sources from national statistics offices, transmission system operators, and additional data projects or commercial databases, as shown in the task flow in Figure 1. This flow was performed several times until a difference lower than 5% was reached.
As previously mentioned, at this stage, the database does not contain the extra information needed for solar and wind plants. To assign an orientation for each solar power plant, in a first step, plants are classified as rooftop or open field plants based on the installed capacity.
Power plants with an installed capacity lower than 0.1 MW are classified as rooftop, based on the maximum typical power for rooftop-systems as stated by [33]. Plants with a larger installed capacity are classified as open field.
Based on this classification, the orientation of the panels for open field plants is considered ideal in all cases, i.e., facing south.
On the other hand, for rooftop plants, the database is randomly and evenly divided into three sets of same number of locations. For each group one of the following three orientations is randomly assigned: south, south-west, and south-east. The latter is done to consider an ideal case for rooftop,

but also contemplating that it is not always possible to face the panels directly towards the south in this type of plants.
Regarding the tilt angle, an ideal tilt angle for each country is considered, based on the data provided by Jacobson & Jadhav, and assigned to each power plant depending on its location. [34]
Regarding the detailed data needed for wind turbines, the hub height and rotor diameter for each location is obtained from "The Wind Power" data. However, for some locations, there are no specifications for these parameters. In these cases, using the available information, a correlation analysis is performed at country level plotting the hub height depending on the rotor diameter, or vice versa, depending on the information of interest, and using the tendency of the relation to compute the missing information.
Finally, the completed 2021 study database is used as a base for the creation of the 2030 database, with the implementation of two additional tasks. In a first step, the power plants with decommissioning date previous to 2030 are removed from the 2021 study database. Subsequently, new power plants are added to the 2021 study database; these additional power plants are the ones that are already planned or in construction for wind, open field solar PV, natural gas, and nuclear. This information comes mainly from the databases of GEM (Global Energy Monitor), The Wind Power, and IAEA (International Atomic Energy Agency).

3.2. Policies analysis

As a second major step in this study, the European policies described in the literature review (European Green Deal, Fitfor55, and REPower EU) are analyzed to define which objectives stated in these policies to consider in the definition of scenarios and setup of the model.
Since this study focuses on the transition of the electricity generation system, and after analyzing the content of the policy packages, three targets are considered for the setup of the model.
Renewable energy share in the electricity generation mix, reduction in natural gas consumption (with a focus on the objective of reducing the natural gas imports from Russia), and GHG emissions reduction.
A limiting condition is that FINE cannot directly implement certain targets, like the share of renewable sources, since it considers the techno-economic parameters of the system to compute the most cost optimal system. Hence it is not possible to define the share of electricity generation by type of plant. This can be indirectly controlled by the techno-economic parameters used in the setup of the system, which is tackled in section 3.3.
Nonetheless, it is possible to define limits on commodities input (import) from outside the system, enabling the direct application of the REPower EU policies on the limitation of gas imports from Russia, and the import and production of green hydrogen.
For the objectives in GHG emissions reduction, the model allows to limit them at country level or for a group of countries; however, in this study they are limited at country level, based on the objective stated in the NECP (National Energy & Climate Plans) of each of the country members of the EU and in the equivalent national strategies of the other analyzed countries. These targets as well as the ones for RE share at country level are shown in Table 3 of the appendix 1.

3.3. Model setup

3.3.1. FINE settings

The final step to obtain the results of this study is the definition of the settings to setup the model and their variations depending on the scenarios to analyze.
Five main categories of parameters to setup the model are defined: techno-economic parameters for operating (existing) power plants, techno-economic parameter for new power plants, commodities price, 2030 policy targets, and additional information. The detail on which parameters are considered in each category and the source for this information is shown in Table 3. More detailed information on the sources used for each parameter are provided in appendix 2.

Table 3. Parameters considered in the setup of FINE.

Category	Parameter	Source
Techno-economic parameters for operating power plants	OPEX per capacity	Danish Energy Agency (DEA), World Bank, Fraunhofer institute
	OPEX per operation	
Techno-economic parameters for new power plants	CAPEX (investment) per capacity	
	Interest rate	
	Economic Lifetime	
Commodities price	Commodities price in 2021	RepowerEU, World Bank, IEA, ENTSO-E, Statista
	Commodities price in 2030 (2021 forecast)	
	Commodities price in 2030 (2022 forecast)	
Emission factors	Default emission factor by type of power plant	CoM Default Emission Factors for the Member States of the European Union
2030 policy targets	GHG emissions reduction national target	National Climate and Energy Plans (NCEPs), Fitfor55 & REPowerEU
	Reduction of natural gas imports	
Additional information	Energy imports (electricity, hydrogen & natural gas)	Eurostat
	Electricity Demand	eXtremOS
	Hydrogen demand	FZJ – IEK-3*
	Techno-economic parameters of storage and transmission infrastructure.	FZJ – IEK-3*

**Information gathered by other members of the research group at IEK-3*

In the first category, the techno-economic parameters for operating power plants, two parameters are considered: OPEX per capacity (fixed cost) and OPEX per operation (variable cost). Table 4 in the appendix 1 shows the values considered for these parameters for each type of power plant.

For the techno-economic parameters of new power plants, in this study, FINE is set to create new power plants for just five types of plants: open field solar PV, wind onshore, wind offshore, natural gas, and hydrogen fueled power plants. The parameters considered in this case are the CAPEX or investment cost per capacity unit, the interest rate, and the economic lifetime. Table 5 in the appendix 1 shows the values considered for these parameters for each type of power plant.

The techno-economic parameters for both operating and new power plants are considered just at the level of type of plant, without differentiating between geographies.

For the third category of commodities price, it is important to highlight that due to the effect of the conflict in Ukraine at the beginning of 2022, the prices of several energy commodities, especially Natural Gas, saw a huge increase, and therefore, the forecast and estimations for all the energy commodities prices by 2030 that were previously done in 2021 are no longer valid. Table 6 in the appendix 1 shows both forecasts, with values coming from different sources.

The fourth parameter considered in the setup of the model are the emission factors for fossil power plants. These factors are defined for each type of power plant, and they are not differentiated between geographies either. The values considered are shown in Table 7 of the appendix 1.

Related to the previous category, the 2030 policy targets category considers the analysis described in section II. For the GHG emissions reduction, the values considered are the ones shown in Table 3 of the appendix 1; while for the reduction of natural gas imports, the values described in section I of chapter 1, in line with the European policies, are the ones used in this study, and they are assigned as limitation of gas imports specifically from Russia.

Finally, although this thesis has a focus on the electricity production infrastructure, the other elements of the energy system are also relevant for the model to solve the optimization problem. For this, additional information is added to the setup of the model: the electricity and natural gas imports, defined on the basis of historic data from Eurostat. Electricity demand coming from data of the eXtremOS project. [35] [36]
The values for hydrogen demand and the techno-economic parameters for storage and transmission infrastructure are provided by the information of projects from other members of the research group at the IEK-3 from FZJ. Specifically for these techno-economic parameters, the values used in the setup of the model are shown in Table 8 of the appendix 1.
Finally, it is worth to mention that two of the key parameters that the model uses to prioritize electricity generation from one source to the other are the commodities price for non-renewable sources and bioenergy, and the time series of generation obtained from RESKit for wind and solar. Nonetheless, there is no parameter to limit the electricity generation from hydropower; hence, to avoid an overestimation of electricity generation from this source, a maximum full load hours (FLH) of 2172 hours is defined in the setup of the model. This value of FLH is based on the average capacity factor of 25% for this technology in the 2021 status quo, shown in the analysis of chapter 4.2.

3.3.2. Definition of scenarios

In order to analyze the possible landscape of the European electricity production system by 2030, ten scenarios were defined based on the variation of the different parameters defined in the previous sections for the setup of the model. These scenarios and the considerations for each of them are shown in Table 4.
The first scenario, *2021 optimal cost*, aims to be used to finalize the validation of the study database, and to provide a comparison between the real status quo of the European energy system. The latter to also assess to which extend the model can reflect the real behavior of the electricity system.
The *baseline* scenario aims to be, as its name describes, a baseline for the comparison with the rest of the scenarios, considering the most recent commodities forecast, the creation of new power plants to satisfy the demand, and without considering any limitation in terms of emissions or gas imports.
The war in Ukraine has had an unprecedented impact on the European energy system, especially with its effect on commodity prices and as a driver of the implementation of new energy transition policies, such as REPower EU, as described in previous sections.

Table 4. Description of the considerations at each scenario defined in this study.

Scenario	2021 optimal cost	Baseline	No War			After War				
Sub scenario	-	-	Indifferent	Fitfor55	Ambitious	Indifferent	Fitfor55	Ambitious	Coal phase-out	Nuclear phase-out
Demand	2020	2030	2030	2030	2030	2030	2030	2030	2030	2030
Database	2021	2030	2030	2030	2030	2030	2030	2030	2030 – No coal PP	2030 – No nuclear PP
Commodities price	2021 Forecast	2022 Forecast	2021 Forecast	2021 Forecast	2021 Forecast	2022 Forecast	2022 Forecast	2022 Forecast	2021 Forecast	2021 Forecast
Natural Gas imports reduction from Russia	0 bcm	0 bcm	0 bcm	-116 bcm	-155 bcm	0 bcm	-116 bcm	-155 bcm	-116 bcm	-116 bcm
New RE plants	-	-	-	Allowed	Allowed	-	Allowed	Allowed	Allowed	Allowed
New NG plants	-	-	-	Allowed	-	-	Allowed	-	Allowed	Allowed
New H_2 pipelines & H_2 imports	-	-	-	-	Allowed	-	-	Allowed	-	-
H_2 production	-	-	-	Allowed	Allowed	-	Allowed	Allowed	Allowed	Allowed
Limit emissions	-	-	-	National targets	National targets	-	National targets	National targets	-	National targets

As such, the rest of the scenarios are classified into two main different groups, *No War* in which a situation without the effects of the war on commodities price is simulated, and *After War*, in which the commodities price forecast of 2022 is used.
For each of these groups, three sub scenarios are defined: *Indifferent, Fitfor55*, and *Ambitious*. The Indifferent scenarios consider a situation in which Europe becomes indifferent to the electricity infrastructure needs of the 2030 energy system. Hence, these scenarios use the 2021 power plant database, even if the demand is that of 2030. They also omit the implementation of any policy, reduction in gas imports or limitation in emissions.
The *Fitfor55* scenarios aim to simulate what would happen in a situation where the additional strategies stated in REPower EU are not implemented. In this sense it keeps the natural gas reduction objectives of 116 bcm from Fitfor55, and it also does not consider the import of hydrogen from outside Europe, even if it allows the use of technologies to produce and transform hydrogen.
In contrast, the *Ambitious* scenarios implement the increase on the natural gas reduction objectives stated in REPower EU to 155 bcm. Additionally, these scenarios do not allow the construction of new natural gas power plants to evaluate what an ideally ambitious transition would look like for the European electricity system.
Considering that Russia is currently the main provider of natural gas for the countries analyzed in this thesis, and that the policies of REPower EU aim to achieve independence from Russian gas. The latter reductions on natural gas imports in the model are assigned only to Russia. As such, these reductions represent 68% (116 bcm reduction) and 92% (155 bcm reduction) from Russian gas imports compared to the reference pick of 169 bcm of imports in 2019. [37]
Furthermore, two additional scenarios are defined based on the settings for the *Fitfor55 – After War* scenario but considering a total phase out of coal power plants and nuclear power plants.
The latter is to evaluate the effect that these hypothetical phase-outs could have in the European electricity system. The motivation to evaluate a phase-out from coal is that most of the countries in Europe are compromised to phase out coal by 2030, as shown in Table 9 of the appendix 1. While the motivation for the *Nuclear Phase-out* scenario is that countries like Germany or Belgium also have plans to remove this energy source from their electricity generation mix.

4. 2021 European electricity system analysis

This chapter focuses on the presentation of the different results obtained from the analysis of the information contained in the created database and its subsequent use to model the different scenarios for 2030 described in the previous chapter.
The chapter is divided into three parts: the first one shows the analysis done to validate the reliability of the study database, contrasting it to the reference data.
Having validated the database and showing the existing gaps in infrastructure towards 2030, the second part of this chapter tackles in more detail the current status of the electricity generation infrastructure throughout the 33 countries. This analysis highlights the main differences among the countries in terms of installed capacities and electricity generation. The data used in this analysis are the validated study database, and the reference data for electricity generation from Ember (British global energy think tank)[38].
In turn, the third section focuses on analyzing the renewable energy penetration in the European electricity generation system. It makes an emphasis on comparing the current status of renewable energy share against the 2030 targets established by each country at their NECPs. Especially focusing on the gaps that they need to fill in their electricity generation infrastructure to accomplish their objectives.

4.1. Study database analysis

As mentioned in the previous chapter, this thesis produced two sets of data with the installed capacity of electricity production plants, with both geographical and technical information. Figure 3 shows the total additional capacity by energy source, categorized by country, in the 2030 study database compared to the 2021 study database.

It can be seen that solar and wind, especially wind offshore are the energy sources which have the largest amount of capacity already planned or under construction expected to be online by 2030. This figure also shows the countries with the largest share on each source, being The UK and Ireland for wind offshore, and Greece and Spain for both wind onshore and solar. Additionally, there is already a large amount of capacity expected to be installed from natural gas, being the source with the largest amount of expected new capacity just after the aforementioned renewable sources. The countries that largely contribute to this increase in natural gas capacity are The UK and Italy.

Furthermore, there is an expected increase in the installed capacity also for nuclear power, even with the decommissioning of nuclear plants in countries like Germany, which is also reflected in the chart. Additionally, there is a net increase of 8.4 GW, mainly due to the Hinkley (3.26 GW) and Olkiluoto (two reactors of 1.6 GW each) plants under construction in The UK and Finland respectively.

On the other hand, a net decrease in the total capacity of coal sources can be observed, with a largest decrease on hard coal, this shows the planned decommissioning of coal power plants according to the phase out plans of several countries, as portrayed in Table 9 in the appendix 1.

It is also relevant to mention that although after the beginning of the Ukraine war in 2022, several countries recommissioned some already disconnected coal plants and planned to connect other plants in the following years; however, they all kept their coal phase out objectives, and they are planning to decommission all these additional coal power plants before 2030.

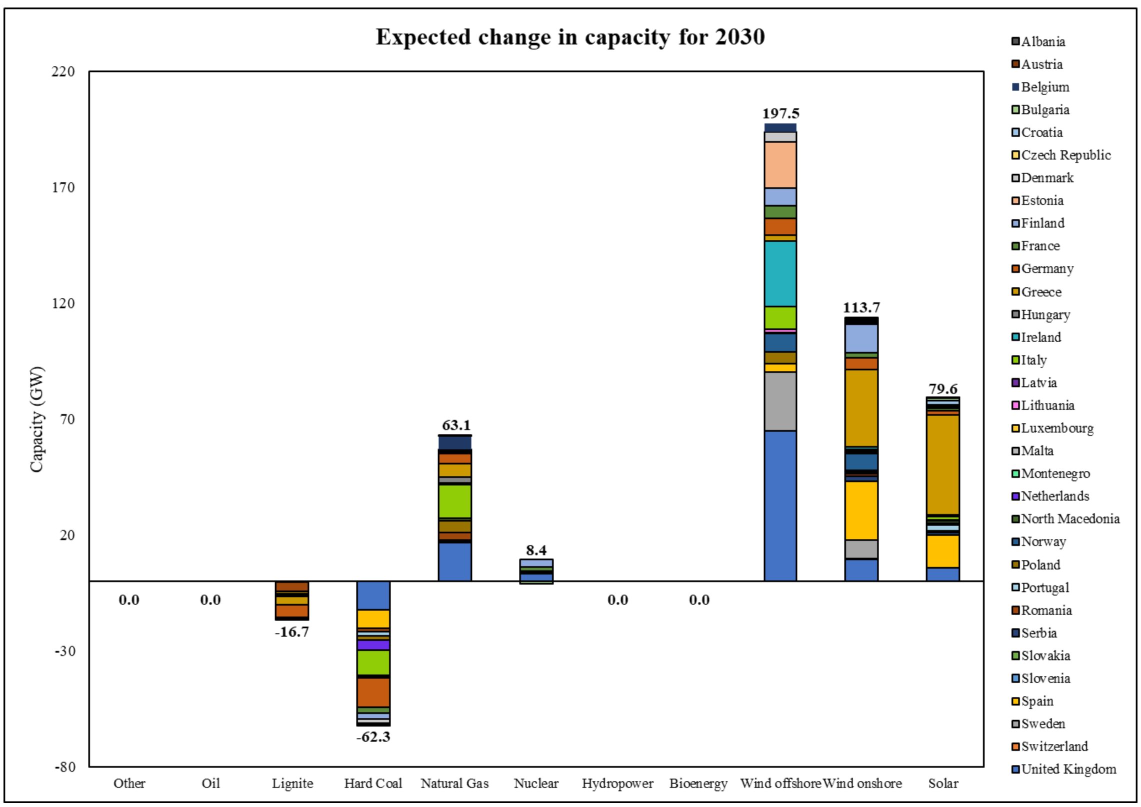


Figure 3. Expected change in installed capacity by source between 2021 study database and 2030 study database.

In order to ensure the reliability of the study database, and considering that the reference database contains information of 2021, the 2021 study database was explored and a comparison analysis with the reference data was performed.

Figure 4 shows the geographical location and proportional size (in terms of installed capacity) of the power plants of the 2021 study database, divided into two different categories: traditional sources (Figure 4 a & b), including nuclear, natural gas, hard coal, lignite, and oil power plants; and renewable energy sources (Figure 4 c & d), including solar, wind (not differentiating between onshore and offshore), bioenergy, and hydropower plants.

It can be observed that traditional power plants are present in a lower density than renewable energy sources, as can be seen by the difference in the population of points between Figure 4-a and Figure 4-c. In contrast, comparing Figure 4-b and Figure 4-d shows that traditional power plants tend to have a larger installed capacity, especially in the case of nuclear power plants.

In terms of geographical distribution, Figure 4-a shows an important presence of natural gas plants in western and central Europe, especially in France, Germany, Belgium, The Netherlands, and The UK, with also an important population of plants in Italy. Coal power plants are present in the whole analyzed region; however, they have a larger presence, especially for lignite power plants in eastern Europe and Germany. Regarding nuclear power, its predominance is clear in France with some other important plants in Spain, Belgium, Sweden, and the Czech Republic.

The geographical distribution of renewable energy sources can be clearly seen in Figure 4-c, due to the high number of plants distributed in the analyzed region. The presence of hydropower plants along the mountain ranges of the Alps and the Pyrenees is noticeable. Additionally, a predominance of hydropower can also be observed in Norway, Sweden, and Albania. Regarding bioenergy, the only important presence can be seen in France.

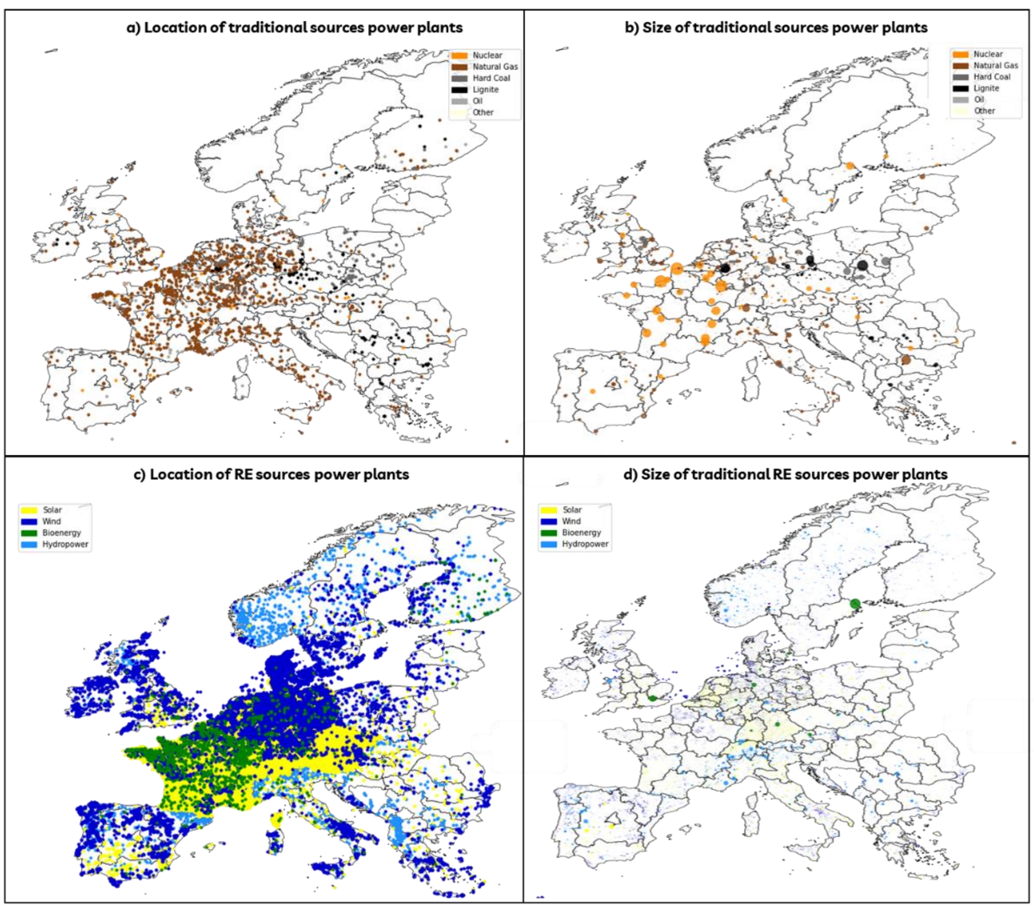


Figure 4. Location and size of power plants in the 2021 study database.

For the case of solar and wind plants, Figure 4-c shows that they are located all around the 33 countries analyzed, with a remarkable density in western and central Europe. In contrast eastern Europe, the north of the Scandinavian peninsula, and the Baltic countries show a low density of these type of power plants. The latter exposes the gap in wind and solar installed capacity between the aforementioned regions.

Especially for solar, its predominance can be seen in France, Germany, Switzerland, Austria, the Czech Republic, and the south of Spain; while for wind, there is a remarkable presence in central an northern Germany, the north of France, Ireland, The UK, Belgium, Netherlands, Denmark, the south of Sweden, eastern Romania, Greece, southern Spain and the south of Italy.

The previous analysis demonstrates that the study database contains a logical geographical distribution of power plants throughout the 33 analyzed countries and allows to further continue with the direct contrast of this database with the reference data.

Both data sets were compared based on the difference in the value that each of them has in total installed capacity. A positive difference means an excess of capacity in the study database, while a negative difference means a lack of capacity in the study database with respect to the reference database. These differences are analyzed by energy source and country level, as shown in Figure 5.

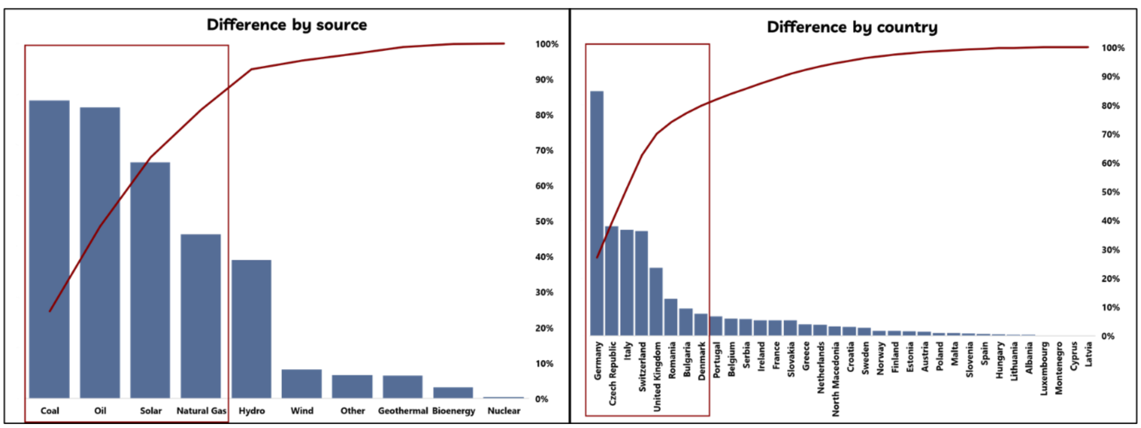


Figure 5. Differences between the study and reference databases.

The total installed capacity for electricity production in the 33 analyzed countries in the reference data was accounted for 1159 GW, while the total installed capacity under the same assumptions for the 2021 study database was accounted for 1203 GW, showing an excess of 4% compared to the reference. 80% of this difference is located in just 8 countries and related to 4 sources (coal, oil, solar, and natural gas), as shown in Figure 5. These can be explained due to the use of sources with very detailed data, such as the solar installations registered at the German MASTR (core energy market data register) database. It could also be plausible that although the duplicates were removed from the database, there are still some double values coming from duplicated power plants that are hard to recognize as such.

Nevertheless, this difference was considered acceptable since it is lower than 5% and would not reflect a major disruption in the accuracy of the results of the scenarios to be analyzed.

Additionally, a comparison analysis for the total installed capacity by each country at each database was performed with a correlation plot, as shown in Figure 6, each dot represents the correlation between the total installed capacity of each country in the study database compared to the total installed capacity of the same country in the reference database. Due to the large differences in the total installed capacity between large and small countries.

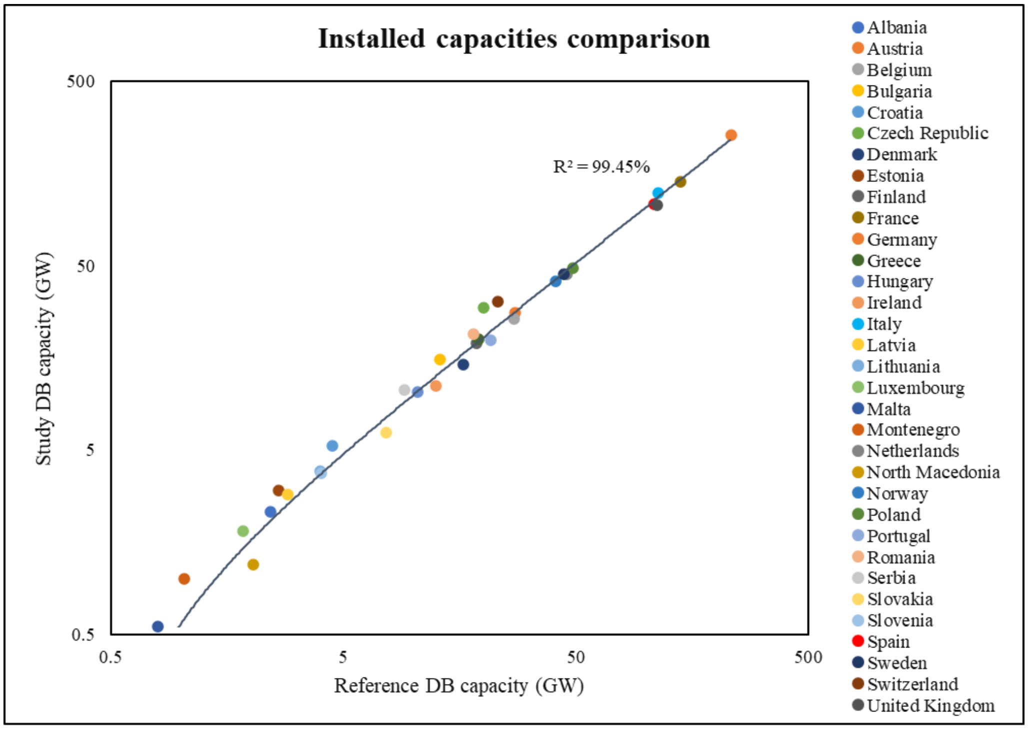


Figure 6. Correlation of installed capacity in study database vs reference database.

Most of the plotted data tends to alienate with the correlation line, which results in a correlation coefficient of 99.45%, confirming a sufficient level of reliability of the study database. An important remark is that the countries which deviate the least from the correlation line are the ones with the largest amount of installed capacity, contributing in this way to increase the correlation of the whole database with the reference.

A more detailed analysis at country level was performed, as shown in Figure 7, which exhibits the comparison of the study database and the reference database in terms of the geographical distribution and the share of installed capacity by energy source.

It can be observed that in general the geographical distribution is similar in both sets, having 80% of the installed capacity in eleven countries for both databases. These countries are almost the same in the two databases, apart from the last two positions: being Austria and Belgium for the reference database, and Switzerland and the Czech Republic for the study database. This can be explained by a combination of the differences previously explained and the fact that these four countries have a similar total installed capacity, all of them being around 24 and 28 GW.

It can also be observed that for most of the countries, the distribution of installed capacity by source is kept, which gives a good sign of the level of reliability of the study database.

Finally, it is of upmost importance to highlight that in this last aspect, the study database has a larger level of detail on the categories of sources, adding a differentiation between onshore and offshore for wind capacity, and between hard coal and lignite for coal; adding up twelve categories for the study database compared to nine in the reference database.

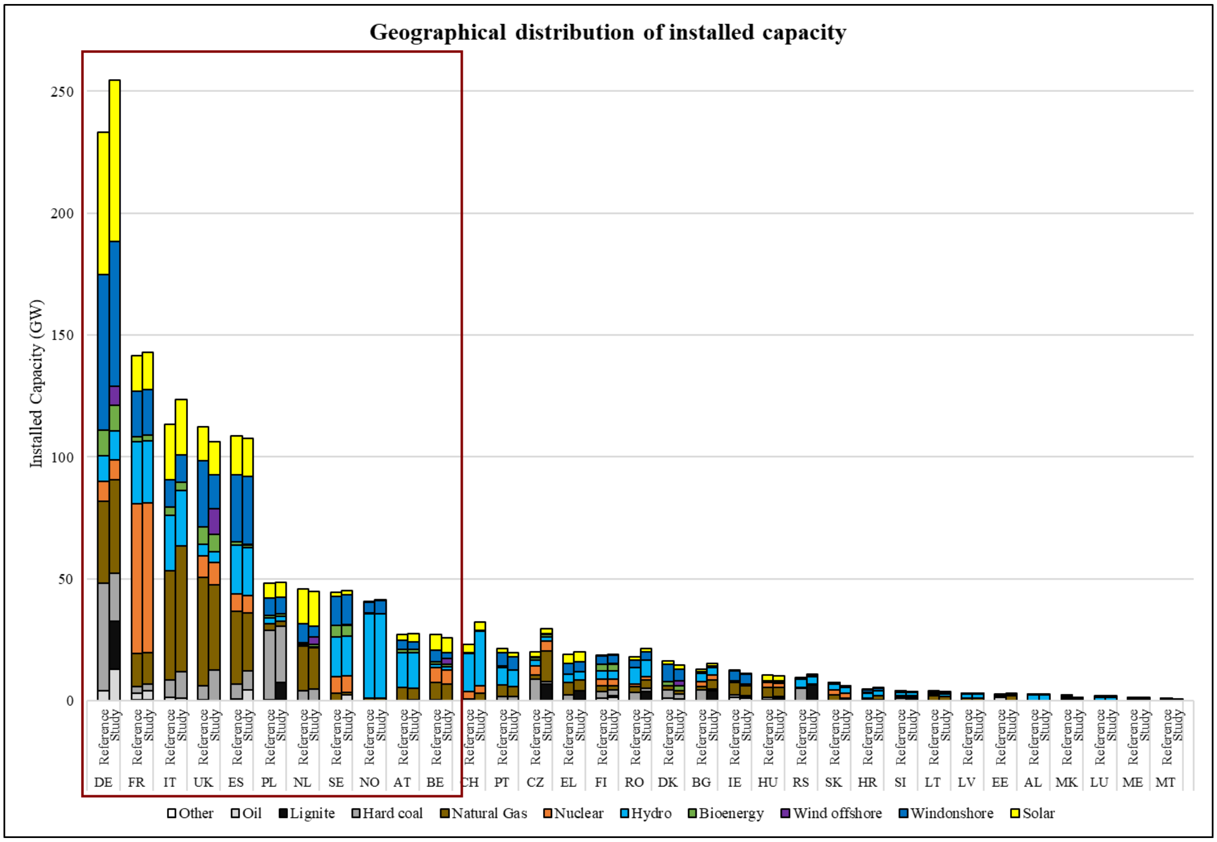


Figure 7. Comparison of the geographical distribution of installed capacity databases.

4.2. Study database and the European electricity generation: installed capacity vs electricity generation

Figure 8 shows the comparison of the share of generation and installed capacity by source for the cumulative of the 33 countries of the analysis. The chart shows that the share for each source is different in each mix, which exhibits that the installed capacity is not directly related to the generation. For the non-renewable sources of electricity, it can be observed that the share of installed capacity almost corresponds to a similar share of generation, especially for natural gas, hydro, and coal; the only major exception is nuclear, which just having 10% of the total installed capacity in the whole region of the 33 countries analyzed, it is the largest source of electricity generation, with 23% of the total annual generation in 2021.

In terms of renewable sources, hydropower, wind and solar are arguably the most relevant renewable energy sources in terms of penetration for the analyzed countries. Combined, they account for 52% of the total installed capacity in the study database, being the second, third and fourth sources with the largest share. Nonetheless, they fall behind in terms of generation share, accounting for a cumulative of 34%, all of them decreasing their share in the mix, with a remarkable decrease of solar from 16% in its share on the total installed capacity to just 5% in the total electricity generation.

The differences between the share of installed capacity and electricity generation for solar and wind evidences the infrastructure challenges of the European energy system on its path to decarbonization. Mainly because these differences show that to increase the renewable energy share in the electricity generation mix, a considerably higher share of installed capacity from these sources is needed. In turn, this means a higher need for investment on wind and solar infrastructure. Thus, it is relevant to analyze in further detail these differences and its possible causes.

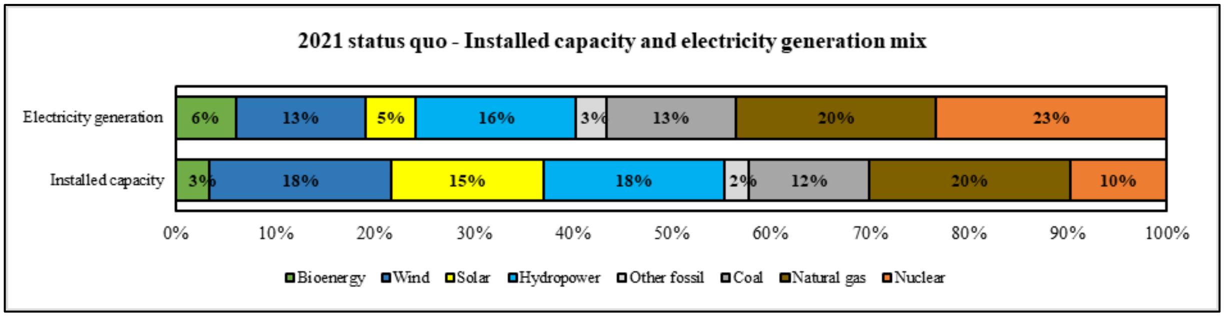


Figure 8. 2021 status quo mix for installed capacity and electricity generation for the 33 countries analyzed.

These differences between installed capacity and electricity generation could be explained by several reasons; however, the full load hours (FLH) come as a relevant indicator to analyze in order to explain this discrepancy. The full load hours allow to measure the degree of utilization of a power plant, and it refers to the time for which a plant would have to be operated at nominal power to generate the same amount of electricity as the actual generation in a defined period of time. FLH vary for different energy sources, due to the technical constraints that each of the technologies have to operate continuously throughout the year. This indicator can also vary on a geographical level due to different weather conditions, especially for wind, solar, and hydropower.

In turn, these full load hours allow to compute the capacity factor, which comes from comparing these hours to the total amount of hours in a year (8760), hence the capacity factor gives an indicator on the relative full load utilization of the power plants.

Figure 9 shows the distribution by country of the capacity factor value for electricity production power plants for each type of energy source.

It can be observed that nuclear energy is with great difference, the source with the highest average capacity factor among all the technologies, it also has a lower dispersion in country values compared to the other non-renewable sources.

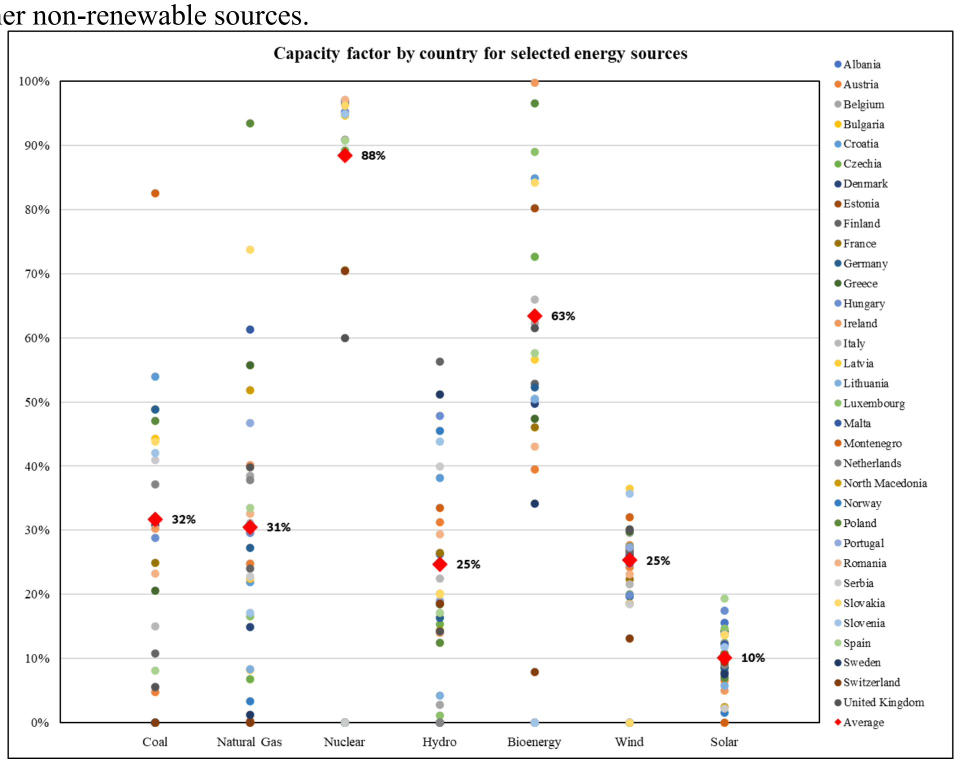


Figure 9. Capacity factor distribution by country for selected energy sources (2021 data).

This fact helps to explain previously mentioned shift of nuclear power from the third to last smallest source by share of installed capacity to the largest share source of electricity generation, since on average for 2021, nuclear power in Europe generated the electricity that it could produce at full load of its installed capacity for 88% of the year, three times more than most of the other energy sources.
For the rest of non-renewable sources shown in Figure 9, natural gas and coal, have a comparable average value of capacity factor, being around 30%, which could explain their similar values in the mix. As Figure 8 shows, for both sources, there is a one p.p. difference between their share in installed capacity and electricity generation, being positive for coal (with an average capacity factor of 32%), and negative for natural gas (with an average capacity factor of 31%).
Focusing on the renewable sources, both hydropower and wind, with average capacity factor of 25%, show a decrease in share between the capacity mix and the generation mix; however, this decrease is not abrupt being two p.p. for hydropower and four p.p. for wind.
Having comparable capacity factors for the last four mentioned sources (coal, natural gas, hydropower, and wind), and being these sources the ones with the lowest levels of discrepancies between their shares, it can be seen that an average capacity factor around 30% relates to a low level of variation between the installed capacity and generation shares of each source.
Following the analysis on renewable sources, it is noteworthy that having the second largest average capacity factor (63%), bioenergy is not among the main sources of electricity generation. This can be explained by the low levels of installed capacity for this source, and also by the dispersion (the largest among all the energy sources) of the capacity factor value among the different countries, as shown in Figure 9. However, it is relevant to highlight that even if in the whole mix, it does not represent a large share of electricity generation, it is double its share of installed capacity, being almost at the same level of share increase as nuclear power.
Proceeding the analysis, solar energy is with difference, the source with the lowest average capacity factor (10%), 15 p.p. lower than the second lowest (25%). This fact helps to explain the drastic change in the relevance of solar energy between the capacity mix and the generation mix, with a decrease of 11 p.p., the largest among all the analyzed sources.
It is also evident in Figure 9, that with the exception of nuclear, wind, and solar, all the other sources show a high level of dispersion in the capacity factor value for each country, showing that each technology faces different operational conditions and challenges in the different countries analyzed, which also can give an idea on the most suitable source for each country. However, it is important to highlight that the data shown represents just one year, hence the conclusions on the last point might be biased due to particular conditions in the energy market or weather for each country during 2021.
Finally, it is worth to mention that even with the lowest average value of capacity factor, both wind and solar are the sources with the smallest dispersion at country level, which could reflect the fact that these sources, as variable renewable sources, face similar challenges in terms of intermittence along all the 33 analyzed countries.

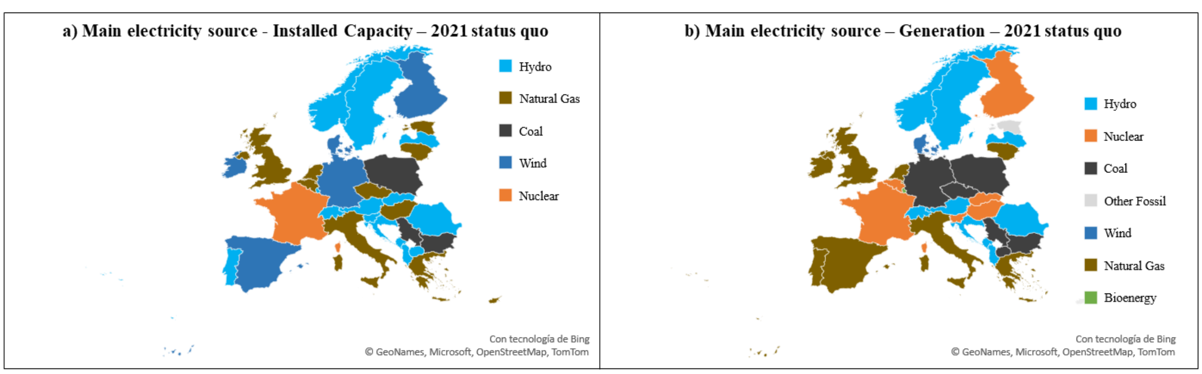


Figure 10. Comparison on main energy source for installed capacity (a) vs electricity generation (b) for the 2021 status quo.

Following this analysis on the differences between the installed capacity and electricity generation systems along the region of analysis, comparing the source with the largest share of electricity generation with the source with the largest share of installed capacity for each country in the region becomes a relevant matter to envision which countries might face more challenges to accomplish a transition to a decarbonized electricity production system.
As shown in Figure 10 several countries have a clean energy source as the main one for their installed capacity, with a remarkable majority of them having either hydropower or wind; natural gas is also a frequent main source for installed capacity, being so for ten countries in Europe. Coal is still the main source for the installed capacity of three countries: Poland, Serbia and Bulgaria, and finally just France has nuclear power as the main source installed.
As expected, based on the differences already highlighted with the information of Figure 8 and Figure 9, the picture changes substantially for the main source of electricity generation, being the two most common, natural gas and nuclear power. This shows that even countries that have a clean source as the one with the highest share of installed capacity, rely more on other less intermittent sources for their electricity generation. Even some countries with hydropower (a non-intermittent source) as main installed capacity source like Portugal, Slovakia, and North Macedonia, where hydropower is not the main electricity generation source. This can be explained by the low value in the capacity factor that these countries have for hydropower as will be more extensively discussed in the following section of this chapter.
It is also relevant to highlight that even with all the efforts that have been done in the recent years to phase out coal from the energy systems of the region, it is still the main source of electricity for six countries, and more importantly for Germany, the largest producer of electricity in the region, as shown in Figure 11.
As final comment on this matter, the cases of Denmark and Luxembourg are worth of mention, since they are the only two countries with renewables as the main source of electricity, with wind and bioenergy respectively.

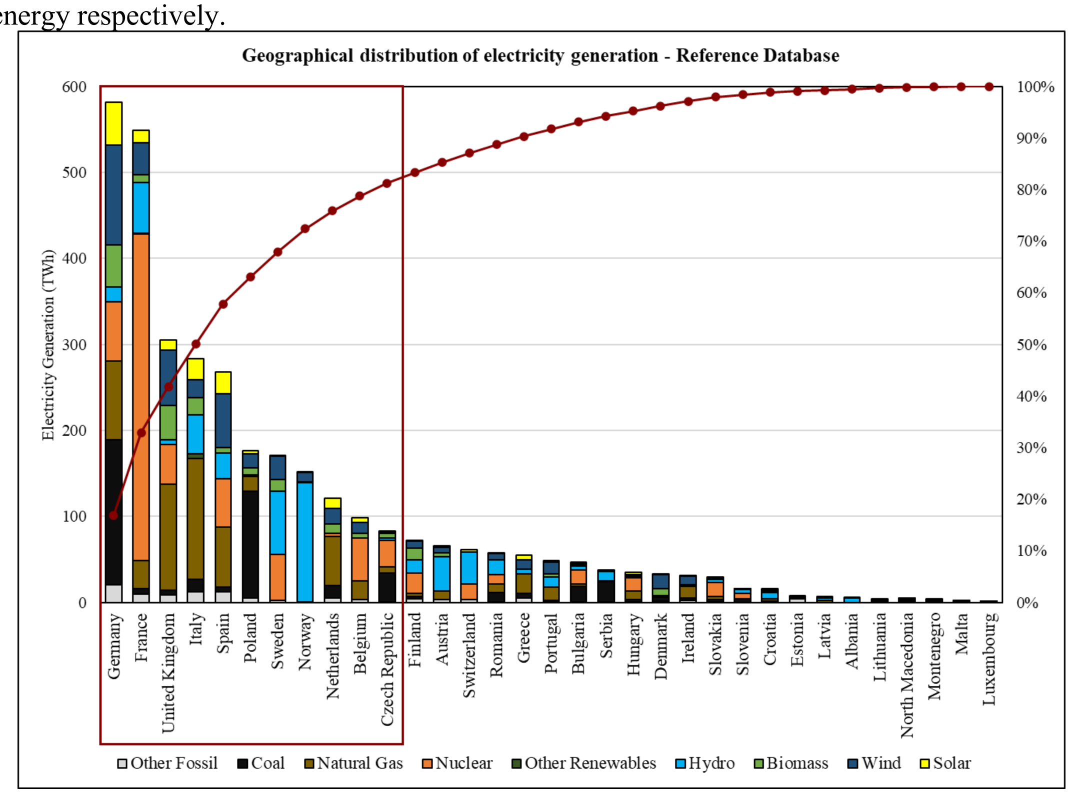


Figure 11. Geographical distribution of electricity generation in 2021 for the 33 analyzed countries.

4.3. Renewable sources in the European electricity generation: current status, 2030 perspectives and challenges

Following the discussion of the general differences in installed capacity and generation, an assessment of the current penetration of renewable sources can help to better understand the challenges that these countries face to accomplish the 2030 targets.

As discussed in the literature review, the European Union has set clear objectives for both reduction of greenhouse gas emissions and share of renewable energy in their electricity generation mix on its policy packages, mainly in the European Green Deal, and the subsequent scope expansion with the Fitfor55 package. These objectives aim to reduce the GHG of the EU plus The UK by 55% in 2030 compared to the reference level of 1990 and reaching a 42% share of renewables in the electricity mix; this last objective is furtherly expanded to 69% in the REPower EU package.

In order to achieve these objectives, the European Union has encouraged each of its country members to define National Energy and Climate Plans (NECPs) with clear individual targets to contribute for the latter regional objectives. In this section of the chapter, the individual targets for each country on renewable sources share in the electricity generation mix by 2030 will be contrasted to the current levels based on the 2021 data.

Most of the national targets on RE share are specified in the NECP of each country; however, for countries which are not members of the European Union, their national 2030 target was consulted on their respective national strategy for decarbonization.

It is worth to notice that these national targets are established based on the 42% regional target from the Fitfor55 package. After the release of the new objectives in the REPower EU package, the EU has encouraged the member countries to update their own national targets; however, at the date of the analysis done in this thesis, there are still no updated on the national objectives for almost any country. Hence, in this analysis, although the global objective of 69% is kept for the European Union, the other targets are just the ones established before the release of the REPower EU package.

It is also important to highlight that not all the countries consider the same energy sources in their renewable share target for 2030, some of them consider hydropower, and bioenergy, and some others just consider solar and wind. Table 10 of the appendix 1 shows the sources that each country considers on its target.

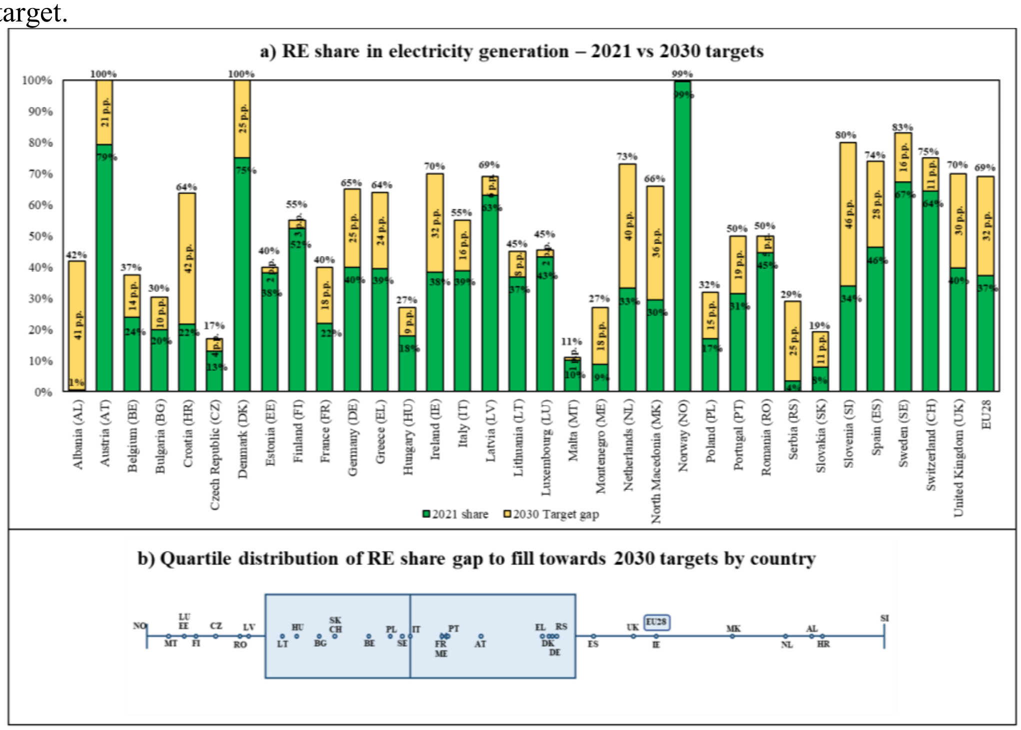


Figure 12. RE share in electricity generation in 2021 vs 2030 target at country level.

Figure 12 shows the current level of penetration of renewable sources, as defined in Table 10 in appendix 1, compared to the target for each country for 2030, highlighting in orange the gap that each country needs to fill to accomplish its objective.
It can be observed that the gap varies a lot in all the analyzed countries, showing that each of the countries face a different level of challenge to achieve its target. Figure 12-b shows the classification of the countries based on the quartile distribution of their gap to achieve the 2030 targets.
18 countries face gaps lower than the average gap value of 18 p.p., and they belong to the second, third, and fourth quartile of highest values, showing that these countries might not face significant challenges to achieve their objectives, especially those belonging to the third and fourth quartile.
On the other hand, 15 countries have to fill a gap higher than the average, among them, eight: Slovenia, Croatia, Albania, The Netherlands, North Macedonia, Ireland, The United Kingdom, and Spain will face major challenges to achieve their objectives considering that they belong to the first quartile of highest gap values among all the analyzed countries.
Even if more than half of the countries have gaps lower than the average, some of the countries which contributes the most to electricity generation are also the ones with highest gaps, such as The UK, Spain, The Netherlands, Germany, and France. This shows that Europe as a whole faces major challenges to achieve a decarbonized energy system, reflected by the gap of 32 p.p. to achieve the objective for the European Union.
The previous analysis highlights the efforts that must be done in Europe to tackle this challenging scenario of renewable energy penetration, more considering the high gap to reach the global EU objective of 69% share for electricity generation by 2030 stablished in the REPower EU package. [4], [6]

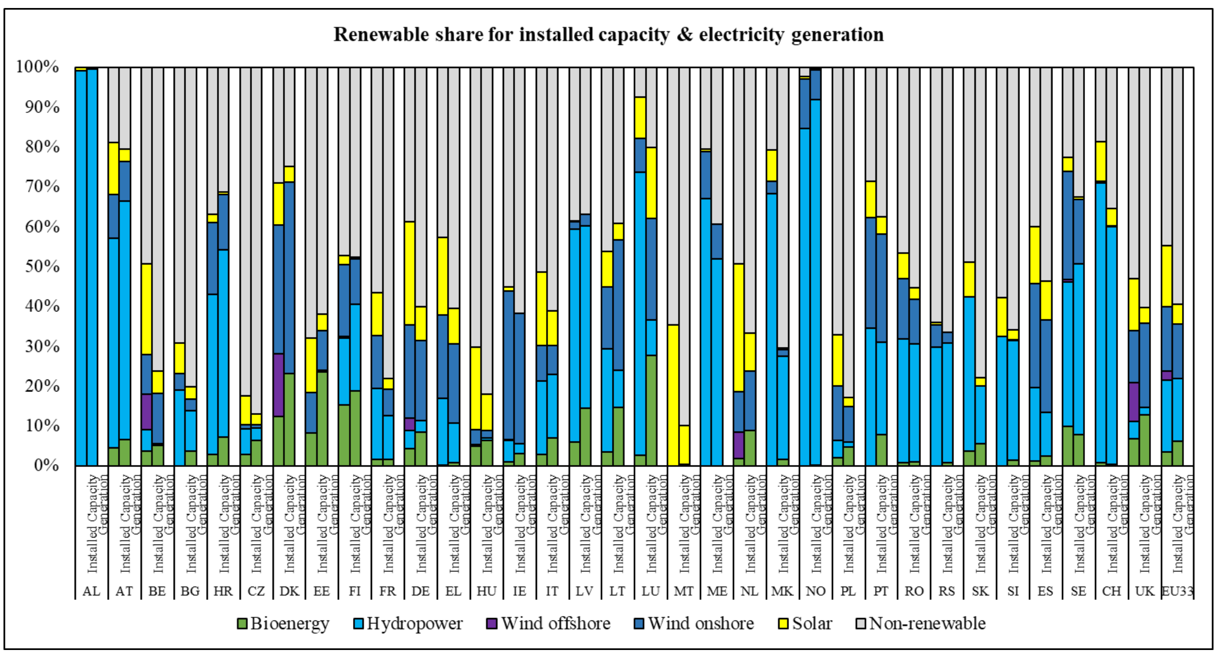


Figure 13. Comparison of renewable share for installed capacity vs electricity generation at country level.

Considering the differences highlighted in Figure 8 and Figure 10, an analogous analysis can be done focusing now on the renewable energy share at country level. Figure 13 shows the comparison between renewable energy share by source for installed capacity and electricity generation for each of the 33 analyzed countries and for the total set of countries (EU33). In this chart the sources considered as renewable are hydropower, bioenergy, wind, and solar.

It can be observed as a general trend that the renewable share in installed capacity is higher than its share in electricity generation, with the exception of seven countries: Croatia, Denmark, Estonia, Latvia, Lithuania, Albania and Norway.

The cases of Albania, Norway, Croatia and Latvia are easily explained by the predominance of hydropower in their mix and the high values of capacity factor they have for this technology. Albania and Norway have almost 100% share of hydro in both capacity and generation mix and have a hydropower capacity factor of 20% and 45%, respectively. Croatia has a 53% hydro share in its capacity mix, a 47% share in its generation mix and a 38% capacity factor. Finally, Latvia accounts for a 53% hydro share in capacity, 46% share in generation, and 20% capacity factor.

For Denmark and Estonia, wind and bioenergy represent the most relevant renewable sources, but the larger share of these sources in the electricity generation mix of these two countries could be mainly explained by the high value on capacity factor for bioenergy, and to a lower level in wind, that these two countries have. In the case of bioenergy Denmark has a capacity factor of 50%, and Estonia has an astonishing 80%; for the case of wind Denmark has a capacity factor of 26%, and Estonia 27% both larger than the 25% average value for this source.

The case of Lithuania is quite particular, having hydropower as the main renewable source of installed capacity (48% of all the renewable capacity), it would be expected that this source would have a similar relevance in the electricity generation mix, as the case of Albania, Norway, Croatia, and Latvia. However, with a hydropower capacity factor of 4%, one of the lowest among the analyzed countries, it just accounts for 15% of all the renewable generation. Still, Latvia has an overall larger share of renewable generation than renewable capacity, which more similarly to Denmark and Estonia, it could be explained by the value of capacity factor of 50% that it has for bioenergy.

Similarly to Latvia, there are several countries that even with a large share of hydropower in their capacity mix, the respective share for generation drops abruptly compared to the general tendency, all of them explained by the low values in capacity factor for this technology, such cases are Slovakia (20%), Portugal (19%), Spain (17%), Germany (16%), the Czech Republic (15%), Ireland(14%), North Macedonia (14%), Poland (12%), Belgium (3%), and Luxembourg (1%); which also helps to explain some of the differences observed in Figure 13.

For the rest of the countries, a similar tendency to the global (E33) picture, hence similar causes based on capacity factors, can be observed on the discrepancies of renewable share between the capacity and generation mixes.

Most of the countries with high levels of renewable penetration in both mixes have an important predominance of hydropower infrastructure, due to their high values for capacity factor for this source. This combination of high levels of penetration, and high value for capacity factor shows that the challenges on hydropower infrastructure are lower compared to other renewable energy sources in Europe.

The latter, in combination with the different definitions for renewable sources showed in Table 10 of the appendix 1 show that the gaps to achieve the 2030 target might also underestimate the real extend of the challenge in terms of RE infrastructure that Europe faces to achieve a decarbonized energy system. Thus, to better evaluate this challenge, a comparison on how the RE share in the installed capacity mix falls removing hydropower from the mix is highly relevant for this thesis.

Figure 14-a shows the comparison between RE penetration in the installed capacity mix with the RE definition used by each country for the 2030 targets. Figure 14-b shows the RE penetration using the same definition without considering hydropower in the RE mix. And Figure 14-c shows the share reduction after the comparison of both definitions.

In Figure 14-c, it can be seen that there are regions which show a larger decrease in the penetration of the RE sources considered in the 2030 target without the contribution of hydropower in the mix, being the Scandinavian Peninsula, the Alpine countries of Switzerland and Austria, Greece, Bulgaria, Romania, and Latvia the ones with the largest decrease, which makes sense considering the large amount of hydropower capacity that these countries currently have, as shown in Figure 4.

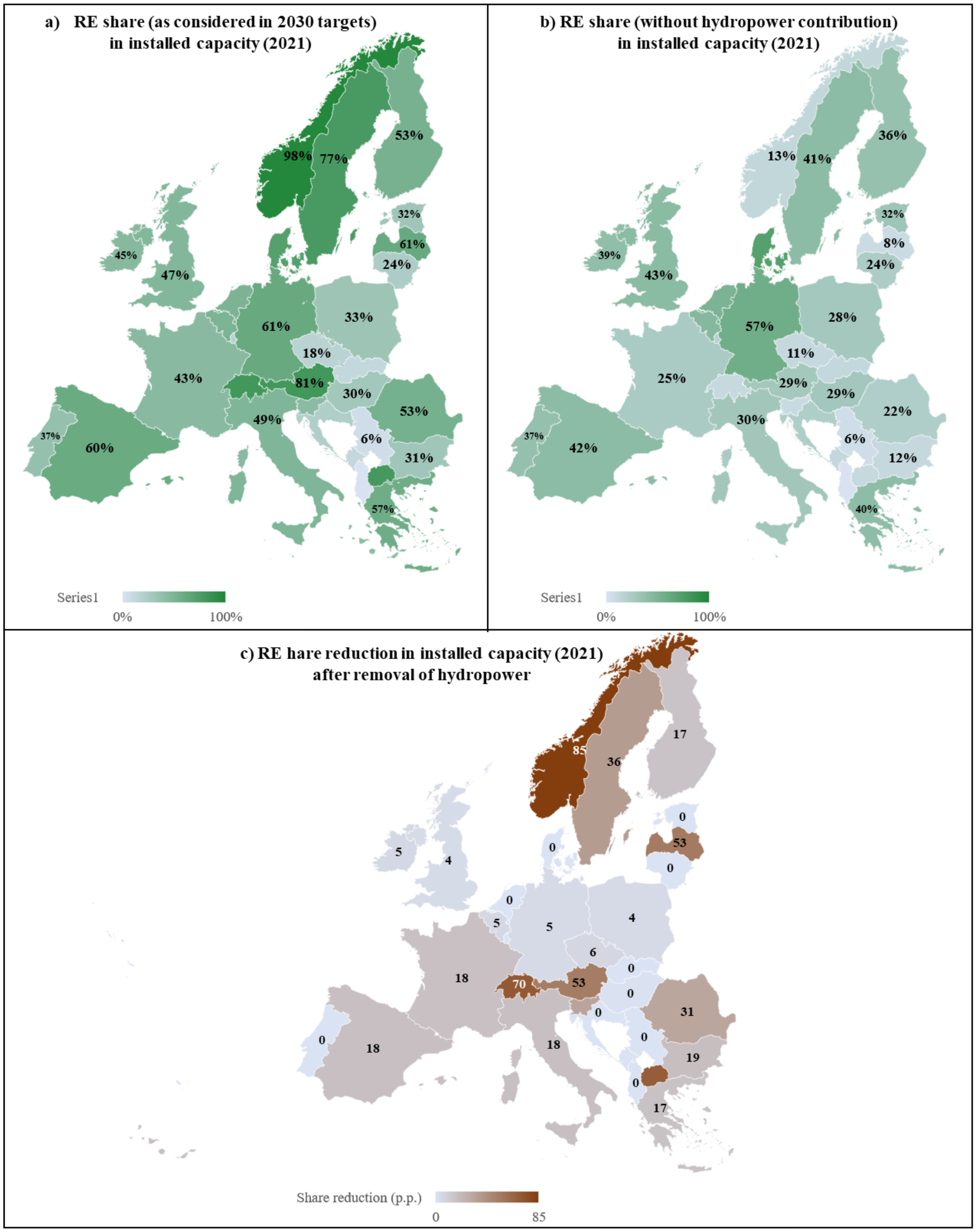


Figure 14. Comparison of RE share in installed capacity (2021) with and without the consideration of hydropower.

It is especially relevant to mention the cases of Austria, Latvia, North Macedonia, Switzerland, and Norway, since all of them face a decrease of more than 50 p.p. on the RE share without the consideration of hydropower.

This reflects that while some of these countries might not face many problems to achieve their 2030 targets on RE penetration, having already high levels of RE share in their mix and comparatively small gaps compared to the target, especially for Norway, Switzerland, and Latvia, they rely heavily on hydropower infrastructure for that.

In cases of extreme droughts or heat weaves, which according to the European Environmental Agency are expected to increase with global warming [39], these countries would turn to non-renewable sources if they do not manage to develop their renewable infrastructure in the coming years. This shows that the reliance on hydropower to achieve the 2030 targets could be damaging to the decarbonization of the European electricity system.

The case of North Macedonia and Austria is even more relevant, considering that they have larger gaps towards their 2030 objectives, with 36 p.p. and 21 p.p. respectively.

Sweden, Slovenia, Romania, Bulgaria, Italy, Spain, France, Greece, and Finland show a moderate relevance of hydropower in their RE share in the capacity mix with values between18 p.p. and 44 p.p. for the difference in the comparison of Figure 14.

The Czech Republic, Ireland, Belgium, Germany, Poland, The UK, and Hungary are the countries with the lowest decrease on the RE share in this comparison, with a value lower than 5 p.p., reflecting the low level of relevance of hydropower in their mix.

Finally, the countries which face no change in their RE share in the comparison of Figure 14, are the ones that already discard hydropower in their 2030 targets. Even if this shows that these countries prioritize the improvement of wind and solar infrastructure to achieve their 2030 RE share objectives, this does not mean that they don't need a major effort on it. For instance, Albania, Croatia, and The Netherlands do not consider hydropower in their 2030 target, but at the same time they belong to the group with the greatest gaps.

Based on the information of Figure 14 and combining it with the gaps shown in Figure 12, the 33 countries were classified in three groups, with respect to the level of challenge on the investment on wind, and solar infrastructure they might face to achieve their targets: high level of challenge (H), medium level of challenge (M), and low level of challenge (L). This will be a useful classification for the following section of this chapter.

This classification was done based on a factor defined based on the value of two variables: the decrease in percentage points between the RE share considering hydropower or not, and the existing gap towards 2030 targets. A value of one to four was assign to each country for each variable depending on the quartile of highest values to which it belonged, being four for the highest quartile.

Then each country was assigned to the H category if it had a factor higher or equal to seven, to the M category if it had a factor between four and six, and as L if it had a factor lower than three. There is just one exception to the previously described methodology, for the countries which already do not consider hydropower in their 2030 targets, the classification was done based just on the quartile to which they belonged in terms of their gap to achieve the RE share targets.

Table 5 shows the assigned classification to each of the 33 analyzed countries.

The current low values in capacity factor for wind and solar, and their low penetration in the current European electricity show that to achieve the 2030 targets there is a major need for investment on infrastructure from these sources.

Hence, and considering all the analysis performed in this section, it is clear that at the moment Europe has a long way to achieve a decarbonized energy system in line with the 2030 targets, as such, the analysis of different scenarios in the following section of this thesis, dives into the perspectives towards 2030 in order to assess the challenges and the possible approaches to consider for energy infrastructure to reach the objectives.

Table 5. Classification of countries based on the level of challenge they phase to accomplish the 2030 RE share target.

	Low level of challenge (L)	Medium level of challenge (M)	High level of challenge (H)
Countries	• Belgium • The Czech Republic • Estonia • Finland • Hungary • Luxembourg • Malta • Poland	• Bulgaria • Denmark • France • Germany • Greece • Ireland • Italy • Latvia • Lithuania • Montenegro • Norway • Portugal • Romania • Serbia • Slovakia • Sweden • Switzerland • United Kingdom	• Albania • Austria • Croatia • Netherlands • North Macedonia • Slovenia • Spain

5. 2030 scenarios analysis

As described in chapter 3.3.2, ten scenarios of the European electricity system were modeled under different conditions to assess the transition of electricity production infrastructure under the framework of the Fitfor55 and REPower EU policies packages.

In order to organize the discussion of the results obtained from these scenarios, and to be able to relate this analysis to that of chapter 4, this chapter is subdivided into five sections: *2021 optimal cost* scenario, installed capacity landscape, installed capacity vs electricity generation, electricity cost, and assessment on 2030 targets.

The first section briefly discusses the results of the optimal cost scenario for the 2021 electricity system in comparison to the status quo.

The installed capacity landscape section tackles the comparison of the electricity production infrastructure among the different scenarios and the 2021 status quo.

Subsequently, the third section makes an analogous analysis to the one performed to the 2021 status quo in chapter 4.2, comparing the installed capacity to the electricity generation among the results of all the 2030 scenarios.

The fourth section discusses three aspects: the investment on renewable energy infrastructure, the total cost of electricity production for the whole European system, and finally the electricity cost for the 108 regions analyzed in this study.

Finally, the section of assessment on 2030 targets analyzes the extension in which the policies targets are achieved in the different scenarios. Specifically, those of hydrogen production and imports, and renewable energy shares.

5.1. *2021 optimal cost* scenario

As stated in chapter 2.4, energy systems models still face challenges to represent real systems, hence it is relevant to assess to which extend the model used in this thesis can represent the current status quo of the European electricity system. The *2021 optimal cost* scenario aims to provide the information to do this assessment.

The *2021 optimal cost* scenario models the behavior of the current European electricity system considering the 2021 demand and using the 2021 study database. Following, the resulting system from the cost-optimization performed by the model is compared against the 2021 status quo discussed in chapter 4.2. Figure 15 shows the comparison between the total installed capacity by country in the 2021 status quo and the total installed capacity used by the model for the resolution of the *2021 optimal cost* scenario.

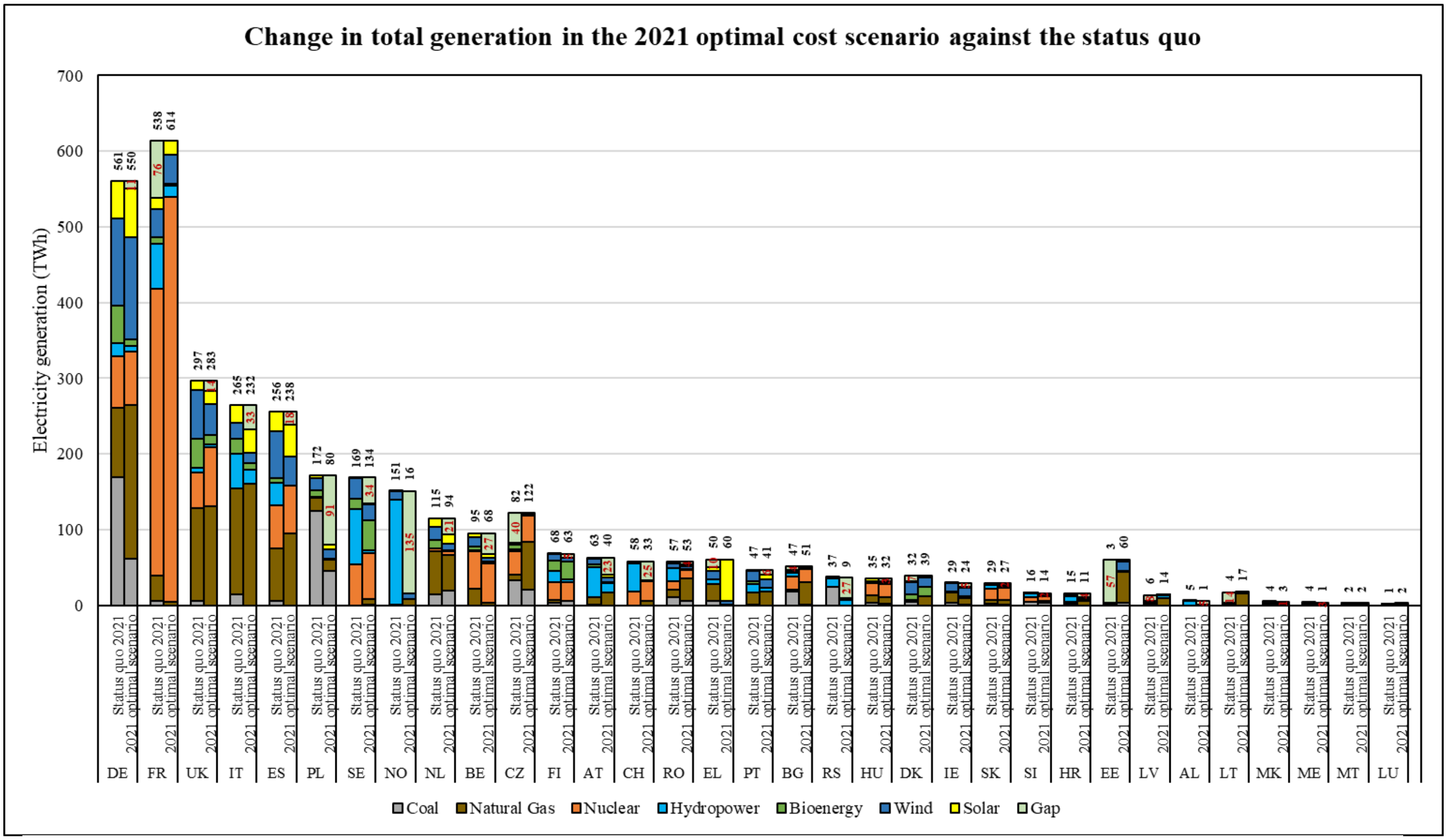


Figure 15. Change in total installed capacity by country between 2021 optimal cost scenario and 2021 status quo.

It can be seen that for most of the countries in the analysis, the optimal cost scenario has a lower installed capacity, with the exception of Greece and Estonia.

For these countries the model uses a larger installed capacity, especially of solar for Greece and wind and natural gas for Estonia.In a similar way, for the rest of the countries the model prioritizes the use of capacity from renewable sources, reducing the capacity used from other sources, especially from hard coal and hydropower. The reduction on hydropower capacity is explained by the default maximum FLH defined for this electricity source, as explained in chapter 3.3.1.

In the case of hard coal, its use is reduced in most of the countries, with the largest reduction in Poland, Germany, The United Kingdom, Italy, and Spain. In opposition, The Netherlands keeps a similar level of hard coal use, and it reduces the use of wind offshore, resulting in almost the same level of installed capacity (2 GW difference) between the status quo and the optimal cost scenario.

In the case of nuclear power and natural gas, the total capacity used for both sources is kept at the same level in both the status quo and the optimal cost scenario.

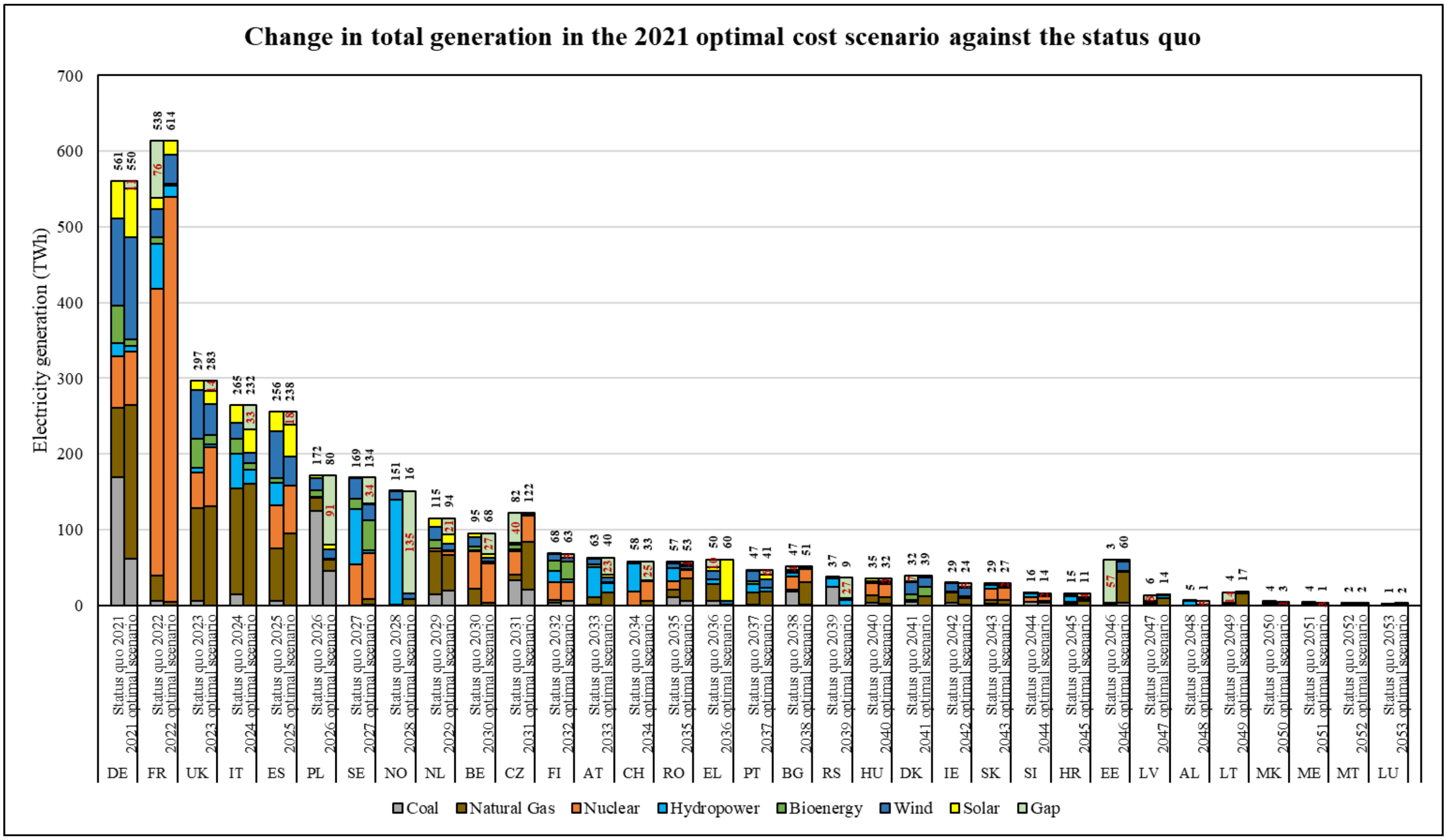


Figure 16. Change in electricity generation by country between 2021 optimal cost scenario and 2021 status quo.

Similar to these differences on installed capacity, Figure 16 shows the change in total generation of the *2021 optimal cost* scenario in comparison to the status quo.

In terms of electricity generation, the differences between the optimal cost scenario and the status quo are overall lower compared to the capacity differences. This is because ultimately the electricity demand is the same in both cases.

Nonetheless, some countries still have high differences in electricity generation, such as France, Poland, Norway, Sweden, Italy, Belgium, The Czech Republic, and Estonia.

These countries can be classified between the ones that have a gap on electricity generation compared to the status quo, especially Norway, Poland, Sweden, Italy, Belgium; and those who have an excess of electricity generation compared to the status quo, such as France, The Czech Republic, and Estonia.

Regarding the first group, the country with the largest difference is Norway due to the reduction on hydropower capacity caused by the 25% capacity factor assumption.

And since Norway does not have significant infrastructure from other sources, the lack of hydropower infrastructure causes that in the *2021 optimal cost* scenario it unable to generate electricity to the same level as in the status quo.

The latter is especially evident in Norway due to the high share of hydropower in its current electricity generation mix (almost 100%). However, the limitation of hydropower capacity factor causes a similar result in other countries with high shares of hydropower, such as Sweden, Austria or Switzerland.

The second country with the highest deficit on electricity generation in the *2021 optimal cost* scenario is Poland. This is explained by the reduction on the use of hard coal infrastructure shown in Figure 15. In turn, it is relevant to mention that even with this reductio, the fact that it keeps the same level of lignite infrastructure use causes that coal remains as the source with highest generation share.

On the other hand, electricity generation from France increases in the optimal cost scenario compared to the status quo, especially from nuclear power. This shows that even with a lower installed capacity France can generate even more electricity due to the high value of capacity factor that nuclear power has in this scenario (99%); as shown in Figure 17.

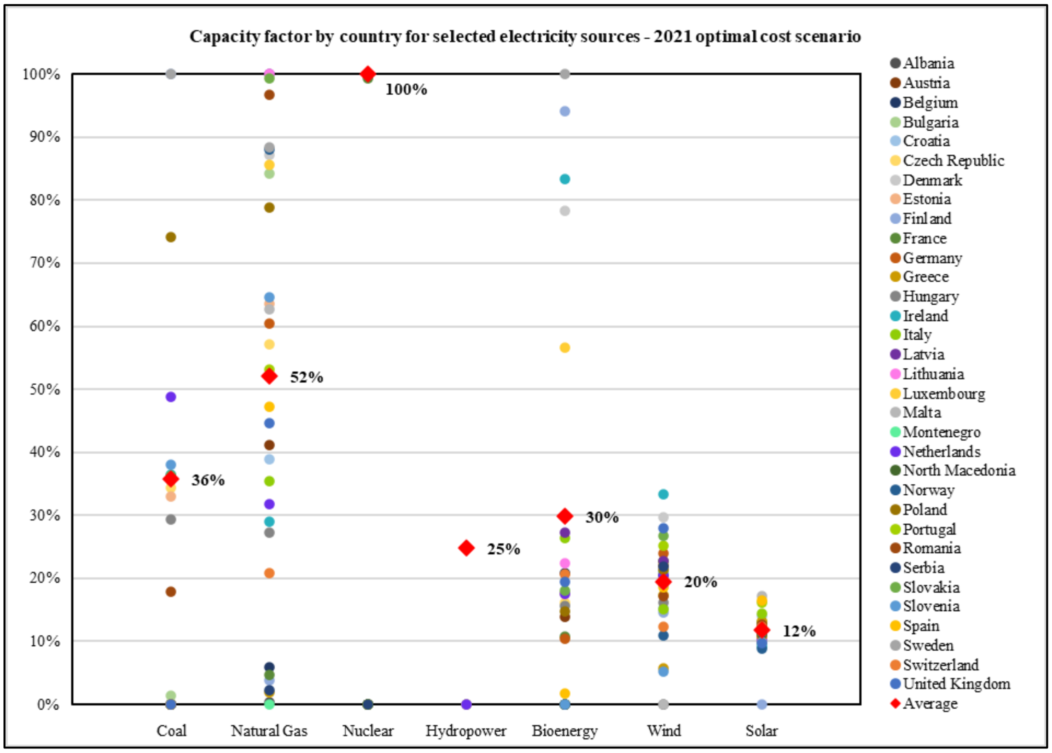


Figure 17. Capacity factor distribution by country for selected energy sources (2021 optimal cost scenario).

Likewise, The Czech Republic generates 40 TWh extra of electricity in the optimal cost scenario compared to the status quo, even with similar levels of installed capacity. This can be explained also by the increase on the value of capacity factor of natural gas for The Czech Republic in the optimal cost scenario (57%). Estonia has the largest excess of electricity generation in proportion to the total generation in the status quo, having an increase from 3TWh to 57TWh.

This excess of electricity generation in the latter countries comes to compensate the gaps from neighboring countries, making use of the transmission infrastructure given to the model. The latter is notably important for the case of Estonia, which produces such an excess of electricity to compensate the big gap of the neighboring countries of Sweden and Norway.

The case of Estonia and Norway show that the reduction on hydropower infrastructure (caused by the 25% capacity factor assumption) in countries that heavily depend on this source in the status quo has a direct impact on the electricity generation system of neighboring countries.

As shown by the latter results the capacity factor of the energy sources that the cost optimization of the 2021 European generates has an important impact in the behavior of the system.

In the cases of France, The Czech Republic or Estonia, their main electricity source has a high value of capacity factor. For these cases, this capacity factor value is higher than the average value in the status quo shown in Figure 9. 99% for nuclear power in France vs 88% average in the status quo; and 57% and 64% for natural gas in The Czech Republic and Estonia respectively vs an average capacity factor of 31% for this source in the status quo.

Figure 17 shows the distribution of the capacity factor by country for each source of electricity for the *2021 optimal cost* scenario. This shows an increase in comparison to the status quo, of the average capacity factor for all 33 analyzed countries for most of the electricity sources, apart from bioenergy and wind.

Finally, it can be observed that the distribution of values among the analyzed countries is similar to the one in the status quo, keeping in general the electricity generation behavior at country level.

There are two major exceptions to this: nuclear power, in which the capacity factor for all the countries where this source is present increases almost to 100%; and hydropower. Except for the specific cases discussed previously, most of the other countries have similar values to the average due to the maximum capacity factor assumption.

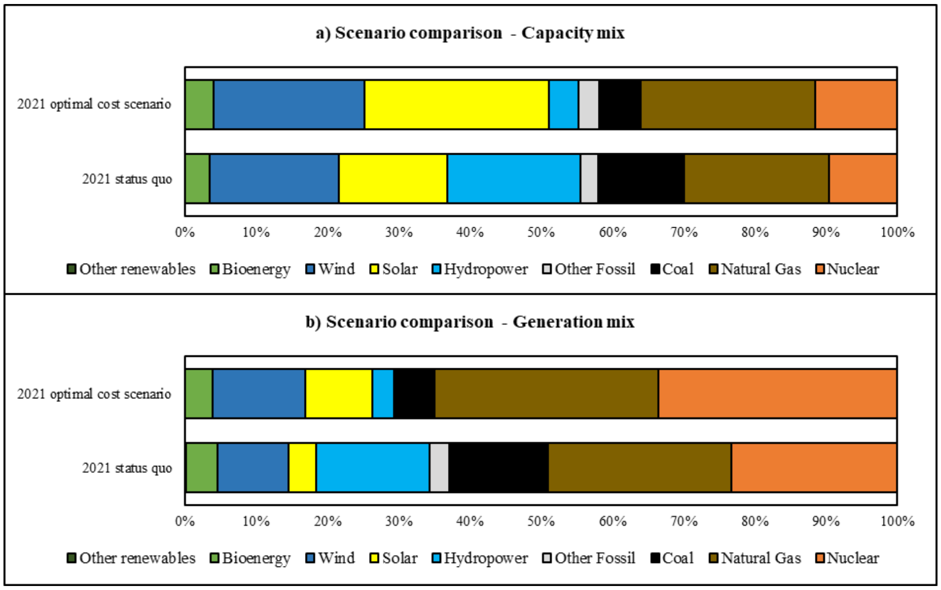


Figure 18. a) Total installed capacity mix comparison. b) Total generation mix comparison

Considering all the previous differences between the *2021 optimal cost* scenario and the status quo, Figure 18 shows the capacity and generation mix for the whole European electricity system (33 analyzed countries) in the *2021 optimal cost* scenario compared to the 2021 status quo.

In terms of installed capacity it can be observed that hydropower is the source with the largest reduction in the optimal cost scenario compared to the status quo, caused by the applied limit in FLH. This causes an increase of all the other sources but lignite.

The lack of hydropower infrastructure is mainly compensated by a larger share of solar energy, as such, in the *2021 optimal cost* scenario, it becomes the source with the largest share of installed capacity with 26% compared to 16% in the status quo.

Wind is also faces an increase in its shar, from 18% to 21%, nonetheles it keeps on staying as the source with the third largest share.

Even if natural gas is displaced as the main source for installed capacity, it increases its share from 21% to 24%, staying as the second main source.

For the electricity generation mix, Figure 18-b shows that both nuclear power and natural gas remain to be the two main sources in the mix, but for the case of the *2021 optimal cost* scenario, their presence in the mix is more important, accounting together for 65% of all the electricity produced.

On the other hand, the relevance of hydropower and coal as electricity sources for generation is drastically reduced by 13 p.p. 8 p.p. respectively, as an effect of the similar reduction of their share in installed capacity.

The case of solar is different to the other sources: even if this source has an 11 p.p. higher share of installed capacity in the optimal cost scenario, its share in generation increases just 4 p.p. from 5% to 9%. This difference in the share change of solar is logical due to the comparatively low average value of capacity factor of this source.

As it can be observed, the optimization done by the model in this scenario has a significant effect on the total mix of both installed capacity and generation in the whole picture of the 33 countries. But, at country level, it also has a major impact as shown in Figure 19.
In Figure 19-a&c, it can be observed that in the optimal cost scenario, solar has a larger relevance as main installed capacity source along Europe, displacing wind as main source in Spain and Germany, and hydropower in Croatia and Greece.

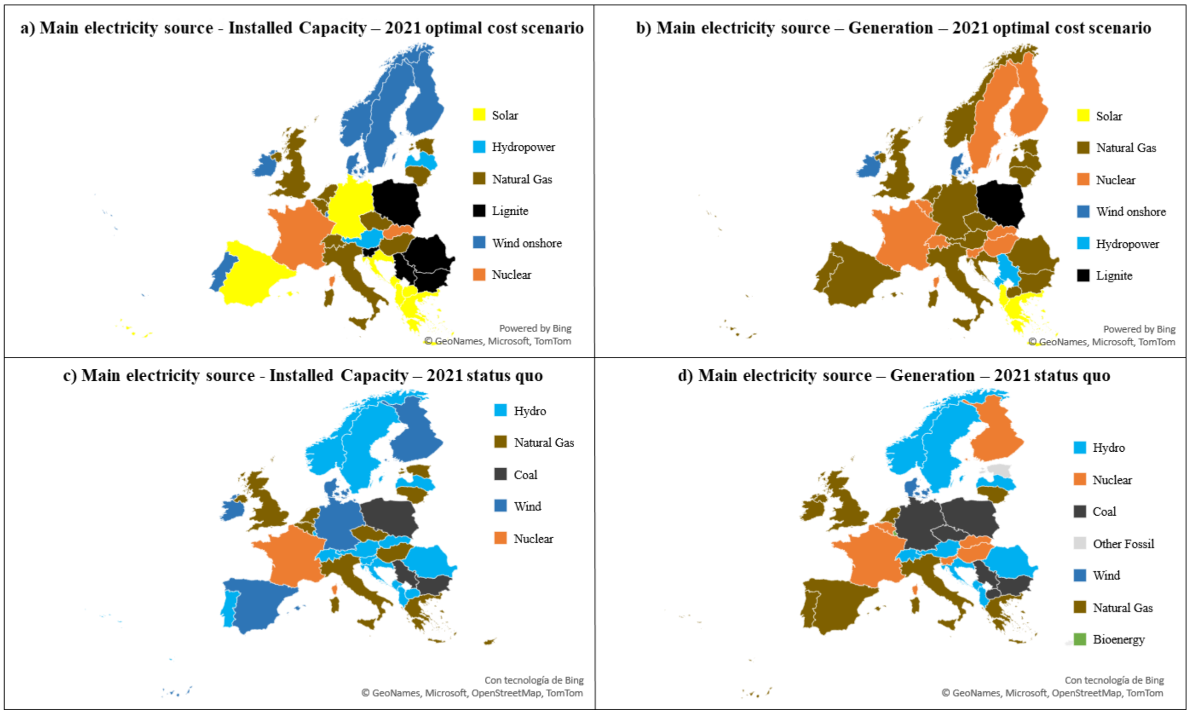


Figure 19. a) Main electricity source for installed capacity by country – 2021 optimal cost scenario. b) Main electricity source for generation by country – 2021 optimal cost scenario.ca) Main electricity source for installed capacity by country – 2021 status quo. d) Main electricity source for generation by country – 2021 status quo.

On the other hand, the reduction in hydropower installed capacity in the optimal cost scenario in comparison to the status quo, causes that instead of being the main source for 14 countries, in the optimal scenario, it is the main source just for Austria and Latvia.
In the rest of the countries, it is mostly replaced by wind and natural gas, but it is remarkable to mention that even if the overall capacity for coal is also reduced, it replaces hydropower as main source in Romania and Slovenia.
Regarding electricity generation, as expected with the predominance of nuclear power and natural gas in the overall mix for the *2021 optimal cost*, they are the main sources of electricity generation for 26 of the 33 countries, compared to 14 in the status quo.
The only countries in which one of this two sources is replaced as main source of electricity generation, is in Greece and Ireland, where natural gas is replaced by solar and wind respectively.
On the other hand, and in logic with the reduction of hydropower generation in the *2021 optimal cost* scenario, this source is kept as main generation source in just one (Montenegro) compared to in the status quo. However, it displaces coal as the main source in Serbia.
Finally, in the *2021 optimal cost* scenario, coal is also drastically displaced as a main source of electricity generation in all but one of the countries in which it is the main source in the status quo:

Poland, being replaced by natural gas in Germany, The Czech Republic, Bulgaria, and North Macedonia, and as previously mentioned by hydropower in Serbia.
The results discussed in this section show that the model is able to optimize the 2021 European electricity system with general characteristics which are comparable to the status quo, especially in terms of geographical distribution of the installed capacity. Nonetheless, it is also evident that there are important differences in terms of the capacity and generation mix, especially affecting the behaviour of coal, natural gas, and solar infrastructure in the system.
It is worth mentioning that these differences are expected from these types of analysis, due to the existing limitations for the representation of a complex energy system in a theoretical model, as discussed in chapter 2.4. In this particular case, these differences are also heavily influenced by assumptions done for the setup of the model, like the limit on FLH for hydropower.
Finally, another important factor is that the operating costs used in the model are standard and historical data that aim to be close to the real costs, but does not necesarilly reflect the exact real costs used during 2021.
In summary, this scenario show a certain level of reliability of the model, especially in greographical terms. However, the results from the 2030 scenarios must be taken with the consideration of the existant differences highlighted in this chapter.

5.2. Installed capacity – 2030 landscape

One of the most important parameters to assess the European electricity system is the installed capacity, as such it is imperative to analyze the way in which the specific conditions given for each scenario affect the total installed capacity used by the model to provide the most cost-efficient solution to the system.
Figure 20 shows the total installed capacity by energy source used by the model in each scenario and the correspondent change in comparison to the 2021 status quo. It can be observed that for the *Indifferent* scenarios the model is able to solve the 2030 system with a slightly higher capacity than the *2021 optimal cost*. However, these results are deceiving to a certain extent due to the existence of an extra component added to allow the resolution of the system. This component is added because logically the 2021 infrastructure is not able to supply the 2030 demand. This point is furtherly assessed in section 5.4.2. The differences given by the *No War* and *After War* scenario do not affect the total installed capacity for these *Indifferent* scenarios.
On the other hand, for the other scenarios a pronounced increase of the total installed capacity can be observed compared to both the 2021 status quo, *2021 optimal cost*, and *Indifferent* scenarios.
Among them, the *Baseline* scenario is the one with the lowest total installed capacity, mainly caused by the lack of hydrogen infrastructure, as defined in the setup of this scenario.
Following with a higher installed capacity are the *Ambitious* scenarios followed by the *Fitfor55* scenarios. In these four scenarios, the installation and use of hydrogen infrastructure is allowed for the model, which can explain the increase in total installed capacity compared to the *Baseline* scenario.
This difference between the *Ambitious* and *Fitfor55* scenario is explained by the lack of new natural gas infrastructure in the *Ambitious* scenarios, given by the default setup of these scenarios.
Additionally, it can be observed that for these four scenarios, the ones with the *After War* classification show a higher installed capacity.
This reflects that the increase in fuel prices expected after the Ukraine war have a direct effect on the decision of the model to install more solar (12 p.p. for *Ambitious* and 13 p.p. for *Fitfor55*) and wind (8 p.p. for *Ambitious* and 5 p.p. for *Fitfor55*) capacity, rather than natural gas capacity.
The *Coal phase-out* scenario has a similar behavior as the "Fitfor55 NW" scenario, but with a higher proportion of installed capacity for natural gas, showing the high reliance on this last fuel in a full coal phase out scenario.

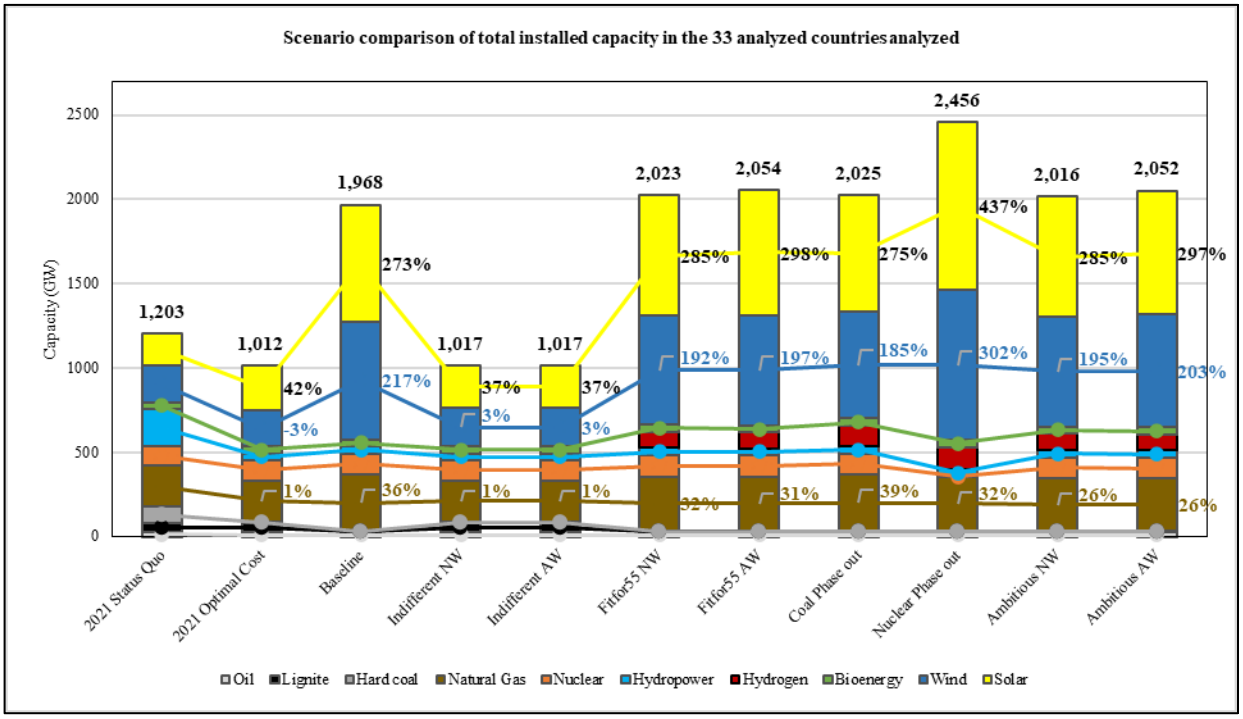


Figure 20. Scenario comparison of total installed capacity in all 33 analyzed countries

The *Nuclear phase-out* scenario is the one with the highest value for total installed capacity among all the scenarios, showing that the lack of nuclear power demands a higher capacity from other sources to cope with electricity demand.

The latter is logical considering that nuclear power is the source with the highest capacity value among all the sources in all the scenarios where it can be used, as sown in Figure 24.

Figure 20 also shows that sources that experience a higher increase of installed capacity in all the 2030 scenarios are natural gas, hydrogen (PEMFC, SOFC, and hydrogen gas engines), wind, and solar due to the possibility given to the model of installing new capacity of these sources based on the techno-economic parameters.

Figure 21 shows the new installed capacity by source and the country distribution at each 2030 scenario where the addition of new capacity is allowed.

Natural gas is the source with the lowest proportion of new installed capacity in all the scenarios in which the new capacity of this source is allowed to be installed. This puts in evidence that hydrogen, wind, and solar power plants enable the model to achieve the most cost-optimal solution to a larger extend than natural gas power plants.

Solar and wind are the sources with the highest relevance in all the scenarios, with installed capacities around five times larger than hydrogen and 40 times larger than natural gas. The values for installed capacity for solar and wind are comparable in all the scenarios, with differences of around 20 GW. Wind is the source with the highest installed capacity in all the scenarios but *Nuclear phase-out*, in which solar has 19 GW more. This is related to the higher capacity factor of wind compared to solar, as shown in Figure 24.

Figure 21 also show that the target of 600 GW of new solar capacity stated in REPower EU is just achieved in the *Nuclear phase-out* scenario. In all the other scenarios, the new solar capacity stays around 150 GW behind this target.

To explain both the prominent difference on new installed capacity for the *Nuclear phase-out* scenario compared to the others, and the change in the source with the highest installed capacity at this scenario, Figure 1 of appendix 1 shows the distribution of new installed capacity in each country for each scenario. It can be observed that the distribution of new installed capacity among the 33 analyzed countries is consistent in all the scenarios, having 80% of the new installed capacity always in 10 countries, varying slightly on the composition of this group, and always having the same countries as the first five with the highest new capacity: France, Italy, The United Kingdom, Poland, and Germany.

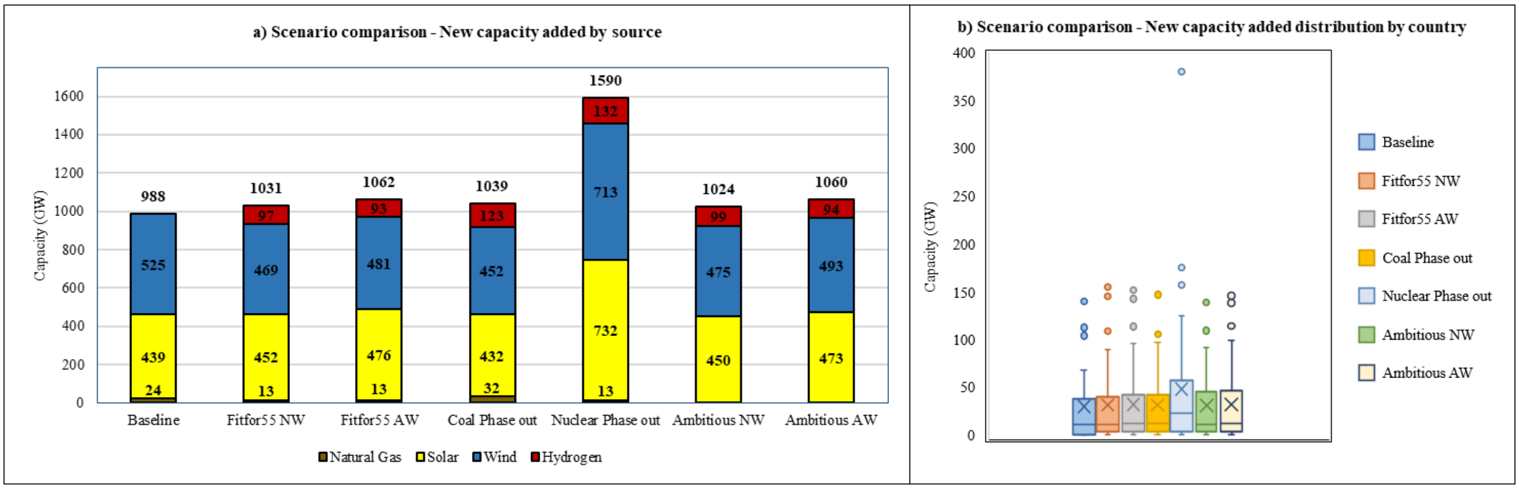


Figure 21. a) Scenario comparison the new capacity added by energy source. b) Scenario comparison of new capacity added by country.

Italy and France are the first or second countries with the highest new installed capacity in all the scenarios but the *Baseline*, in which France is displaced until the fifth position. Additionally, in general the difference between the first two positions is always around 10 GW, but in the *Nuclear phase-out* scenario, in which there is a difference of 205 GW between France in the first position and Italy in the second, in line with the big disparity in the distribution of new installed capacity shown for this scenario in Figure 22-b.

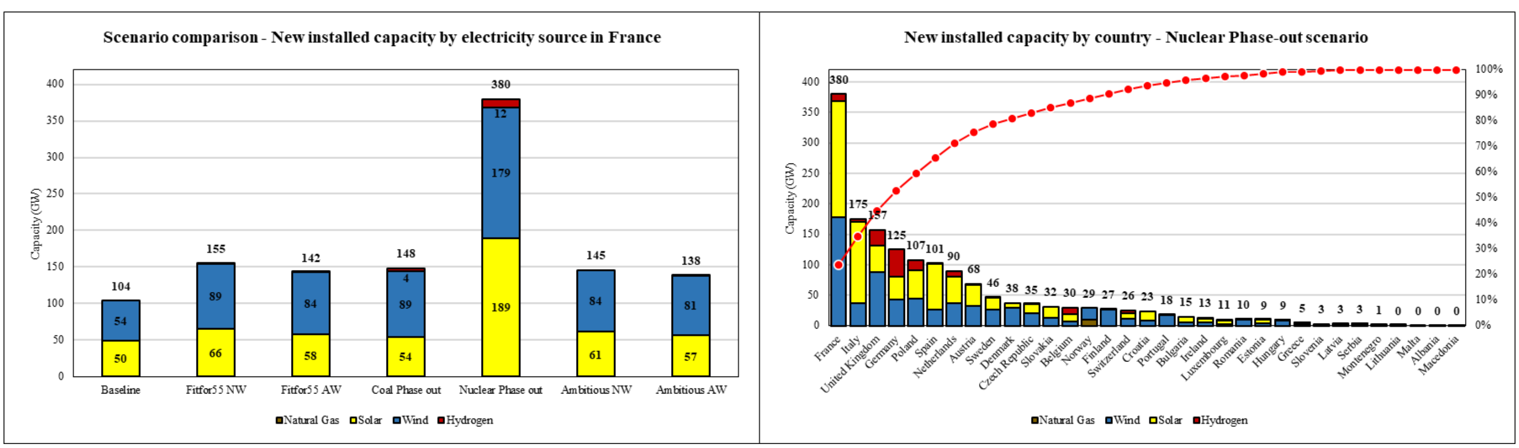


Figure 22. a) Scenario comparison of the new installed capacity by source in France. b) New installed capacity by country - Nuclear Phase-out scenario.

The latter helps to explain the high difference in the overall system for this scenario shown in Figure 20 and Figure 21.
Figure 22 shows the scenario comparison of new installed capacity in France and a zoom to the geographical distribution of new installed capacity for the *Nuclear phase-out* scenario.
Figure 22-a shows that in the *Nuclear phase-out* scenario, the total new installed capacity in France is remarkably higher compared to the other scenarios, being 255 GW higher than the second scenario with highest new installed capacity in this country (*Fitfor55 NW*).
This comes in line with the high dependency of France on nuclear power, on putting in evidence the challenge that this country would face to supply electricity in a nuclear phase out scenario.
It is also important to highlight the also related to the relevance of nuclear power for France, the new installed capacity of new natural gas is almost inexistent in all the scenarios. For hydrogen infrastructure, it is a similar situation, just having installed capacity in the *Nuclear phase-out* scenario and to a lower extend in the *Coal phase-out* scenario

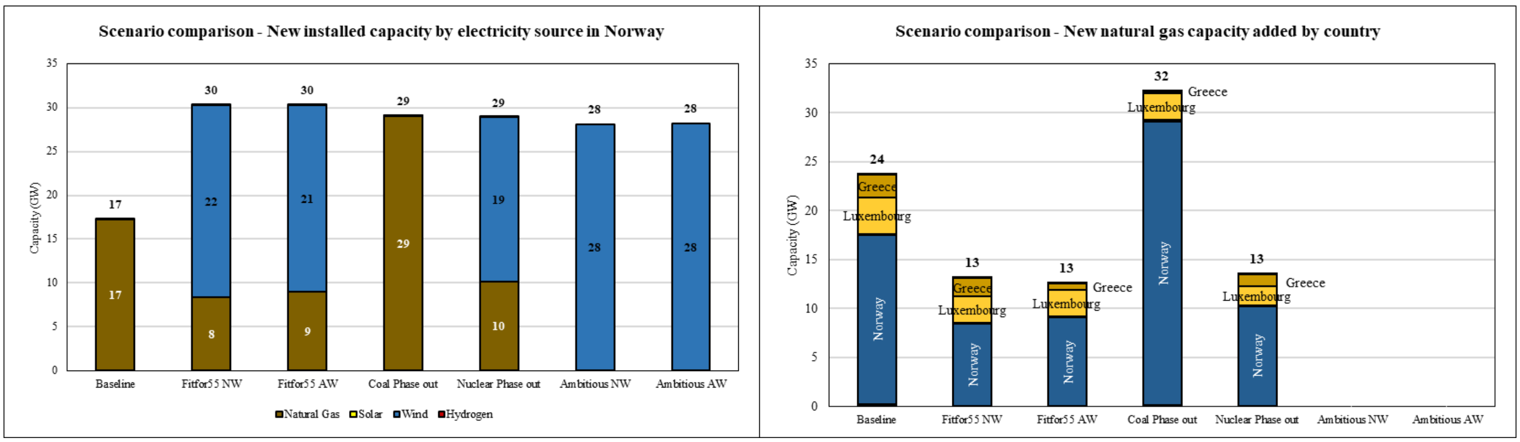


Figure 23. a) Scenario comparison of new installed capacity by electricity source in Norway. b) Scenario comparison of total new natural gas capacity by country.

Finally, it is also relevant to mention that in Figure 1 of appendix 1 it can also be observed that in general the model does not prioritize the installation of new natural gas infrastructure, being the source with the least amount of new installed capacity in all the scenarios and for almost all the countries. There is just one major exception, Norway, in which the limit on FLH for hydropower causes a major investment on natural gas infrastructure as shown in Figure 23.
Even if the case of Norway is caused by an assumption done in the setup of the model, it is useful to show that the implementation of the policies in the *Ambitious* scenarios to limit the investment on natural gas infrastructure allows a larger investment on renewable sources. In Figure 23 this is shown by the fact that the total installed capacity in the *Ambitious* scenarios for Norway is kept at the same level as in the other scenarios but focusing 100% of this new infrastructure on wind.
This analysis shows that the expected demand for the electricity system in 2030 will require a significant increase in the total installed capacity of the European electricity system. This increase could be in the range of 1000 GW, based on the average increase of the capacity used in the *Fitfor55* (1026 GW increase) and *Ambitious* (1022 GW increase) scenarios in comparison to the *2021 optimal cost* scenario.
This increase can be done in the framework of the energy transition with solar, wind, and hydrogen infrastructure, but also from other sources, including natural gas infrastructure.

5.3. 2030 electricity system: installed capacity vs electricity generation

The analysis done in section 5.2 shows that the conditions given to the model for each scenario directly affect the installed capacity that the model uses to satisfy the electricity demand of the system.

Nonetheless, this is also linked to the electricity generation from each source, since some can produce larger quantities of electricity with lower installed capacity, as the case of nuclear power, depending on the capacity factor.
Based on this, and on the cost-efficiency of producing electricity from each source, the model decides in which proportion to use each source to achieve the most cost-optimal electricity system.
Hence, the capacity factor becomes an indicator of the behavior of the electricity system, and it can show the effect that the different conditions at each scenario impact on the electricity mix.

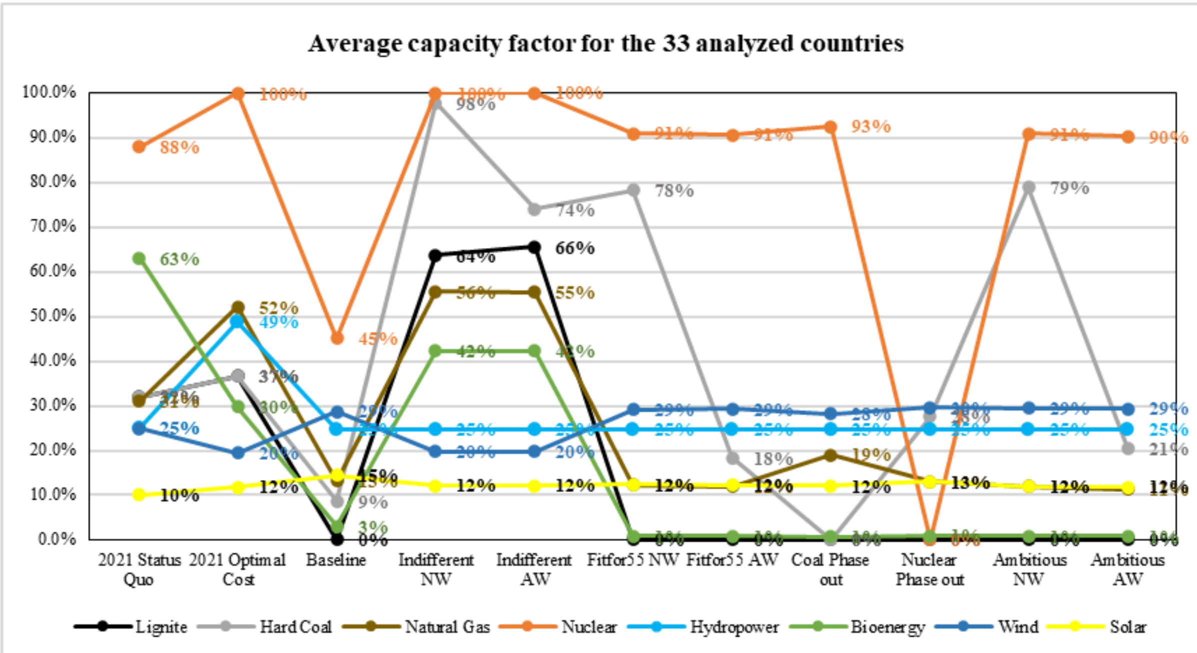


Figure 24. Average capacity factor by energy source for the 33 analyzed countries.

Figure 24 shows the average capacity factor by energy source for all 33 analyzed countries in the 10 scenarios analyzed in this thesis in comparison to the 2021 status quo.
In the case of the *Indifferent* scenarios, it can be observed that in general the capacity factor for bioenergy and all the traditional energy sources (hard coal, lignite, natural gas, and nuclear power) increases compared to the *Fitfor55* and *Ambitious* scenarios. This is logical since the model is not limited to use these technologies. Additionally, it must supply a larger demand with respect to the installed capacity, since in these scenarios it does not create new capacity from renewable sources, and it uses the 2021 power plant database.
On the other hand, for the *Fitfor55* and *Ambitious* scenarios, it can be observed that the capacity factor for bioenergy, and lignite is close to zero, showing that the implementation of the limitations given to these scenarios reduces the use of lignite, but also of bioenergy.
Even with the limitations on emissions, hard coal has a relatively high value of capacity factor in these scenarios, especially in the *No War* category, showing that indirectly the increase in the price of commodities after the war impacts on the level of use of hard coal in the European electricity system.
In the case of the *Coal phase-out* scenario, the lack of hard coal power is mainly compensated by an increase of the use of natural gas infrastructure, increasing the capacity factor of this source from 12% in the *Fitfor55 AW* scenario to 19%.
In turn, for the *Nuclear phase-out* scenario, it can be observed that the energy source that faces an increase on its capacity factor is hard coal.

The capacity factors for solar remain at the same level in almost all the scenarios, explaining the high increase on solar installed capacity for all the scenarios compared to the 2021 status quo, since the demand in 2030 is higher, but the capacity factor is not, hence, the total installed capacity increases.
For the case of wind, the case is like that of solar energy, but having a slight increase on the capacity factor for the *Fitfor55*, *Ambitious*, and *Phase out* scenarios.
Despite the differences of the capacity value by source shown in Figure 24, the capacity and generation mix do not vary significantly between the scenarios, as shown in Figure 25.

Figure 25. a) Scenario comparison - Installed capacity mix. b) Scenario comparison - electricity generation mix.

In terms of installed capacity, for all the scenarios but the *Indifferent*, the two main sources are solar and wind respectively, having both combined more than 50% of the mix. They are followed by natural gas and nuclear, with the exception of the *Nuclear phase-out* scenario.
In contrast to the *2021 optimal cost* and status quo, in the 2030 scenarios, hydropower has a less relevant share in the capacity mix, caused by the assumption on the maximum FLH for this source.
In terms of generation, wind has the highest share for the *Ambitious* and *Fitfor55* scenarios, followed by nuclear. Solar is just in the third position even if it holds the highest shared of installed capacity, in line with the discussion on the capacity factors.
Natural gas is just the fourth source with highest share for these scenarios, in contrast to the *Indifferent* and *2021 optimal cost* scenario and status quo, in which it is the first or second position.
Finally, hydropower has a higher share on electricity generation than hydrogen, even if it has a lower share in the installed capacity mix, also in line with its capacity factor value.
The latter gives a general picture on how the different constraints applied at each scenario affect the behavior on the performance of each energy source in the whole European electricity system (33 analyzed countries).
Nonetheless, the constraints applied at each scenario also have an important effect at country level, causing a change in the main source of installed capacity and electricity generation in each country for the different scenarios, as shown in Figure 3 of the appendix 1.
Figure 3 of appendix 1 shows the main source for installed capacity and electricity generation at country level for each scenario.
It can be observed that the relevance of natural gas and lignite as the main source of installed capacity and electricity generation is predominant in the *Indifferent* scenarios, while nuclear, solar, and wind are the most frequent for the *Fitfor55* and *Coal phase-out* scenarios.
The *Nuclear phase-out* scenario is in which solar and wind have the highest predominance in most of the countries. While for the *Ambitious* scenarios, most of the countries have wind and natural gas as

the main source for installed capacity, and nuclear, wind and solar as the main source for electricity generation.
Finally, it can also be seen that the main effect of the *After War* policies in terms of installed capacity is the higher penetration of solar as the main source for more countries, and the displacement of natural gas for either solar or wind. However, in terms of electricity generation, there is no significant effect on the main source for individual countries.

5.4. Electricity cost

5.4.1. Investment on new renewable capacity

This section aims to analyze the results on the investment done by the model in the different scenarios for the addition of new capacity of solar, wind, and hydrogen infrastructure. The latter with the objective of analyzing the effect of European policies on the implementation and investment on renewable energy infrastructure, and in line with the analysis on new installed capacity done in section 5.4.1.
Figure 26 shows the investment on new renewable energy infrastructure for each of the analyzed scenarios in which the addition of new capacity is allowed in the model. The total investment on renewable energy infrastructure follows the same proportion between scenarios as the total new installed capacity shown in Figure 21. The level of investment is comparable in most of the scenarios but the *Nuclear phase-out*, in which the total investment exceeds the investment of all the other scenarios by at least 500 B€.
The total investment on renewable energy infrastructure is higher for the *After War* scenarios, this is directly related to the higher installed capacity for this scenario shown in Figure 21, and reflecting the effect that the policies established after the conflict in Ukraine have on the investment on new renewable energy in Europe.
At source level, and in contrast to the installed capacity, the investment for wind infrastructure is proportionally higher (1.7 B€/GW) compared to the investment done in each scenario for solar infrastructure (0.7 B€/GW), even if the installed capacity for both sources is similar. While the investment on hydrogen infrastructure has the lowest investment per capacity unit.
Regarding the investment per capacity unit, it can be observed that for solar and wind, this is a constant value, which shows that this parameter is just dependent on the techno-economic parameters of each technology.

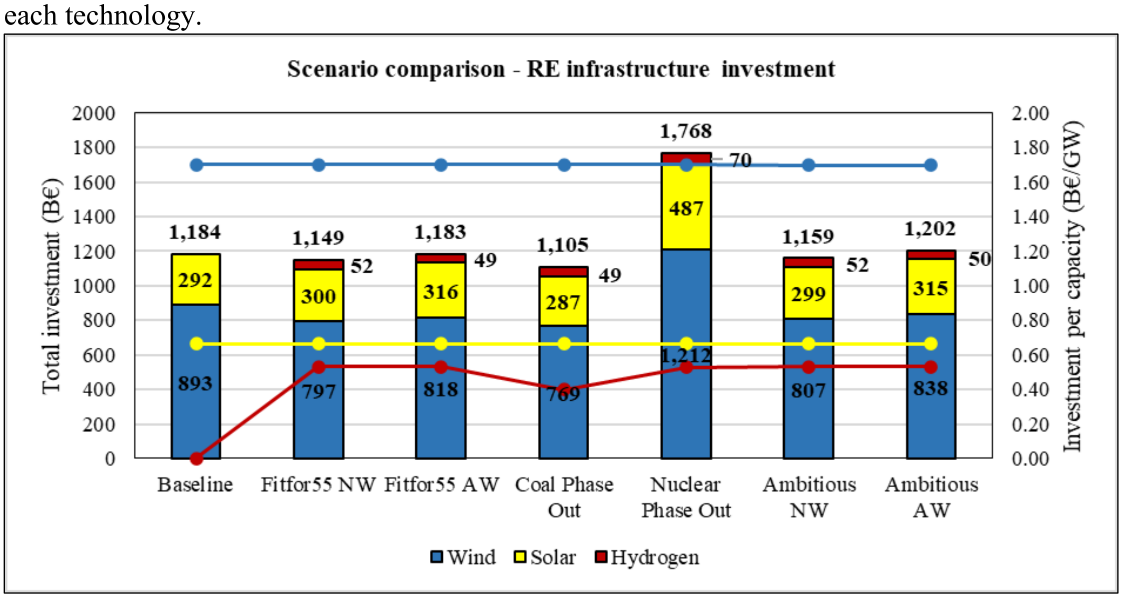


Figure 26. Scenario comparison on total investment on new renewable energy infrastructure.

On the other hand, the investment per capacity for hydrogen infrastructure (PEMFC, SOFC, and hydrogen gas engines) remains constant for all the scenarios but the coal phase out, mainly for the more relevant role of natural gas in this scenario, displacing the investments on hydrogen infrastructure.
The fact that the investment per capacity unit for wind energy is more than two times higher than the one for solar shows that this last energy source becomes a more cost-efficient source for new installations in Europe than wind.
However, and as shown in Figure 24, solar has a lower capacity factor in all the analyzed scenarios, which reduces the attractiveness for the investment on solar infrastructure compared to wind.
As shown, the level of investment and investment per capacity unit in renewable infrastructure have a similar behavior in almost all the scenarios at the European level. At country level this consistency is also maintained, as shown in Figure 4 of appendix 1.

5.4.2. Electricity generation cost

The LCOE (Levelized Cost of Electricity) is also a relevant indicator to assess the European electricity system and the effect of the parameters used in each scenario. This LCOE is computed by the ratio between the total annual cost (TAC) associated to the operation of the power plants and the total electricity generation.
Figure 27 shows the comparison on the LCOE of electricity production for the 2030 scenarios and the *2021 optimal cost* scenario. The LCOE for the *Indifferent* scenarios is almost the same as the one for the *2021 optimal cost* scenario. Nonetheless, this does not mean that these scenarios are more cost-optimal than the *Fitfor55* or *Ambitious* scenarios.
Considering that the *Indifferent* scenarios must supply the 2030 methane demand with the 2021 database without the correspondent infrastructure; logically the model becomes unfeasible. As such, and in order to be able to do the comparison in the other parameters analyzed in this study, an extra component is added to the model to artificially satisfy the methane demand, accounting for most of the total annual cost of the system in these scenarios. Making the LCOE of electricity generation of the *Indifferent* scenarios not suitable for comparison with the rest of the 2030 scenarios.

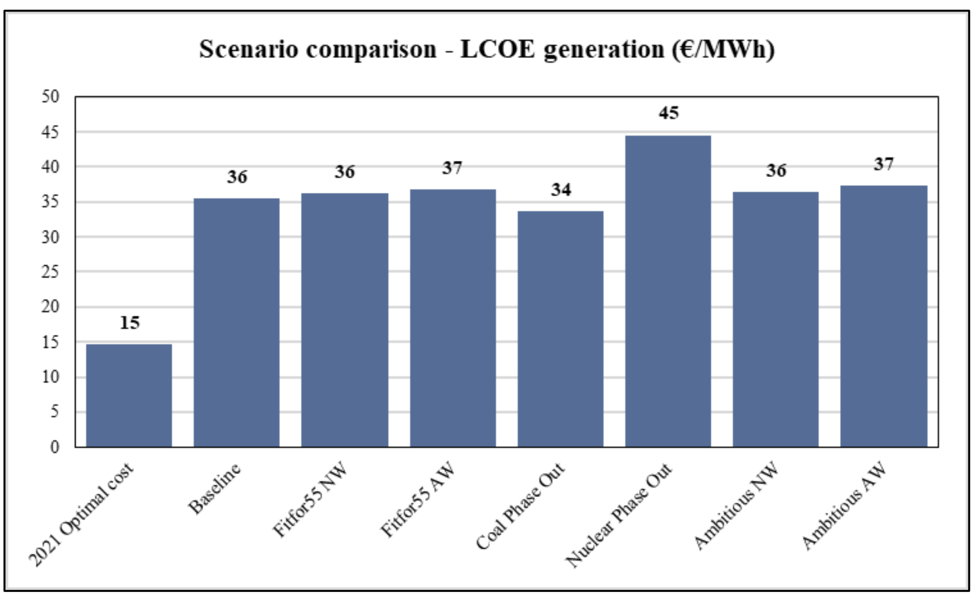


Figure 27. Scenario comparison on the total annual cost for electricity generation of the European electricity system

For the rest of the 2030 scenarios, the LCOE behaves in a similar way to the total installed capacity shown in Figure 20. The *Baseline* scenario has the lowest LCOE, directly related to the lack of hydrogen infrastructure in the mix for this system. The *Fitfor55*, *Coal phase-out*, and *Ambitious* scenarios have comparable LCOE, having a higher cost for the *No War* scenarios. Finally, the *Nuclear phase-out* scenario is the one with the highest cost.
An important remark is that the cost for the 2030 scenarios is significantly higher compared to the *2021 optimal cost* scenario; showing that the logical increase in electricity demand, alongside the higher share of renewable sources in the system, makes it more expensive. This is more evident with the *Nuclear phase-out*, in which the lack of nuclear power, as discussed in section 5.25.3 causes a wider penetration of renewable sources increasing the overall total installed capacity, and consequently the LCOE of the system. Nonetheless, the LCOE is not equal throughout Europe, as shown in Figure 6 of appendix 1. It can be observed that in all the scenarios the highest electricity costs are around 90 to 120 €/MWh, which is consistent with the historic electricity costs in Europe, as reported in Eurostat and shown in Figure 5 of appendix 1. [40]
The case of France is relevant to mention, since it generally has a low electricity cost compared to other regions in almost all the scenarios, but with the *Nuclear phase-out*. In this scenario, the electricity cost of most of the French regions is comparable to the rest of Europe, highlighting once again the high reliance of France on nuclear power. In this scenario, a general increase in the electricity cost is observed in all the continent, in line with the overall increase in LCOE shown in Figure 27.
It can also be observed that even if the *Baseline* scenario is the one with the lowest LCOE, the regions of eastern Germany, western Poland, central Italy, Slovakia, and the southeast of Sweden have a higher electricity cost compared to the other 2030 scenarios. This shows that the policies implemented in the *Fitfor55* and *Ambitious* scenarios help to reduce the electricity cost in these regions.
On the other hand, the opposite is true for the center of Poland, the south of Romania, and Montenegro, especially in the *Ambitious* scenarios.
This analysis on electricity cost shows that the future electricity system will require a high investment on renewable energies, especially on wind infrastructure. At the same time, the LCOE will significantly increase, but due to the also significantly higher electricity generation, the electricity cost of Europe stays at the same level compared to the historic costs before the war in Ukraine.

5.5. Assessment on 2030 targets

The previous analyses are useful to assess the effect on the European electricity system of the policies that can be directly implemented in the model, such as the emission limits at country level, or the reduction on gas imports.
Nonetheless, the crucial objectives on hydrogen production and import, and renewable energy share at national level cannot be directly controlled in the model. Hence, this section aims to assess at which level these two objectives are achieved in each scenario and the effect that this has on the carbon intensity of the European electricity system.

5.5.1. Hydrogen targets

Hydrogen import is just allowed in the *Ambitious* scenarios, hence the assessment on the achievement of the REPower EU objectives of importing 10 Mt and producing 10 Mt of green hydrogen can only be done with these scenarios.
Figure 28 shows the total imports and total production of hydrogen for the *Ambitious* scenarios. It can be observed that the target on hydrogen import is not achieved, with import values lower than one Mt for both *No War* and *After War* scenarios.
On the other hand, the target on production is achieved and exceeded by more than double the 10 Mt objective in both scenarios. In consequence, the objective of having 20 Mt of hydrogen in the European electricity system is achieved but only through the production of hydrogen. This shows that

under the hydrogen price given to the model (Table 6 in the appendix 1) of 710 €/MWh, it becomes more cost-optimal to produce hydrogen inside the European energy system, rather than importing it. The latter highlights the relevance that hydrogen infrastructure has for the European energy system. However, this is conditioned to the existence of the infrastructure to produce and store this hydrogen; as such, it becomes relevant for the 2030 European energy system to assess in more detail the needs to achieve a European hydrogen infrastructure that can cope with this demand.

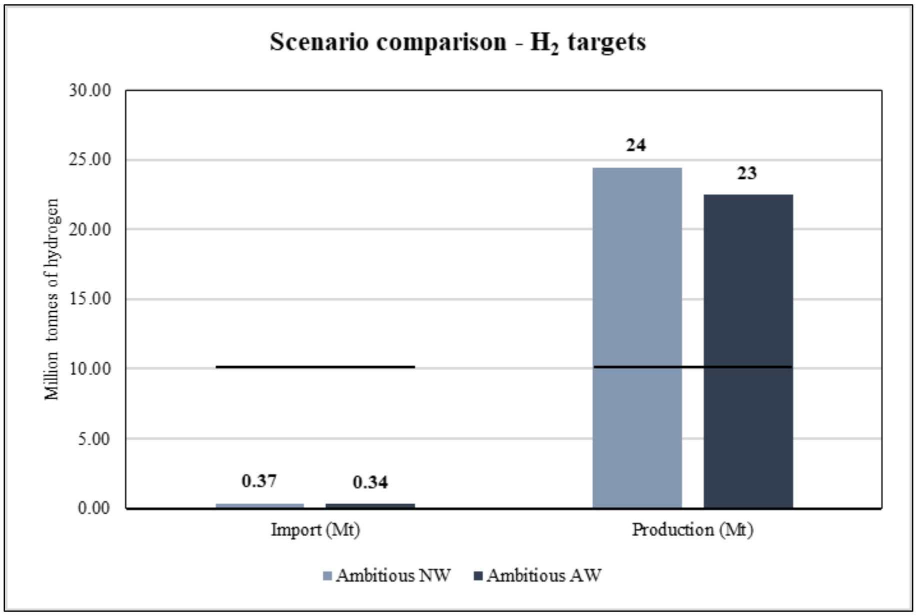


Figure 28. Scenario comparison of import and production of hydrogen.

5.5.2. Renewable energy share

Figure 29 shows the number of countries that achieve the 2030 renewable share target as stated in section 4.3. Additionally, Table 11 in the appendix 1 shows in detail which countries achieve their targets at each scenario, alongside the classification on the level of challenge to increase their renewable share, as shown in Table 5 of section 4.3.

It can be observed that all the 2030 scenarios allow more countries to achieve their 2030 RE share targets in comparison with the *Indifferent* scenarios, especially in the *Ambitious* and *Nuclear phase-out* scenarios. The latter is achieved even if this target cannot be directly given in the setup of the model.

The *Nuclear phase-out* scenario is the one that enables the largest number of countries to achieve its targets, with 29 of 33 countries, just Austria, Denmark, North Macedonia, and Norway not achieving the target. This result is heavily influenced by the reduction on hydropower penetration caused by the FLH limit assumption, considering that these countries consider this source in their target. This can be explained by the large deployment of renewable infrastructure under this scenario, as shown in previous sections of this chapter.

It is also relevant to highlight that the conditions given to the *After War* scenarios, which are related to the policies implemented after the conflict in Ukraine, and also the commodities price increase; allows more countries to achieve their RE share targets. This is especially relevant for Spain, which considered as a country with a high level of challenge to achieve its target, both scenarios *After War* scenarios enable it to achieve its target.

The *Coal phase-out* scenario is the one in which the least number of countries achieve the RE share target, mainly explained by the larger deployment of natural gas infrastructure in this scenario.

Finally, it is worth to mention that the EU objective of reaching 69% RE share is just achieved under the *Baseline* and *Nuclear phase-out* scenarios; as shown in Table 6. However, in the *Ambitious* and *Fitfor55* scenarios, the gap is just around 5 p.p.

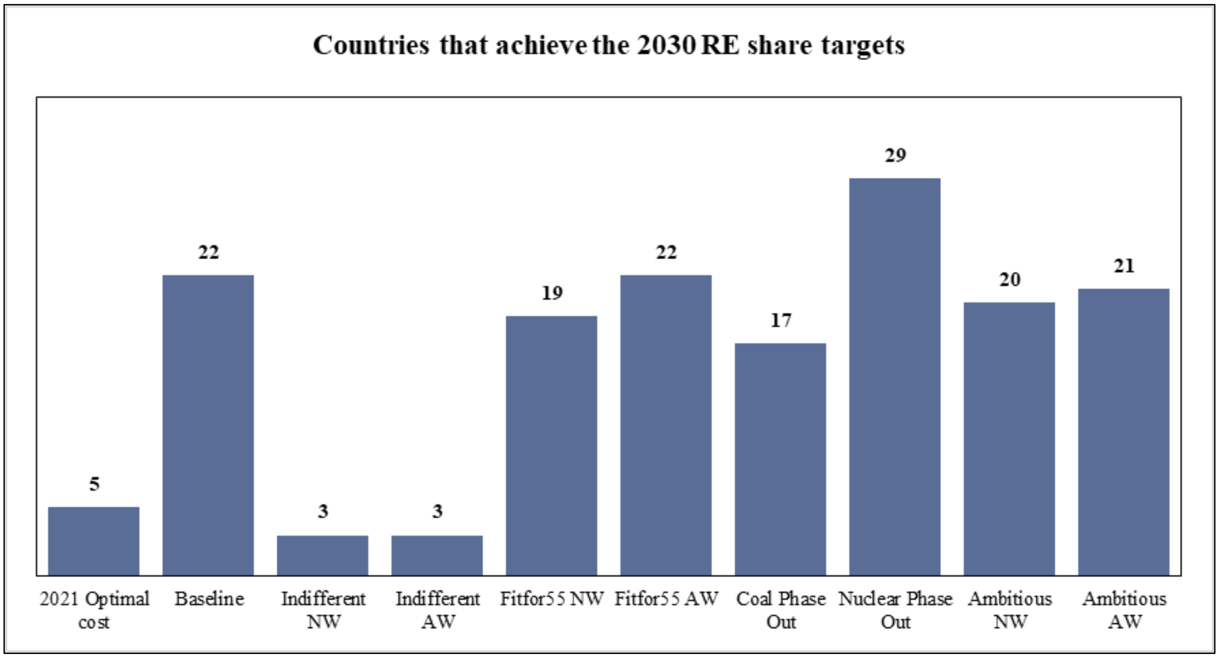


Figure 29. Scenario comparison on the number of countries that achieve their national target on RE share by 2030.

Table 6. Scenario comparison of EU28 RE share in electricity generation.

Scenario	EU28 RE share
2021 optimal cost	25%
Baseline	75%
Indifferent NW	22%
Indifferent AW	22%
Fitfor55 NW	64%
Fitfor55 AW	65%
Coal Phase Out	59%
Nuclear Phase Out	89%
Ambitious NW	64%
Ambitious AW	66%

At regional level, Figure 7 of appendix 1 shows the renewable energy share along the 33 analyzed countries for each scenario, and Figure 8 of appendix 1 shows the change on renewable energy share by region for each scenario compared to the *2021 optimal cost* scenario.
For the *Indifferent* scenarios, the renewable energy share penetration is lower compared to the 2030 scenarios, and with more similarities to the *2021 optimal cost* scenario, having the largest RE shares in Greece, Sweden, the coastal regions of the North Sea in Germany and Poland, the south of Poland, and northwestern Spain.
For the rest of the scenarios, an increase in RE share with respect to the *2021 optimal cost* scenario is evident, having the highest shares in the "Nuclear Phase-out scenarios". For this last scenario, in line with the previous analyses, the increase in RE share is more evident in regions that have a high

dependency on nuclear power, like France, Finland, and Slovakia. This is a signal of the potential effects that the European policies can have to enhance the penetration of renewable sources, even without the presence of such an important energy source in the current mix.
The RE penetration is similar in the *Fitfor55* and *Ambitious* scenarios, with one case worth to mention. Norway has a noticeable higher share of RE share in the *Ambitious* scenario, in line with the higher levels of new wind capacity shown in section 5.4.1. It is also relevant that due to the high level of new natural gas capacity for Norway in the *Baseline* and *Coal phase-out* scenarios, it has a significantly low RE penetration. These results are highly influenced by the effects shown in previous chapters, related to the FLH assumption on hydropower.
This analysis on the assessment of the achievement of the RE share 2030 targets at national level show that more than half of the analyzed countries are able to achieve their targets in terms of RE share under the conditions given in the scenarios that implement the policies established by the Fitfor55 and REPower packages.
The previous results must be understood under the fact that the target on RE share cannot be directly given to the model. Showing that even if the model does not actively aim to reach a particular share of RE, the reduction on gas import and the limitation on emissions indirectly help to achieve this target. However, it is worth to mention that the overall EU objective is not achieved. This shows that in order to reach this objective, a larger number of countries must achieve their individual objectives. The latter might demand more ambitious plans for the regions that show a higher challenge to implement renewable energy infrastructure.

5.5.3. Carbon intensity of electricity generation

In order to sum up the previous analyses, and to generally assess the impact of each scenario in the emissions level of the European electricity system, the carbon intensity is a useful indicator.
Figure 9 of the appendix shows the scenario comparison of the carbon intensity and the reference of the 2021 status quo. This last one is shown with data extracted from Our World in Data. [41]
The carbon intensity of all the scenarios is lower compared to the status quo. This is logical for the *Fitfor55* and *Ambitious* scenarios, in which the emissions are limited.
In line with all the results presented in this thesis, it can be observed that the carbon intensity of the The *Indifferent* scenarios have a comparable carbon intensity to the *2021 optimal cost* and the status quo, and it is also significantly higher in comparison to the rest of the 2030 scenarios. This is logical considering that for the *Fitfor55* and *Ambitious* scenarios the emissions are limited based on the NECPs.
The *Ambitious* scenarios show a similar level of carbon intensity to the *Fitfor55* but allowing Norway to reduce its carbon intensity, even with the reduction on hydropower penetration, and in line with the lack of new natural gas infrastructure, as shown in chapter 5.4.1.
Regarding the *Phase out* scenarios, the *Nuclear phase-out* achieves the same level of low carbon intensity as the *Fitfor55* and *Ambitious* scenarios, in line with the high level of RE penetration shown in the previous section.
The *Coal phase-out* scenario has also similar levels of carbon intensity to those of the *Fitfor55* and *Ambitious* scenarios, with the exception of Norway, with a huge increase in its carbon intensity in this scenario. But allowing a higher decarbonization of regions in the south of Germany. It is also worth to mention that there are regions with carbon intensity levels under 50 kg of CO_2 equivalent per MWh in all the scenarios, such as France, Sweden, Finland, southern Italy, southern Spain, Latvia, and Estonia. On the other hand, Romania, the Western Balkans, Poland, and western Germany are the regions that show a higher level of carbon intensity in all the scenarios, with values higher than 100 kg of CO_2 equivalent per MWh.

6. Conclusions

This thesis aims to assess the current landscape of the electricity generation infrastructure in Europe, and subsequently the assessment of its transition towards 2030 under the implemented policies packages.

To perform this assessment, a database of the installed capacity of active power plants from ten different energy sources is created. The database considers the existent infrastructure in 33 countries of Europe. This database collects information from a diversity of sources of information and it is contrasted with officially reported capacities to validate its reliability.

The obtained study database has a high level of detail in the geographic location and distribution of electricity production infrastructure in Europe. It also has a high level of reliability in terms of total installed capacity, having a 4% difference with respect to the reference data.

On a first step the database is used to assess the current electricity generation system in Europe. This analysis shows that Europe still faces major challenges in the transition to achieve the 2030 objectives. These challenges are especially evident for the RE share target, as shown in chapter 4. This analysis on the existing gaps at national and EU level between the status quo and the 2030 objective highlights how the inclusion of hydropower in the RE targets might underestimate the challenge needed to achieve a decarbonized electricity system in Europe.

The database is consequently used as an input for an energy systems model to evaluate the impact of different parameters on the 2021 and 2030 European electricity systems. These parameters are varied between ten scenarios, which in turn are based on the Fitfor55 and REPower EU policies packages.

The results of the *2021 optimal cost* scenario show the ability of the model to partially replicate the status quo of the European electricity system, especially for the geographical distribution of the use of installed capacity infrastructure. However, it also shows differences in absolute values of total capacity and generation and their respective mix composition. The latter highlights the yet existing challenges in the field of energy systems modeling to represent such a complex and changing system.

Regarding the assessment of the 2030 electricity system in Europe, the analysis of the different scenarios shows that the transition towards a decarbonized electricity system demands an important investment on the increase of the total installed capacity, especially on renewable infrastructure.

In general, it is evident that under the current policies, solar and wind will become key energy sources for the future European electricity system and its transition towards decarbonization.

The investment on new hydrogen infrastructure for electricity generation also shows to be relevant for the 2030 electricity system, especially as a substitute of coal and natural gas infrastructure. Related to this, he EU has similar targets for the production and import of hydrogen (10 Mt). However, this thesis shows that under the assumed hydrogen price (710 €/MWh), the investment on hydrogen production infrastructure for the 2030 European electricity system has the potential to make the local production of hydrogen more cost-attractive than the import of this commodity. This could be potentially benefitial for the energy independence of Europe, since it would reduce the reliance on natural gas imports without causing a similar dependancy on hydrogen imports.

The assessment of the 2030 scenarios also shows that a higher penetration of renewable energy sources and a lower reliance on coal can potentially reduce the carbon intensity of the European electricity system. Nonetheless, this is highly dependent on the level of penetration of natural gas. Thus, the reduction on the dependancy of natural gas cannot just help to achieve a major energy independence of Europe, but also to foster the penetration of renewable energy sources and to achieve the decarbonization of the electricity system of the region.

The analysis of this thesis shows that current policies can still be improved to tackle the infrastructure challenges that the transition of the European electricity system has. Even if they already have a great focus on the investment of solar infrastructure, the results from the scenarios show that they might not be enough to achieve the RE targets. As such, besides an exhaustive follow-up of the current policies, an extended new assessment on new strategies to increase the penetration of solar infrastructure is recommended.

Additionally, even if the envisioned reduction on gas consumption could also potentiate the decarbonization of the future European electricity system, this is conditioned to the hydrogen infrastructure in the region. Hence, a continuation on the development of policies that aim to improve hydrogen infrastructure is also recommended. These policies should have a larger focus on the local production of hydrogen.

To sum up, the results of the assessment of the 2030 scenarios show that the implementation of the current policies foster the investment in renewable energy infrastructure and can potentially help to boost the transition of the European electricity system towards the decarbonization. However they also highlights that there are still challenges to achive the 2030 objectives, and that current policies can still be improved.

Appendix 1

Table 1. Approach and sources for the data in the studies analyzed in the literature review.

Study	Power plant data approach	Energy supply data sources
Capros et al.	Greenfield	Eurostat
Deane et al.	Brownfield	Power plant inventory: ESAP SA & Platts
Collins et al.	Brownfield	Power plant inventory: ESAP SA & Platts Wind detailed data: MERRA (Modern-Era Retrospective analysis for Research and Applications – NASA) Solar detailed data: NREL (National Renewable Energy Laboratory – USA) Hydro generation profiles: ENTSO-E
Fragkos et al.	Brownfield	Power plant inventory: ESAP SA & Platts Eurostat
Henke et al.	Brownfield	Energy Technology Reference Indicators – European Commission IEA World Energy Outlook 2014 Catalog of CHP Technologies. US Environmental Protection Agency IEA ETSAP (Energy Technology Systems Analysis Program) IEA Power generation assumptions in the World Energy Outlook 2018.
Coppens et al.	Brownfield	Walloon regional administration
Blesl et al.	Greenfield	RES2020 Project Consortium EURELECTRIC TSOs websites EWEA (European Wind Energy Association) Solar Power Europe
Tröndle et al.	Greenfield	Renewables.ninja Swiss Federal Office of Energy JRC Hydro Power Database IRENA generation data Ruiz Castello et al. on biomass potentials for 2020
This thesis	Brownfield	Open Power System Data ENTSO-E Europe Beyond Coal Global Energy Observatory World Resource Institute The Wind Power Global Energy Monitor Diverse National Statistics Offices Diverse TSOs databases

Table 2. List of countries analyzed in this study.

Country or region	Abbreviation code	European Union Member
Albania	AL	
Austria	AT	X
Belgium	BE	X
Bulgaria	BG	X
Croatia	HR	X
Czech Republic	CZ	X
Denmark	DK	X
Estonia	EE	X
Finland	FI	X
France	FR	X
Germany	DE	X
Greece	EL	X
Hungary	HU	X
Ireland	IE	X
Italy	IT	X
Latvia	LV	X
Lithuania	LT	X
Luxembourg	LU	X
Malta	MT	X
Montenegro	ME	
Netherlands	NL	X
North Macedonia	MK	
Norway	NO	
Poland	PL	X
Portugal	PT	X
Romania	RO	X
Serbia	RS	X
Slovakia	SK	X
Slovenia	SI	X
Spain	ES	X
Sweden	SE	X
Switzerland	CH	
United Kingdom	UK	
European Union (27 member countries)	EU 27	
European Union (27 member countries) + United Kingdom	EU28	
All the countries of this study	EU33	

Table 3. 2030 targets for RE share and GHG emissions at country level.

Country or region	2030 target in RE share in electricity generation	2030 target in maximum GHG emissions ($MtCO_2eq$)
Albania	42%	5.3
Austria	100%	34.0
Belgium	37%	61.9
Bulgaria	30%	37.6
Croatia	64%	10.9
Czech Republic	17%	78.5
Denmark	100%	24.9
Estonia	40%	8.0
Finland	55%	7.0
France	40%	31.0
Germany	65%	183.0
Greece	64%	9.6
Hungary	27%	6.0
Ireland	70%	18.0
Italy	55%	82.1
Latvia	60%	9.2
Lithuania	45%	16.7
Luxembourg	45%	5.2
Malta	11%	1.6
Montenegro	27%	1.5
Netherlands	73%	14.0
North Macedonia	66%	3.3
Norway	98%	7.8
Poland	32%	108.2
Portugal	50%	2.2
Romania	50%	25.7
Serbia	29%	53.6
Slovakia	19%	4.4
Slovenia	43%	4.6
Spain	74%	21.0
Sweden	83%	18.5
Switzerland	75%	8.5
United Kingdom	70%	89.4

Table 4. Techno-economic parameters of operating power plants.

Type of plant	OPEX per capacity (M€/GW)	OPEX per operation (M€/GWh)
Solar PV	10	-
Wind onshore	13	1.4 x10^3
Wind offshore	40	4.0 x10^3
Bioenergy	150	1.7 x10^3
Hydropower	44	1.3 x10^3
Nuclear	99	4.2 x10^3
Natural Gas	30	4.5 x10^3
Lignite	32	3.0 x10^3
Hard Coal	22	3.0 x10^3
Oil	9	6.4 x10^3

Table 5. Techno-economic parameters of new power plants.

Type of plant	CAPEX per capacity (B€/GW)	Interest rate (%)	Economic lifetime (years)
Solar PV open field	0.57	3%	30
Wind onshore	1.19	4%	25
Wind offshore	2.15	5%	25
Natural gas	0.94	5%	30
Hydrogen	0.52	4%	25

Table 6. 2021 and 2030 forecast commodity price.

Commodity	2021 price (€/MWh)	2030 price – 2021 forecast (€/MWh)	2030 price – 2022 forecast (€/MWh
Natural gas	223	262	376
LNG	405	405	499
Hard coal	262	126	270
Lignite	309	165	165
Oil	731	473	518
Biomass	224	298	298
Uranium	17	17	17
Hydrogen	1500	710	710

Table 7. Emission factor of fossil power plants.

Type of plant	Emission factor ($kgCO_2eq/MWh$)
Natural gas	202
Hard coal	342
Lignite	356
Oil	268
Biomass	197

Table 8. Techno-economic parameters of additional components for the setup of the model.

Component	CAPEX per capacity (B€/GW)	Interest rate (%)	Economic lifetime (years)	OPEX per capacity (M€/GW)
PEM-Electrolyzers	0.69	3%	20	29
PEMFC	0.92	3%	10	59
SOFC	1.5	8%	10	106
Li-ion batteries	0.15	8%	22	1.51
Hydrogen vessels	7.5×10^3	8%	20	0.15
Hydrogen caverns	3.6×10^4	8%	30	7.2×10^3
Natural gas & hydrogen pipelines	1.9×10^4	8%	40	1.0×10^3

Table 9. Coal Phase-out plan for the countries analyzed in this thesis.

Country or region	Coal phase-out year
Albania	Coal never in the mix
Austria	2023
Belgium	Phase out completed
Bulgaria	2040
Croatia	2033
Czech Republic	2033
Denmark	2028
Estonia	Coal never in the mix
Finland	2029
France	2023
Germany	2038
Greece	2028
Hungary	2025
Ireland	2025
Italy	2025
Latvia	Coal never in the mix
Lithuania	Coal never in the mix
Luxembourg	Coal never in the mix
Malta	Coal never in the mix
Montenegro	2035
Netherlands	2029
North Macedonia	2027
Norway	Coal never in the mix
Poland	No expected phase out
Portugal	Phase out completed
Romania	2030
Serbia	No expected phase out
Slovakia	2030
Slovenia	2033
Spain	2030
Sweden	Phase out completed
Switzerland	Coal never in the mix
United Kingdom	2024

Table 10. Renewable sources considered in the national 2030 target for RE share in the electricity generation for each country and the EU global target.

Country	Hydropower	Bioenergy	Wind	Solar
Albania	No	Yes	Yes	Yes
Austria	Yes	Yes	Yes	Yes
Belgium	Yes	Yes	Yes	Yes
Bulgaria	Yes	Yes	Yes	Yes
Croatia	No	Yes	Yes	Yes
Czechia	Yes	Yes	Yes	Yes
Denmark	Yes	Yes	Yes	Yes
Estonia	Yes	Yes	Yes	Yes
Finland	Yes	Yes	Yes	Yes
France	Yes	Yes	Yes	Yes
Germany	Yes	Yes	Yes	Yes
Greece	Yes	Yes	Yes	Yes
Hungary	Yes	Yes	Yes	Yes
Ireland	Yes	Yes	Yes	Yes
Italy	Yes	Yes	Yes	Yes
Latvia	Yes	Yes	Yes	Yes
Lithuania	No	No	Yes	Yes
Luxembourg	No	No	Yes	Yes
Malta	Yes	Yes	Yes	Yes
Montenegro	No	Yes	Yes	Yes
Netherlands	Yes	Yes	Yes	Yes
North Macedonia	Yes	Yes	Yes	Yes
Norway	Yes	Yes	Yes	Yes
Poland	Yes	Yes	Yes	Yes
Portugal	No	No	Yes	Yes
Romania	Yes	Yes	Yes	Yes
Serbia	No	Yes	Yes	Yes
Slovakia	No	Yes	Yes	Yes
Slovenia	Yes	Yes	Yes	Yes
Spain	Yes	Yes	Yes	Yes
Sweden	Yes	Yes	Yes	Yes
Switzerland	Yes	Yes	Yes	Yes
United Kingdom	Yes	Yes	Yes	Yes
EU28	Yes	Yes	Yes	Yes

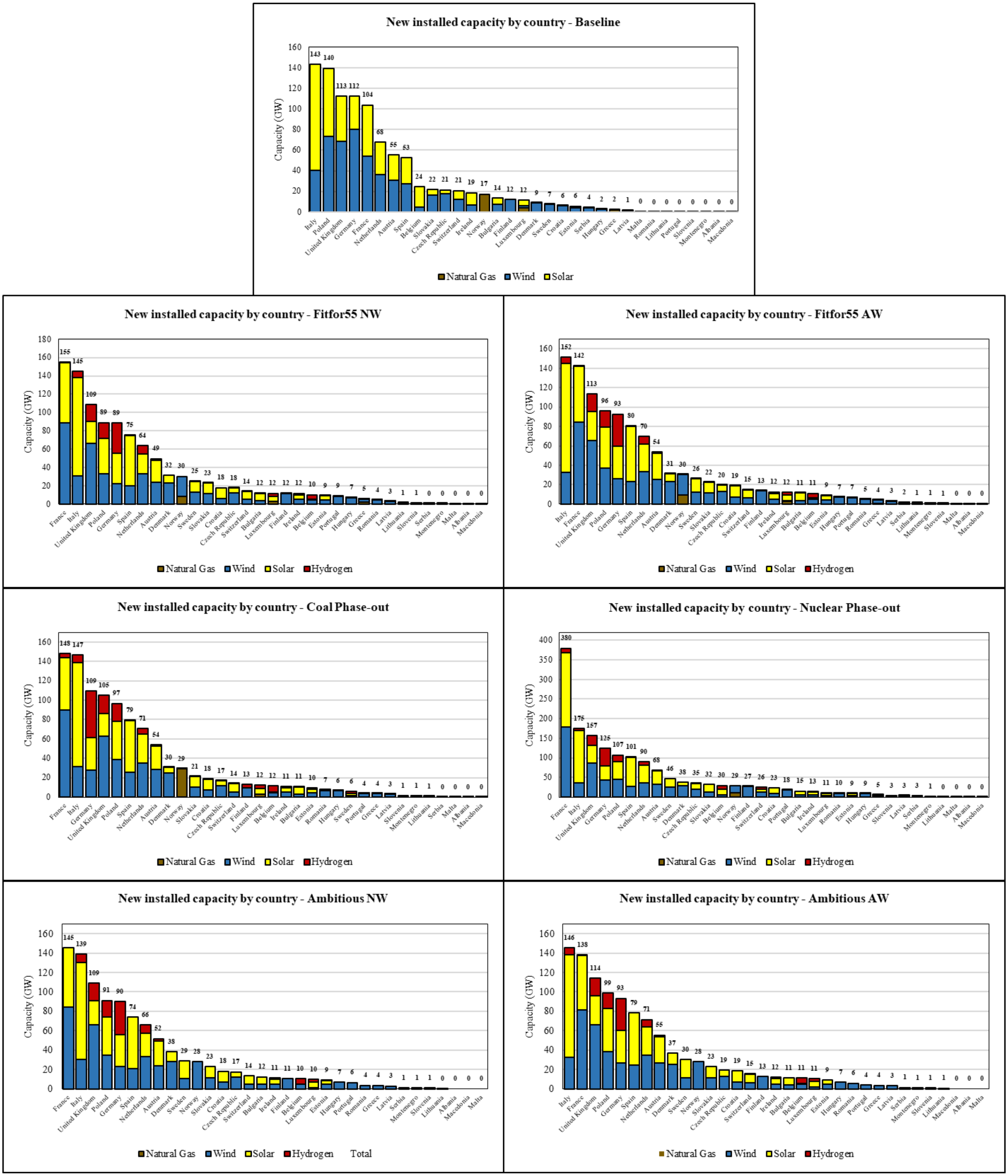


Figure 1. Scenario comparison – new installed capacity by source.

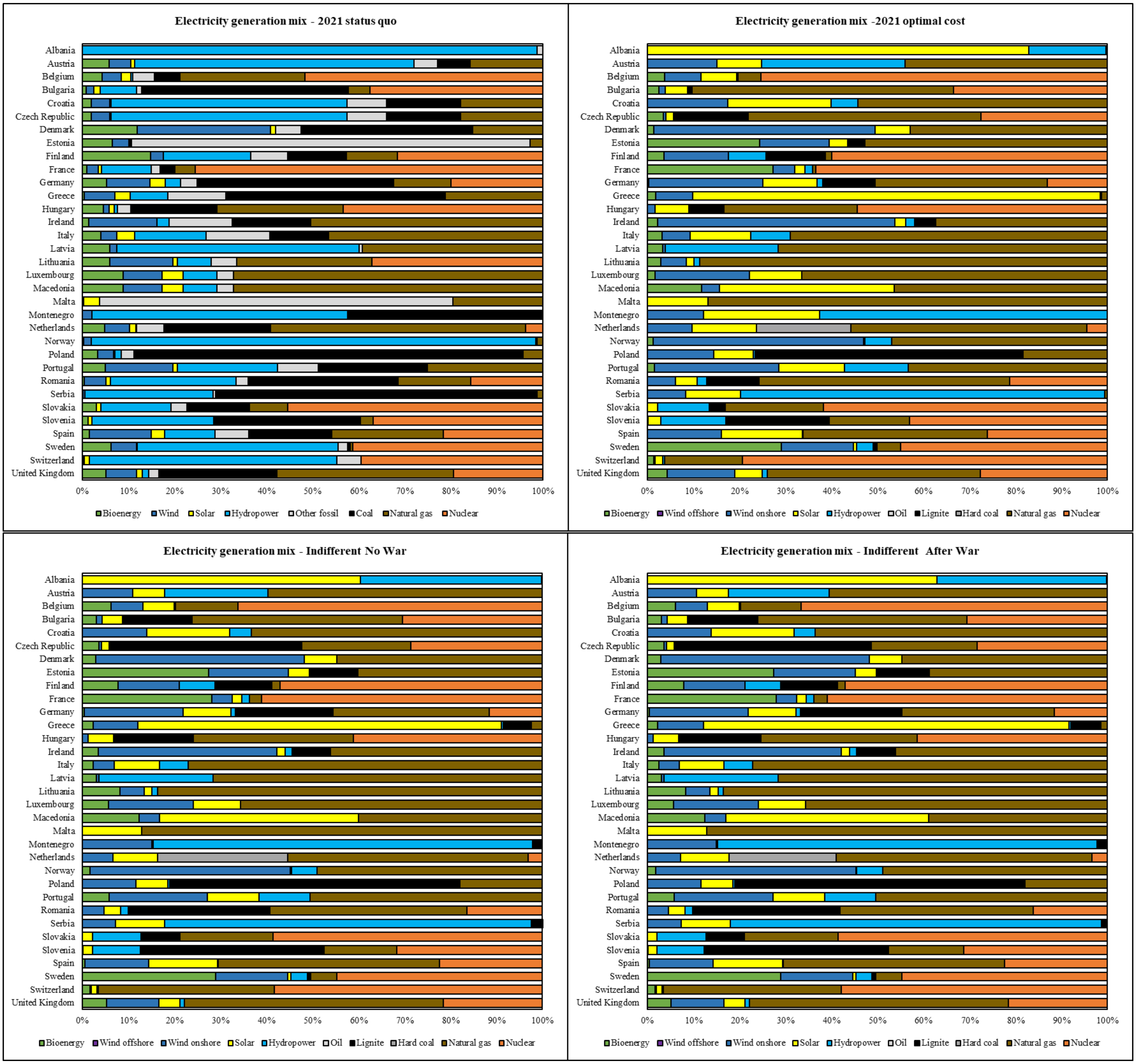


Figure 2.1. Scenario comparison – electricity generation mix by country (2021 optimal cost and Indifferent scenarios)

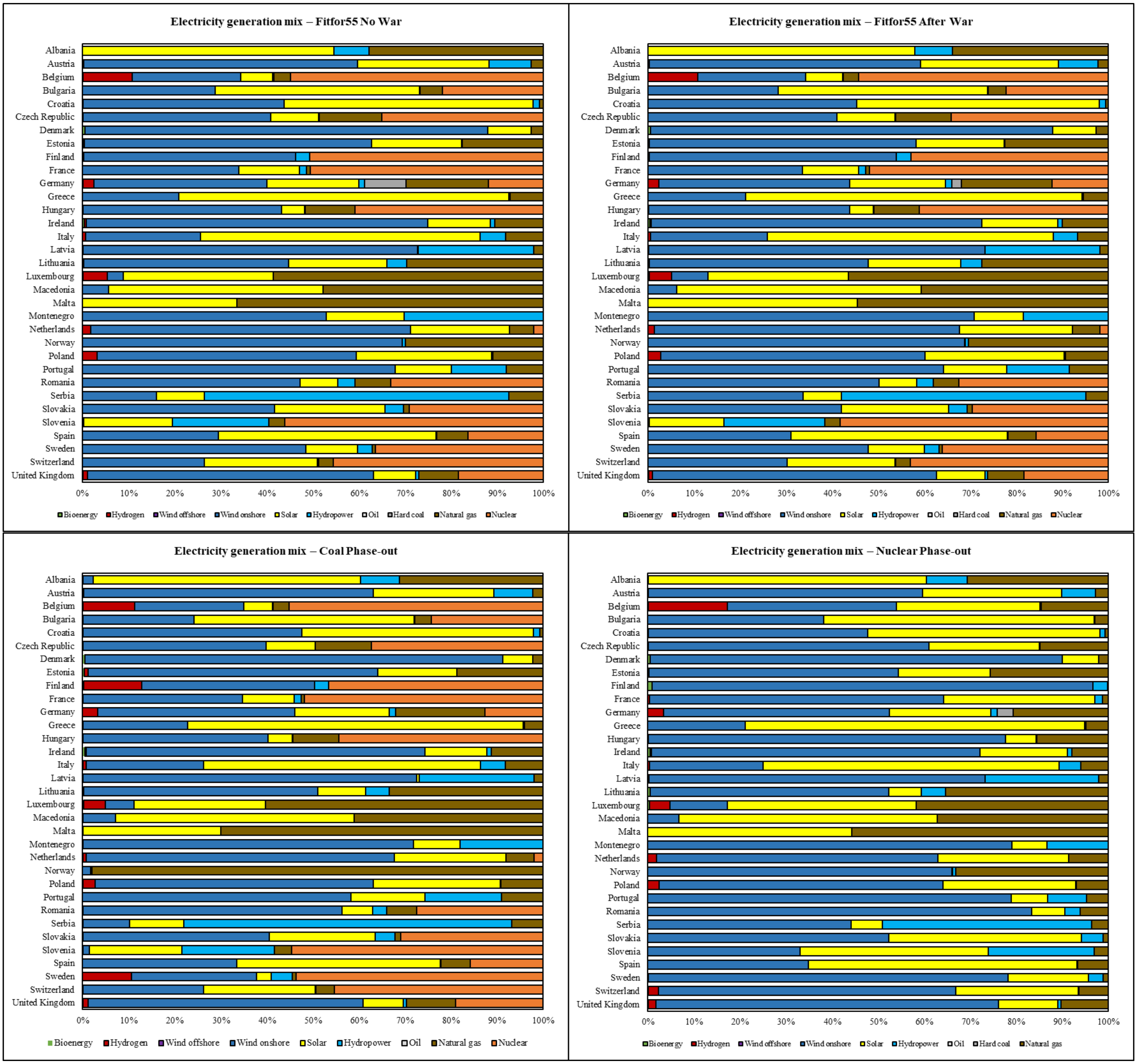


Figure 2.2. Scenario comparison – electricity generation mix by country (Fitfor55 and Phase-out scenarios)

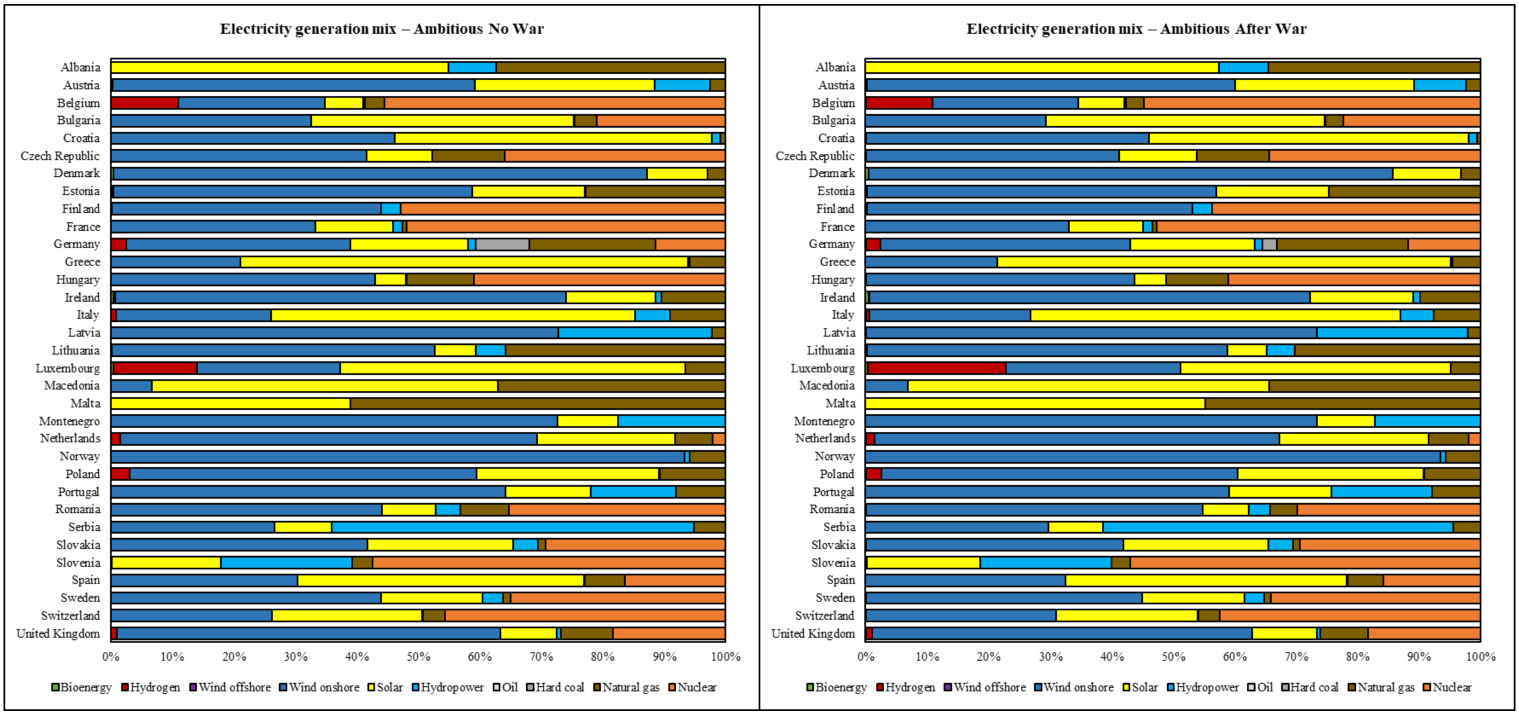


Figure 2.3. Scenario comparison – electricity generation mix by country (Ambitious scenarios)

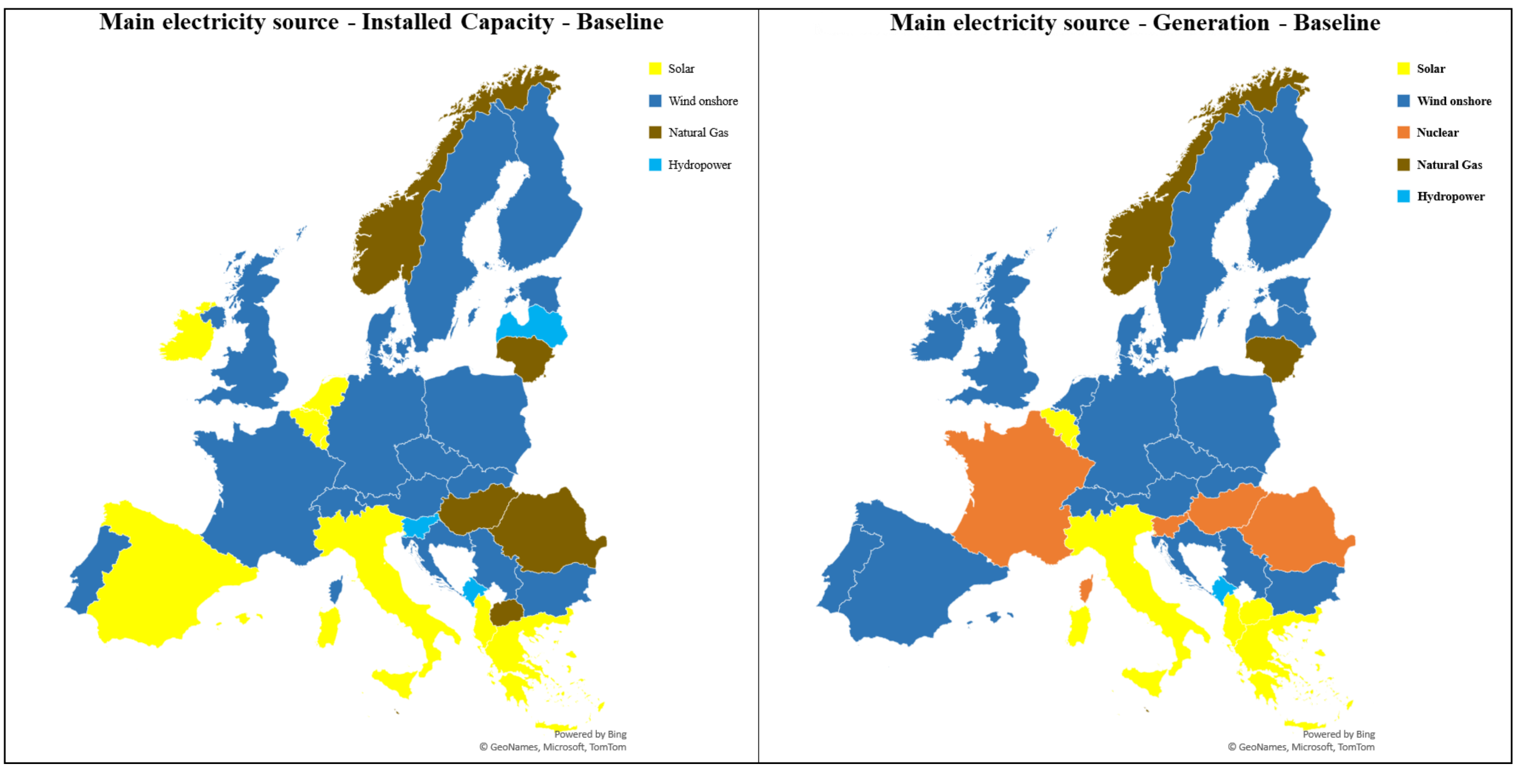


Figure 3.1. Scenario comparison – Main installed capacity and electricity generation source by country (Baseline scenario)

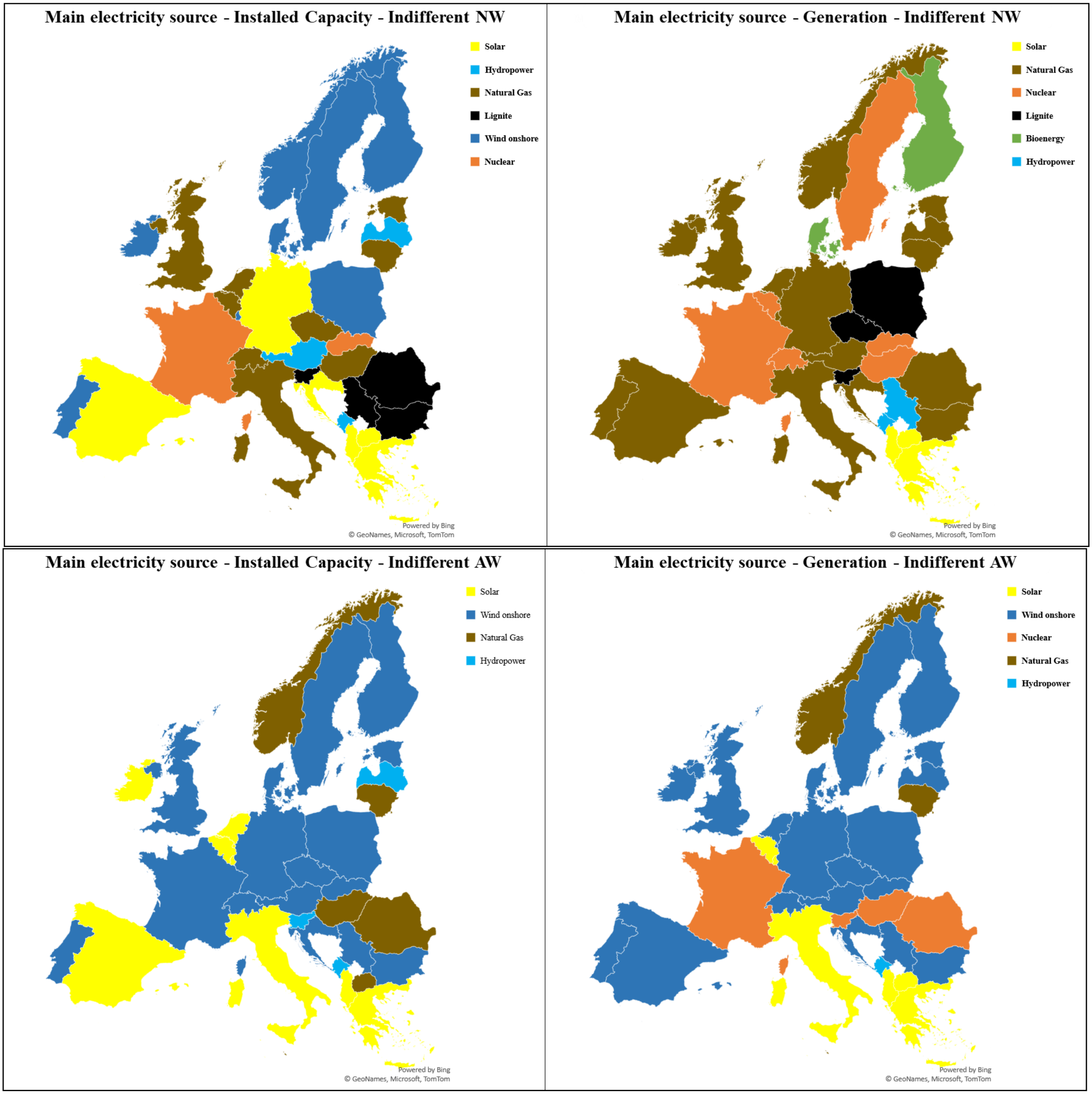


Figure 3.2. Scenario comparison – Main installed capacity and electricity generation source by country (Indifferent scenarios)

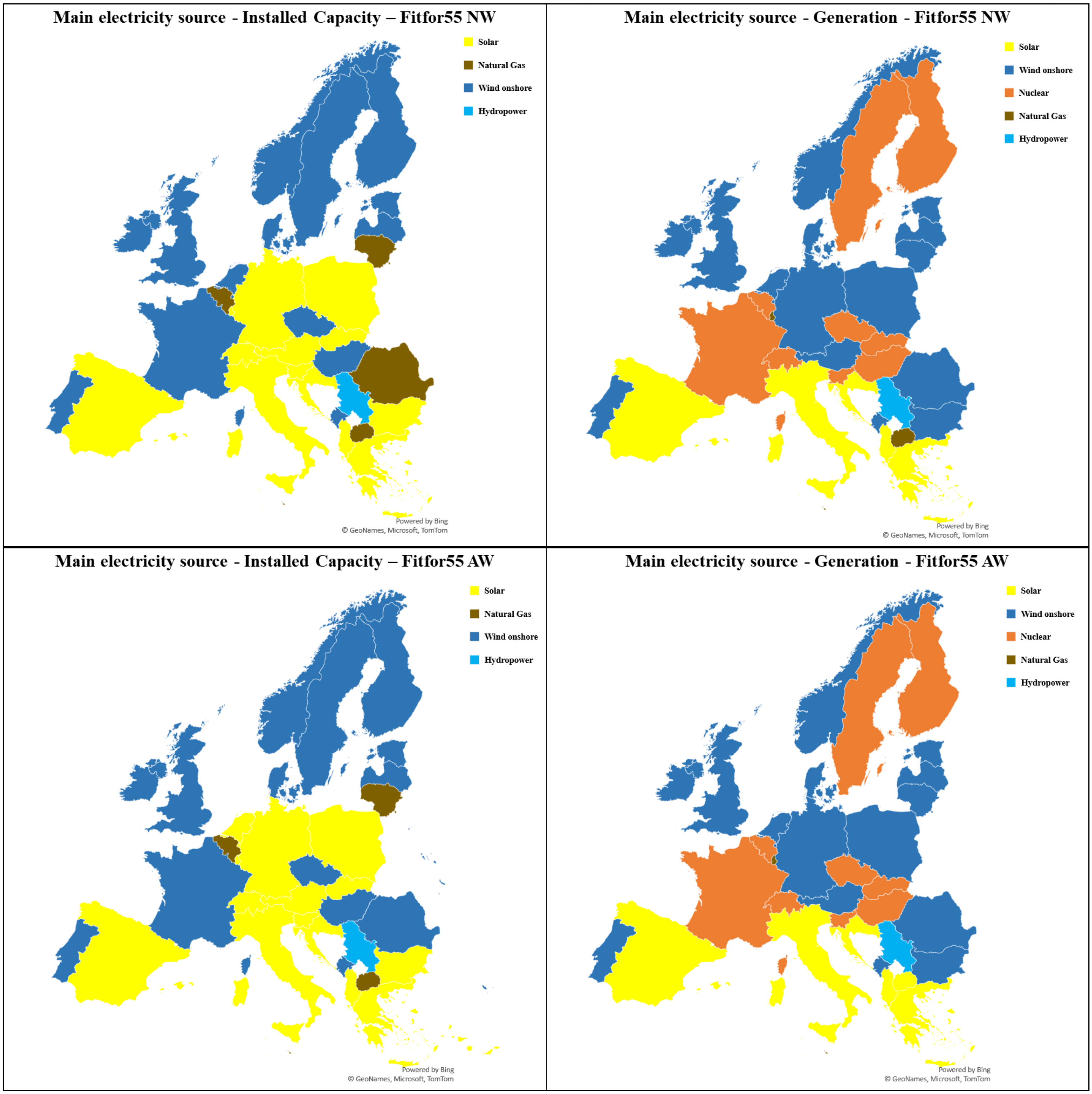


Figure 3.2. Scenario comparison – Main installed capacity and electricity generation source by country (Fitfor55 scenarios)

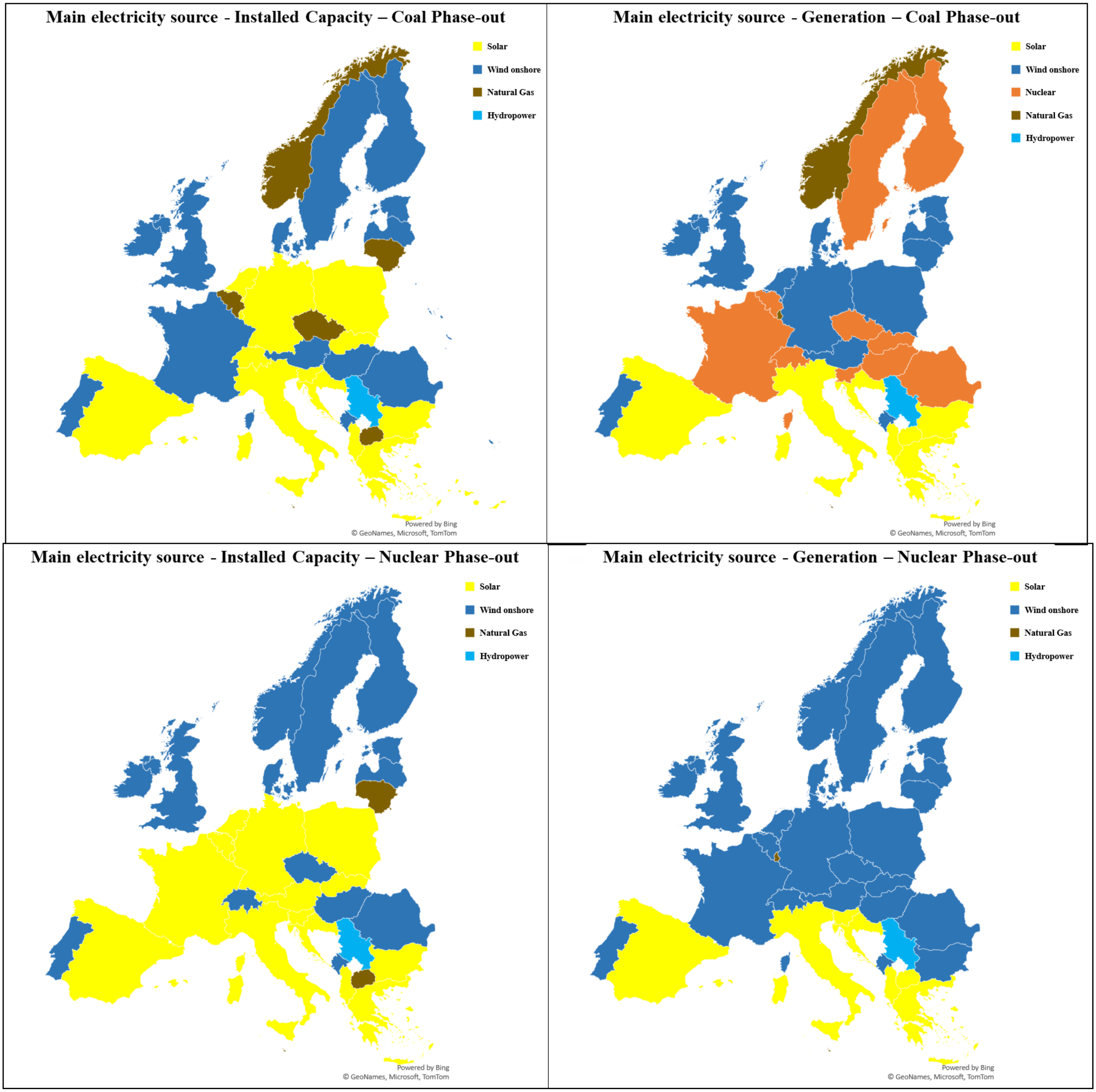


Figure 3.3. Scenario comparison – Main installed capacity and electricity generation source by country (Phase-out scenarios)

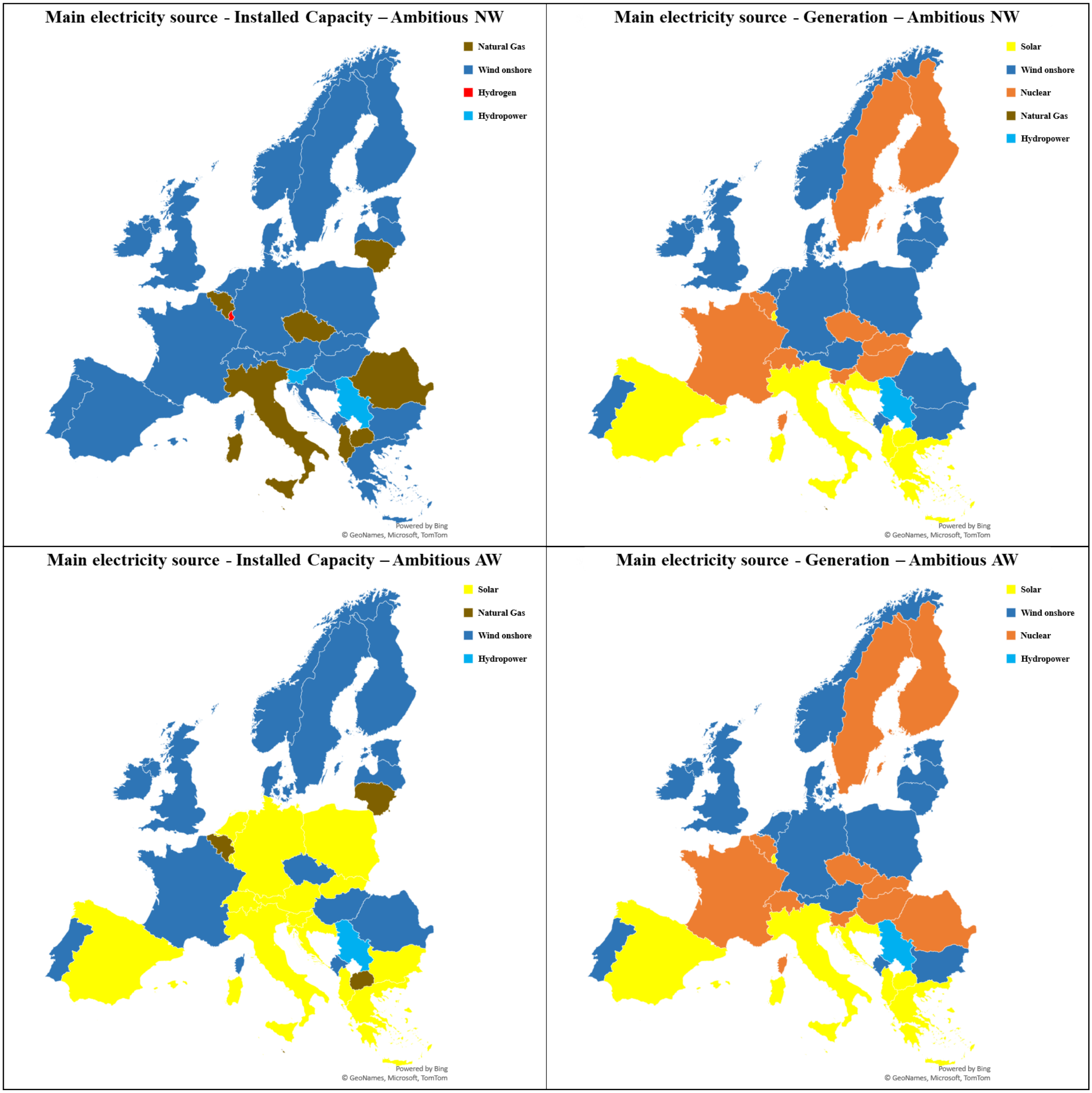


Figure 3.4. Scenario comparison – Main installed capacity and electricity generation source by country (Ambitious scenarios)

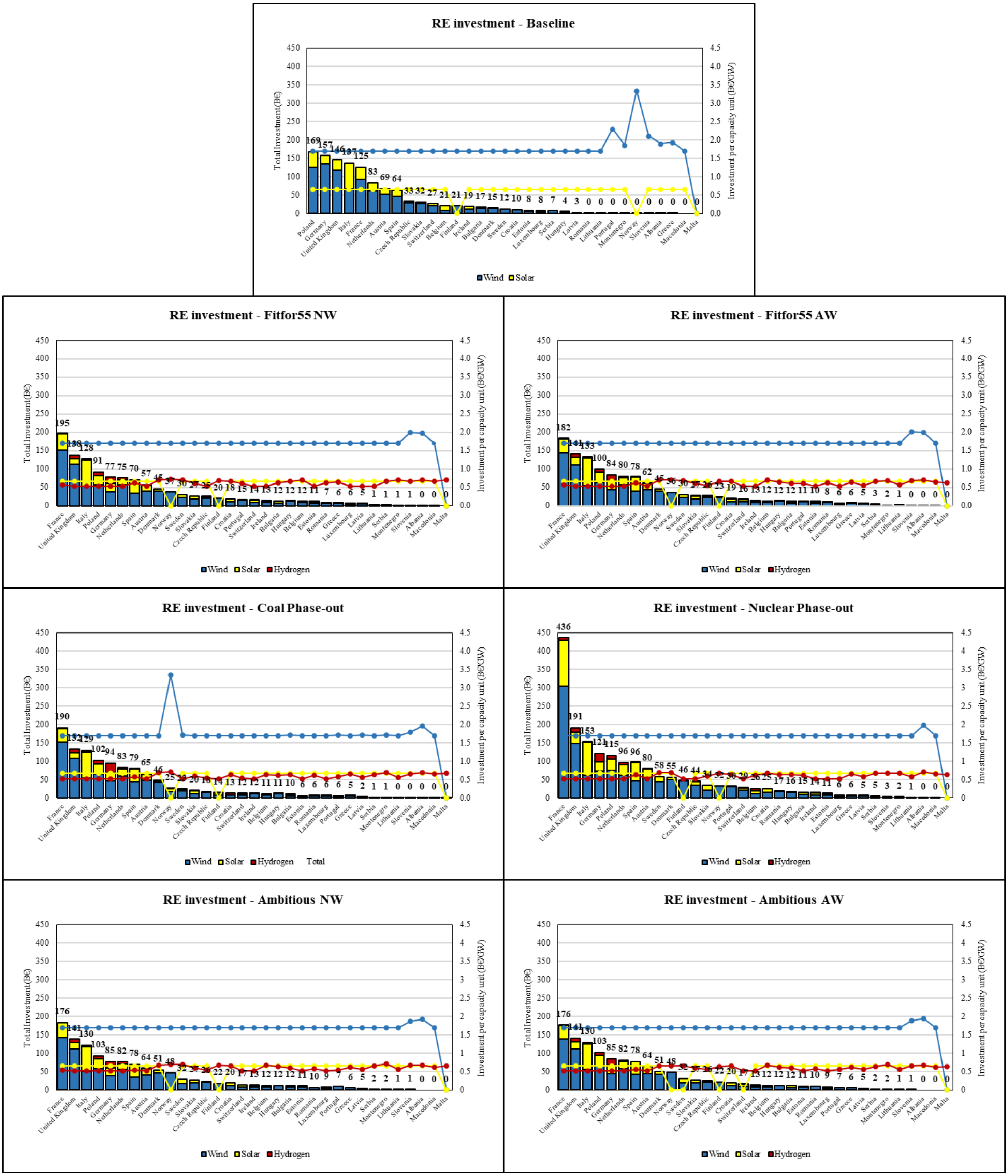


Figure 4. Scenario comparison – Investment on RE infrastructure

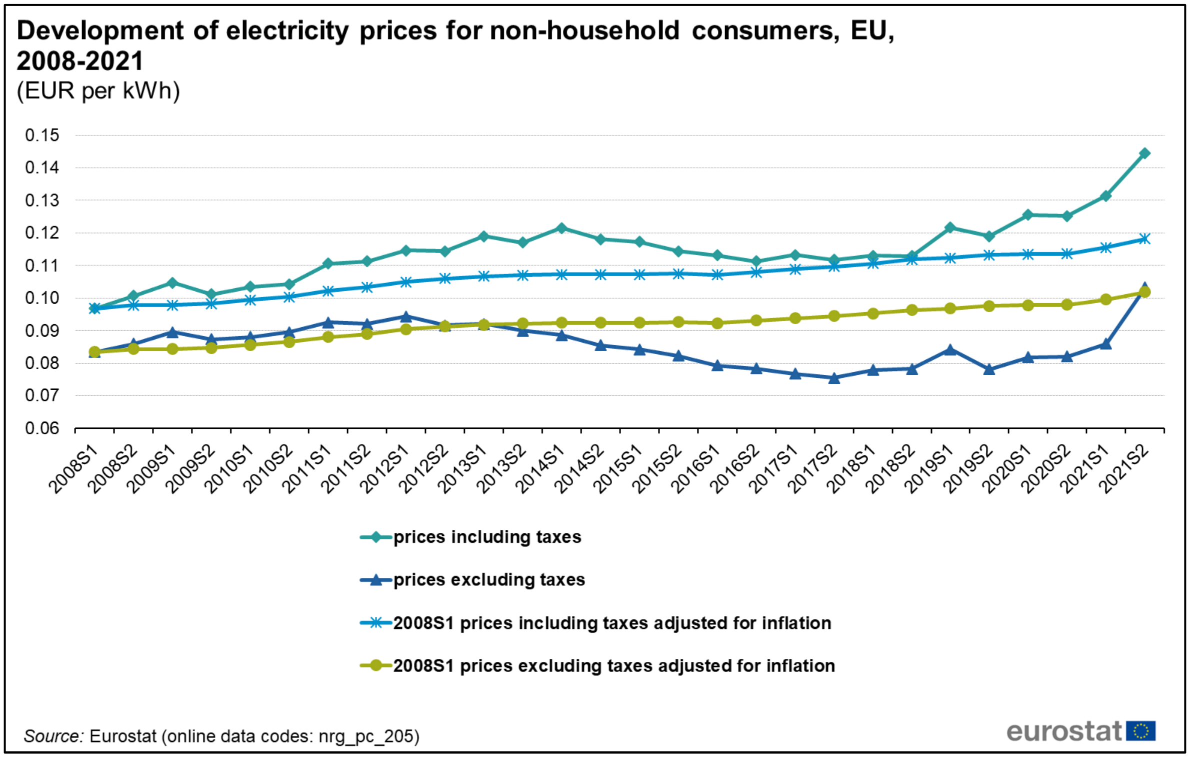


Figure 5. Historic electricity prices for non-household consumers in the EU.

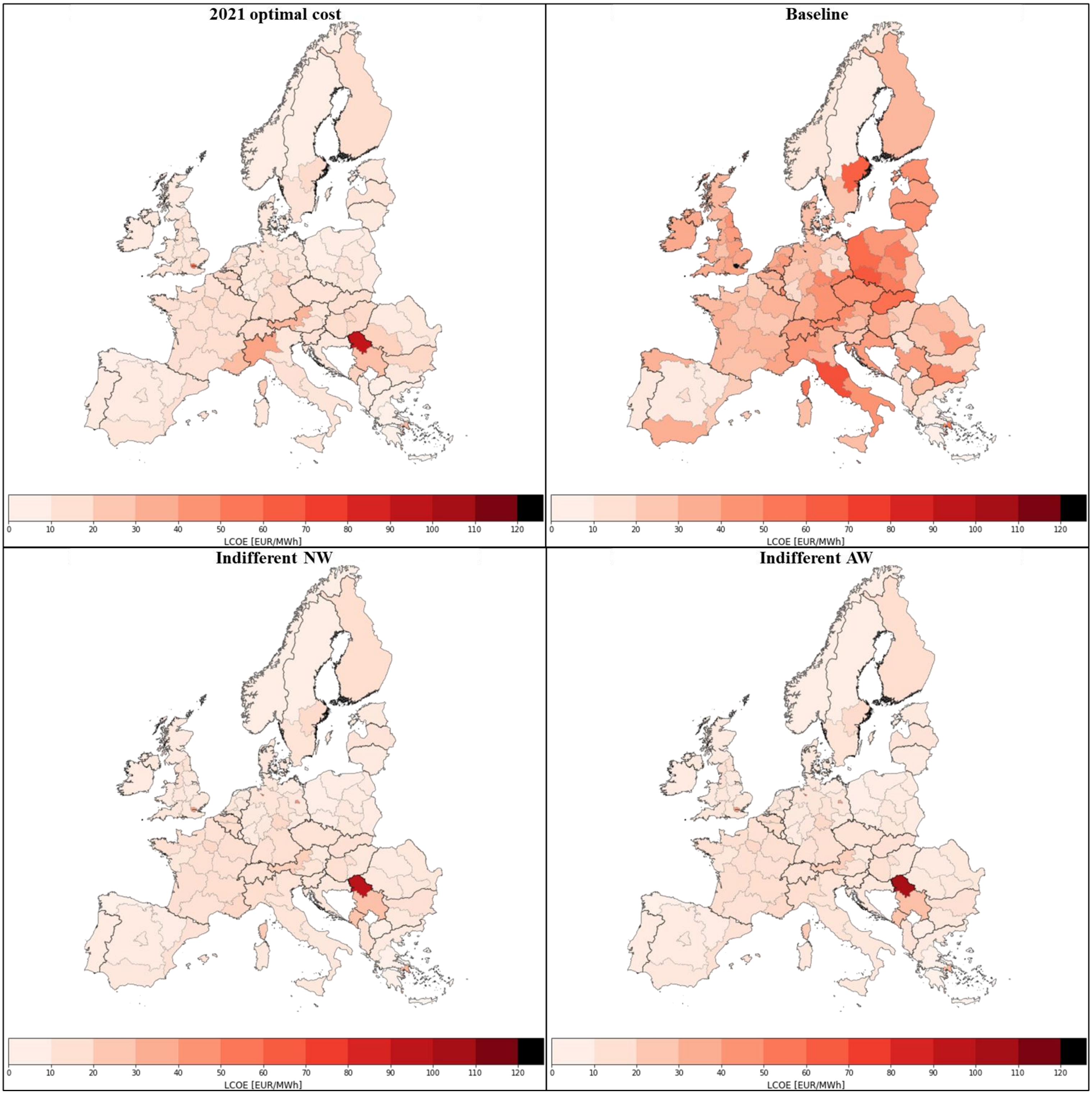


Figure 6.1. Scenario comparison – LCOE by region (2021 optimal cost, Baseline, and Indifferent scenarios)

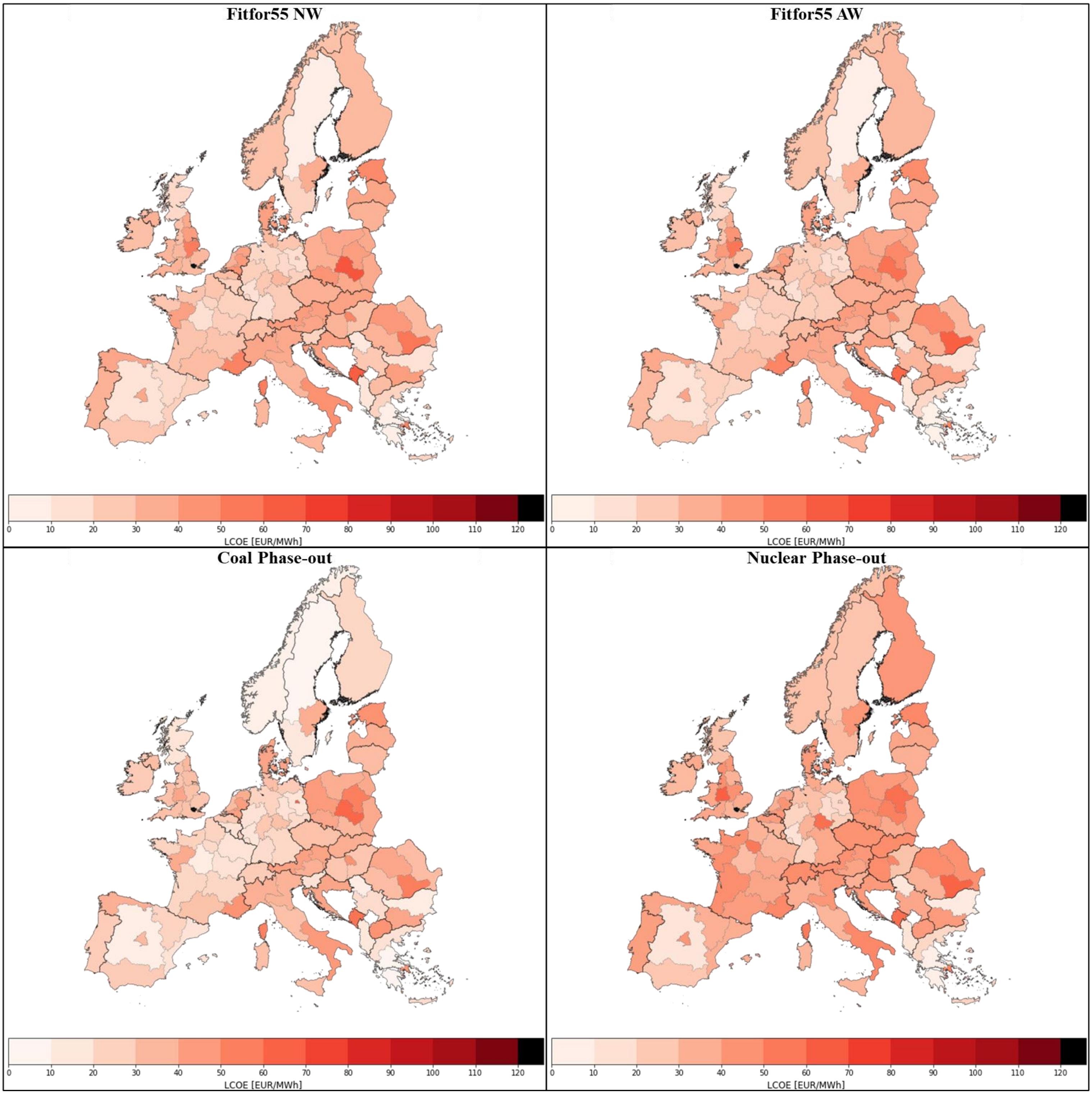


Figure 6.2. Scenario comparison – LCOE by region (Fitfor55 and Ambitious scenarios)

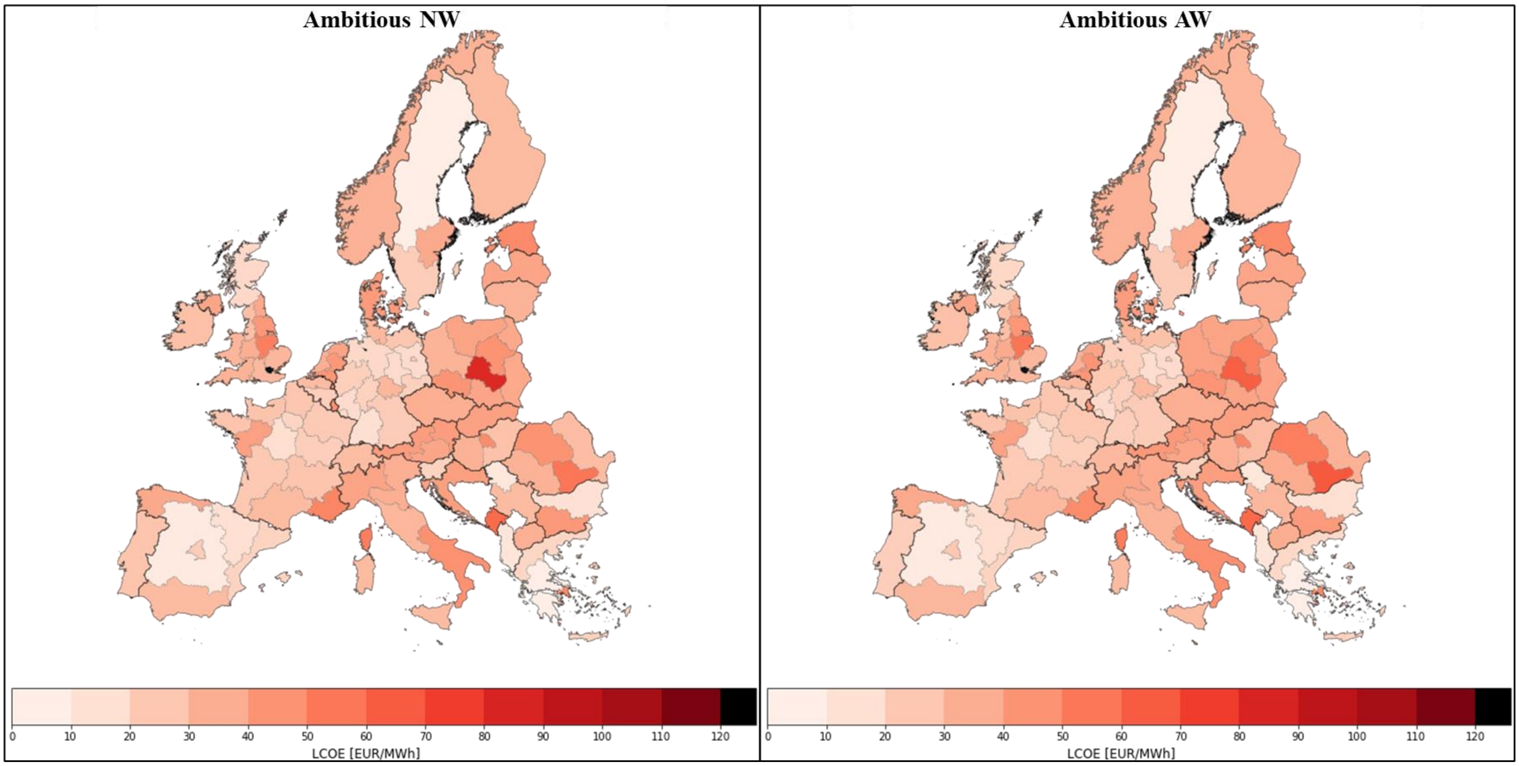


Figure 6.3. Scenario comparison – LCOE by region (Ambitious scenarios)

Table 11. Scenario comparison for the achievement of the 2030 national targets for the RE share in electricity generation.

Country	**Classification**	**Success rate**	***2021 optimal cost***	**Baseline**	**Indifferent NW**	**Indifferent AW**	**Fitfor55 NW**	**Fitfor55 AW**	**Coal Phase Out**	**Nuclear Phase Out**	**Ambitious NW**	**Ambitious AW**
Albania	H	10	X	X	X	X	X	X	X	X	X	X
Austria	H	0										
Belgium	L	2		X						X		
Bulgaria	M	7		X			X	X	X	X	X	X
Croatia	H	7		X			X	X	X	X	X	X
Czech Republic	L	7		X			X	X	X	X	X	X
Denmark	M	0										
Estonia	L	7		X			X	X	X	X	X	X
Finland	L	2		X						X		
France	M	7		X			X	X	X	X	X	X
Germany	M	2		X						X		
Greece	M	10	X	X	X	X	X	X	X	X	X	X
Hungary	L	6		X			X	X		X	X	X
Ireland	M	7		X			X	X	X	X	X	X
Italy	M	8	X	X			X	X	X	X	X	X
Latvia	M	7		X			X	X	X	X	X	X
Lithuania	M	6					X	X	X	X	X	X
Luxembourg	L	7		X			X	X	X	X	X	X
Malta	L	10	X	X	X	X	X	X	X	X	X	X
Montenegro	M	7	X				X	X	X	X	X	X
Netherlands	H	7		X			X	X	X	X	X	X
North Macedonia	H	0										
Norway	M	0										
Poland	L	7		X			X	X	X	X	X	X
Portugal	M	1								X		
Romania	M	4					X	X		X	X	
Serbia	M	5		X				X		X	X	X
Slovakia	M	7		X			X	X	X	X	X	X
Slovenia	H	1								X		
Spain	H	3						X		X		X
Sweden	M	1								X		
Switzerland	M	1								X		
United Kingdom	M	4		X				X		X		X

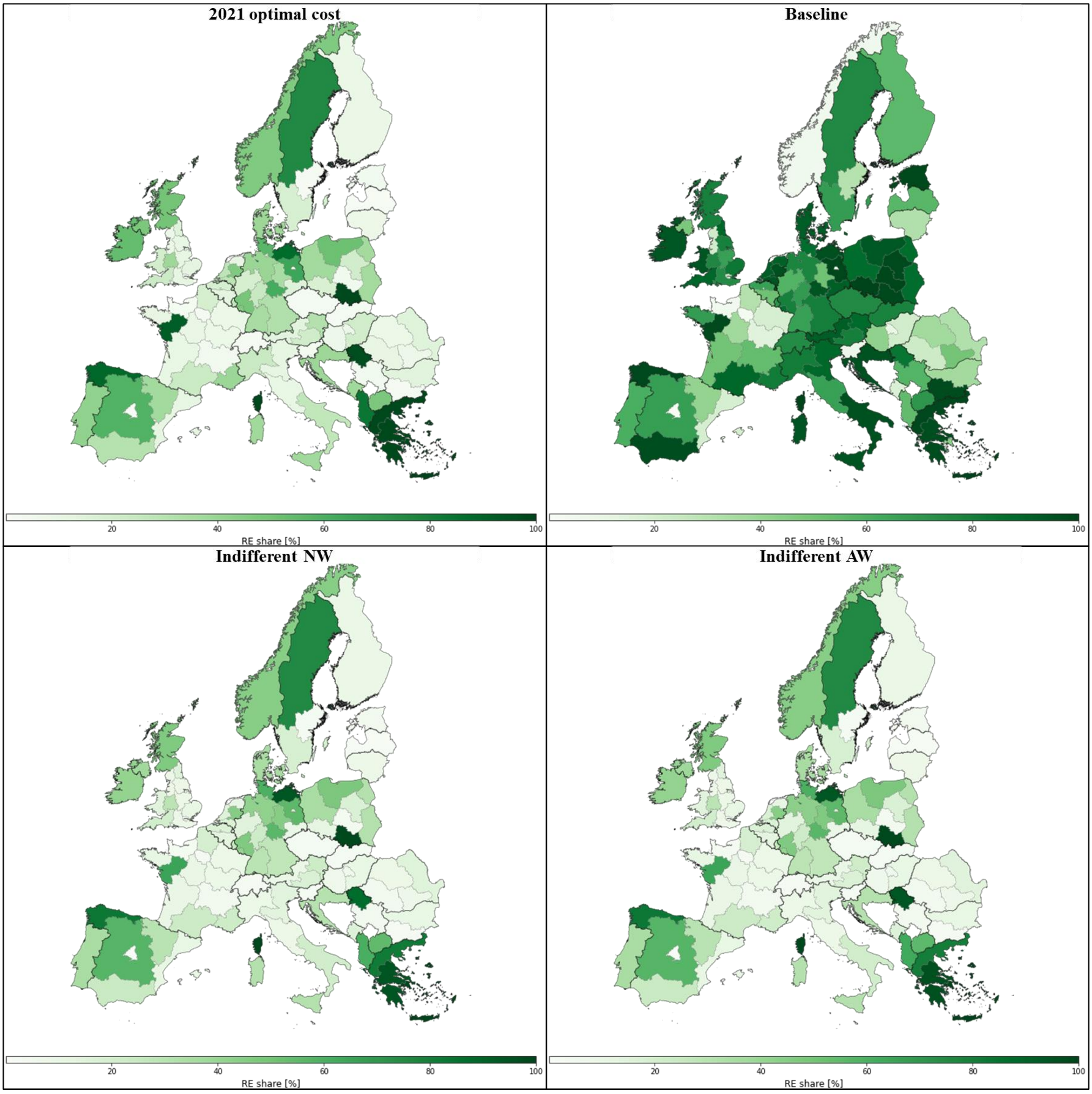


Figure 7.1. Scenario comparison – RE share by region (2021 optimal cost, Baseline, and Indifferent scenarios)

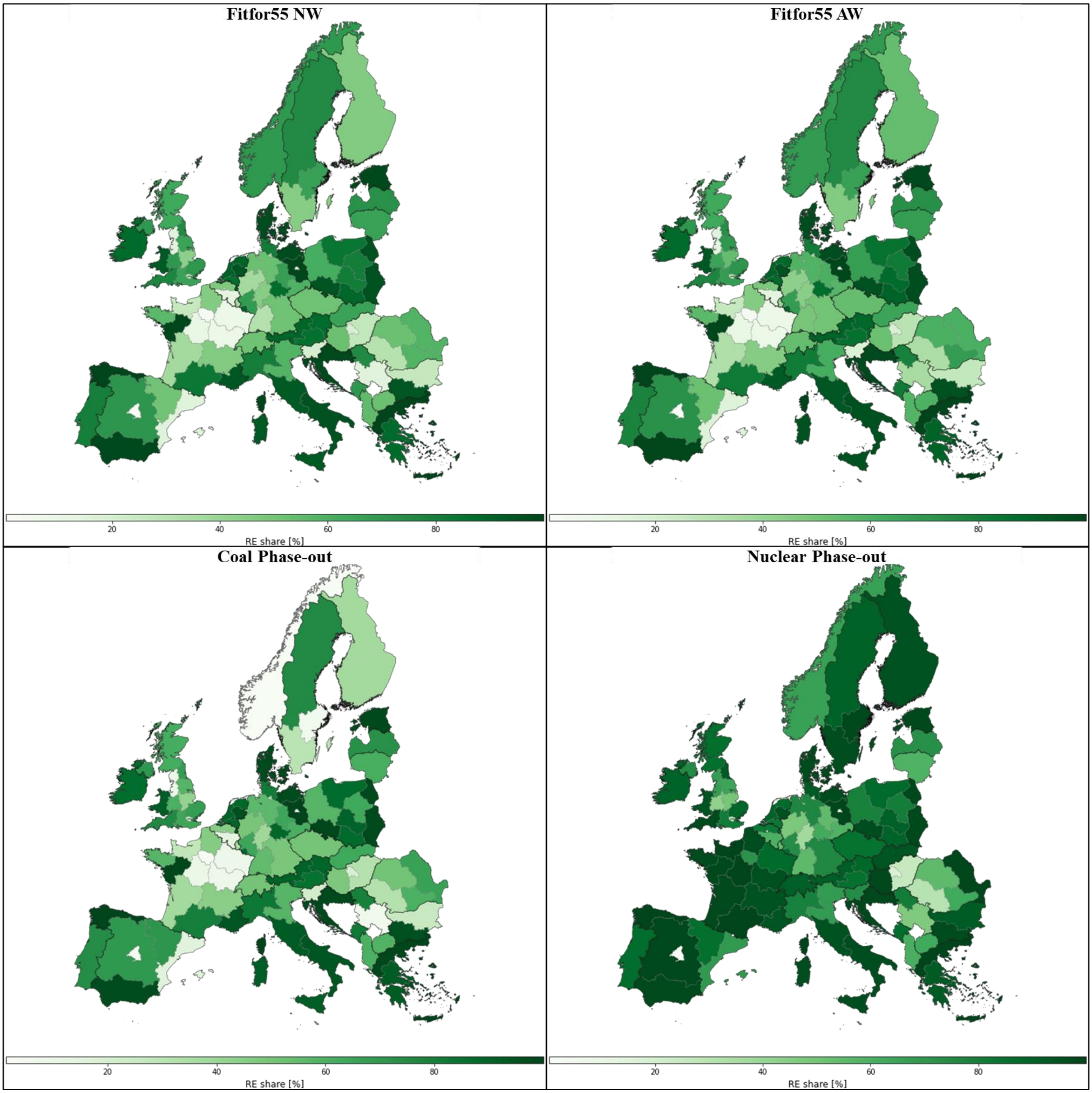


Figure 7.2. Scenario comparison – RE share by region (Fitfor55 and Phase-out scenarios)

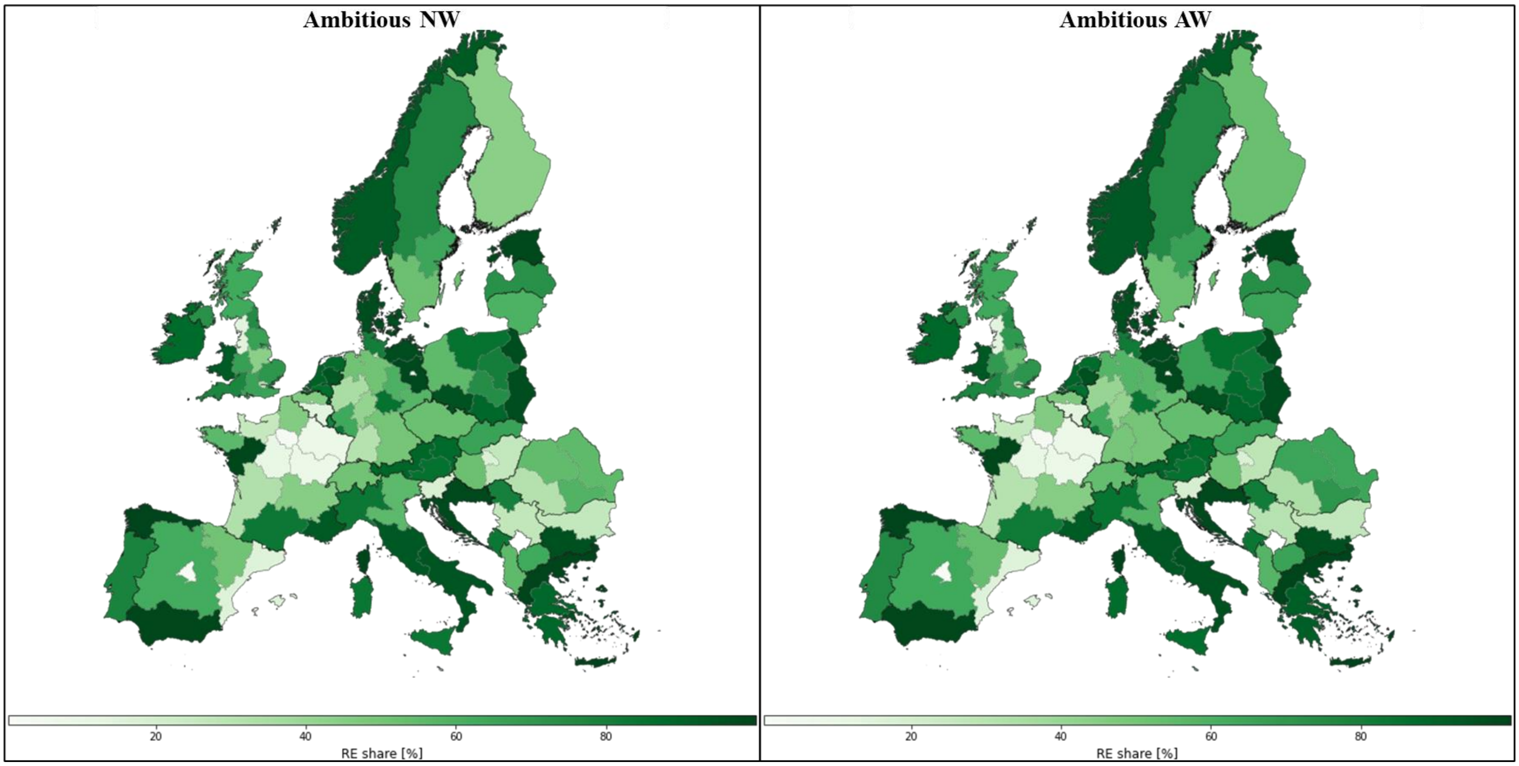


Figure 7.3. Scenario comparison – RE share by region (Ambitious scenarios)

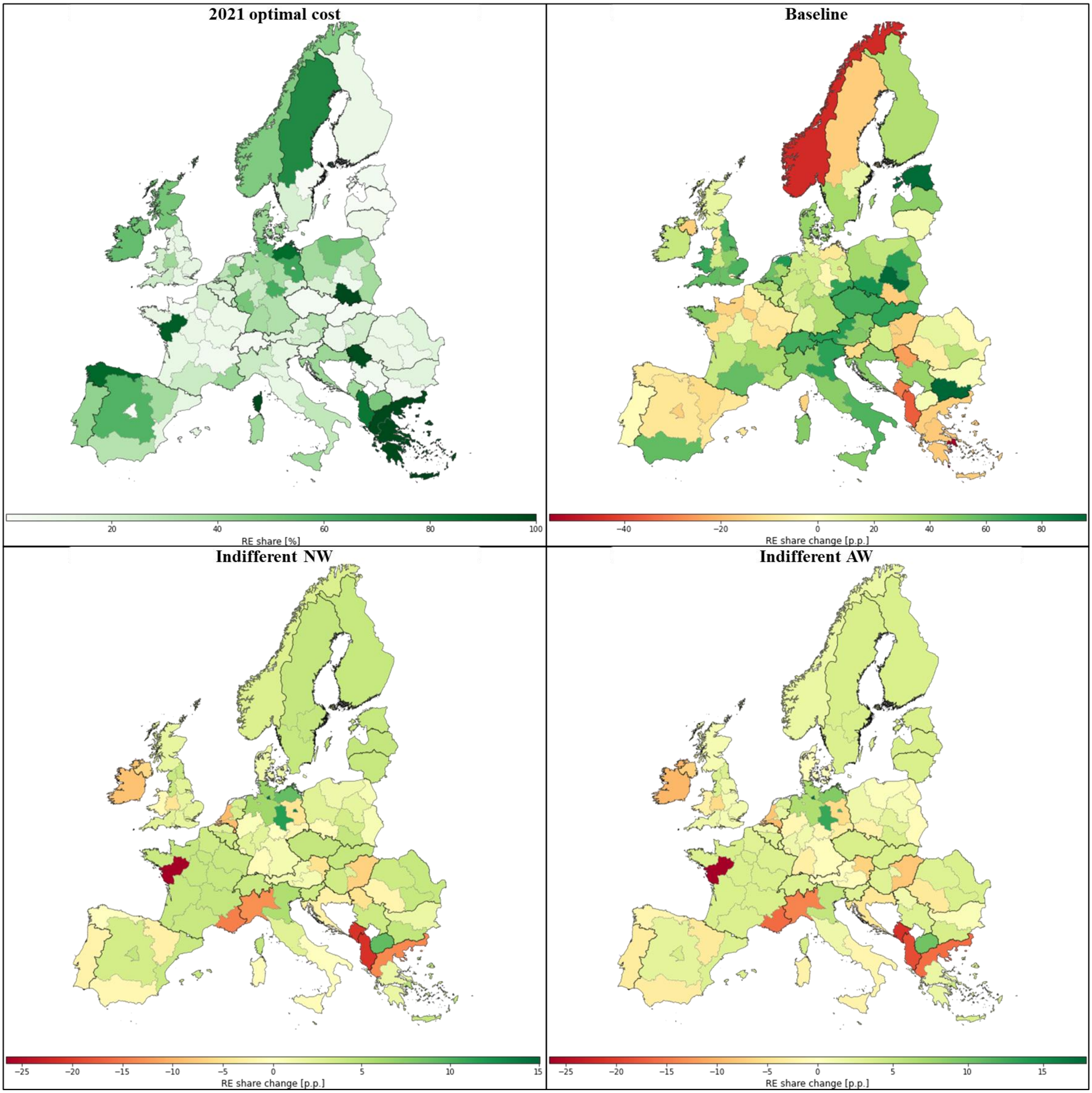


Figure 8.1. Scenario comparison – RE share changed vs 2021 optimal cost scenario by region (Baseline and Indifferent scenarios)

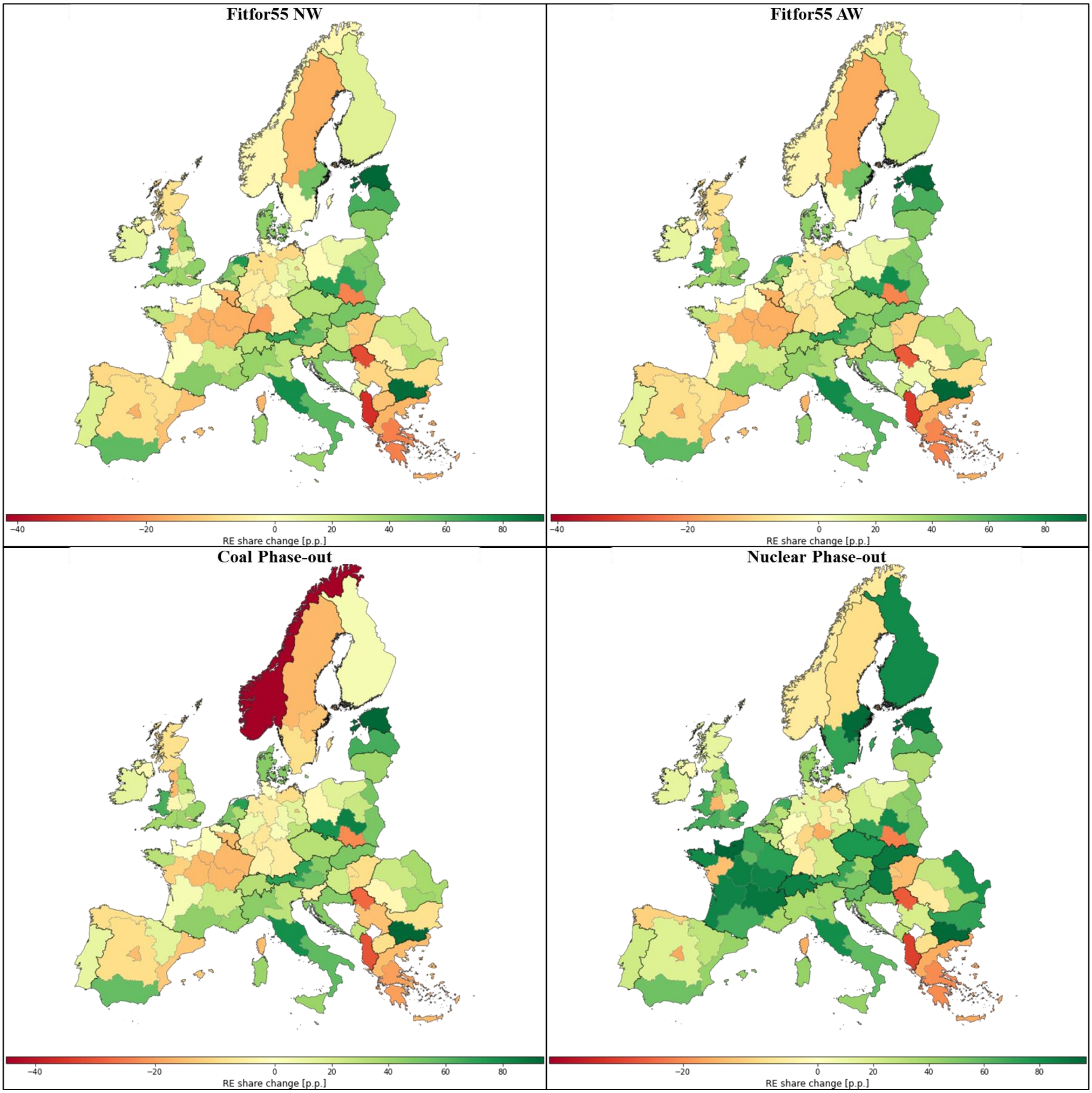


Figure 8.2. Scenario comparison – RE share changed vs 2021 optimal cost scenario by region (Fitfor55 and Phase-out scenarios)

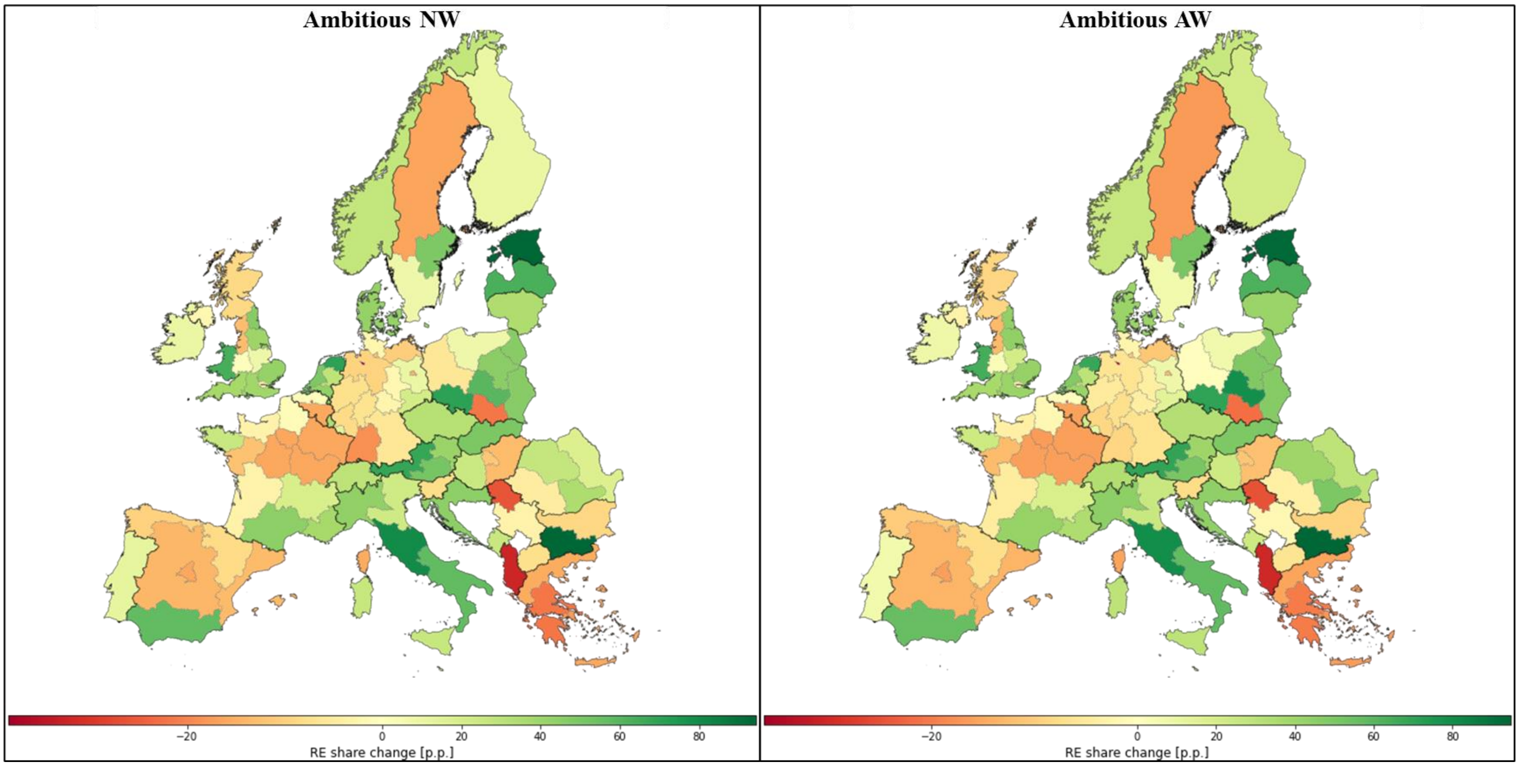


Figure 8.3. Scenario comparison – RE share changed vs 2021 optimal cost scenario by region (Ambitious scenarios)

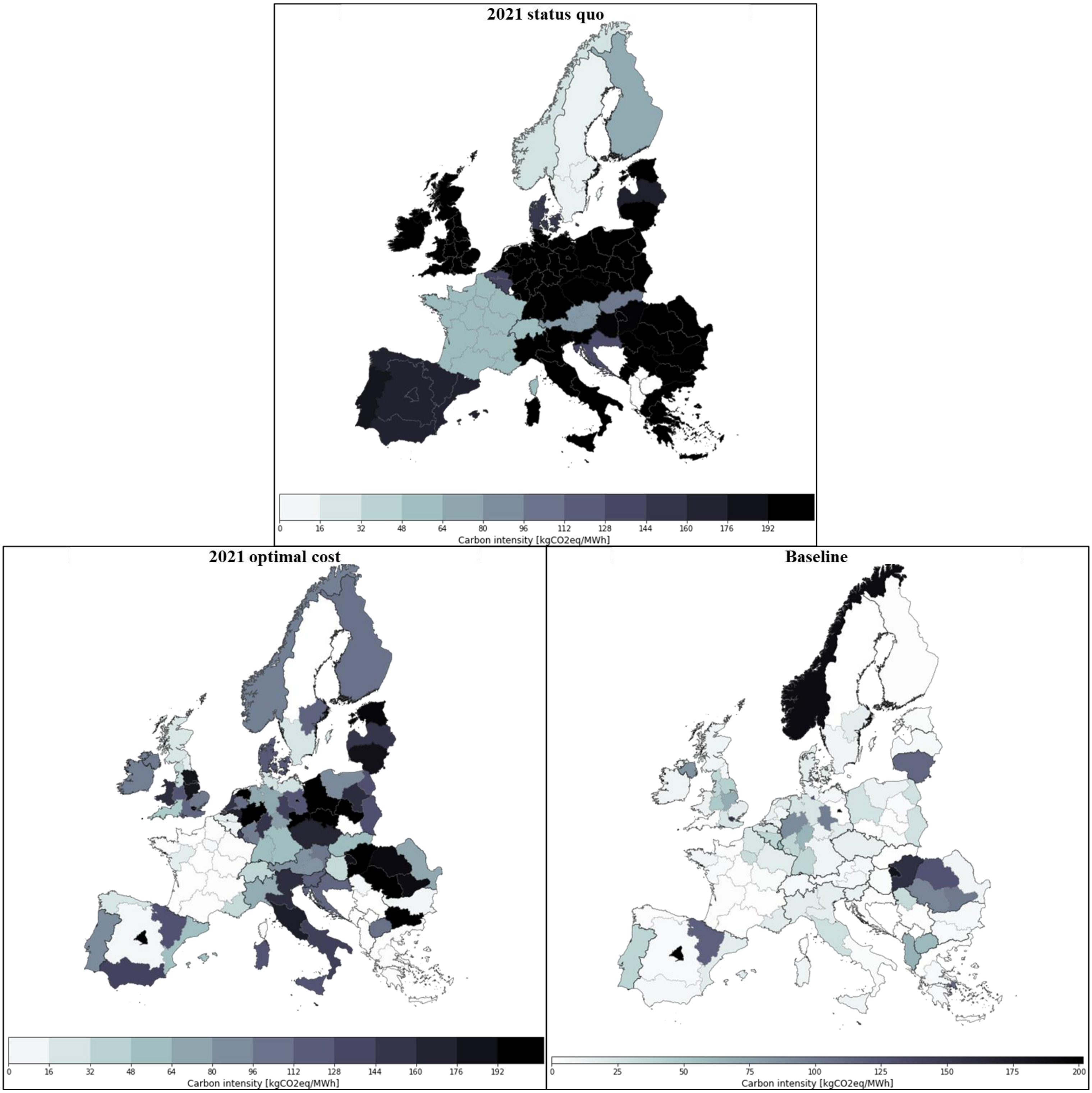


Figure 9.1. Scenario comparison – Carbon intensity of electricity generation by region (2021 status quo, 2021 optimal cost, and Baseline scenarios)

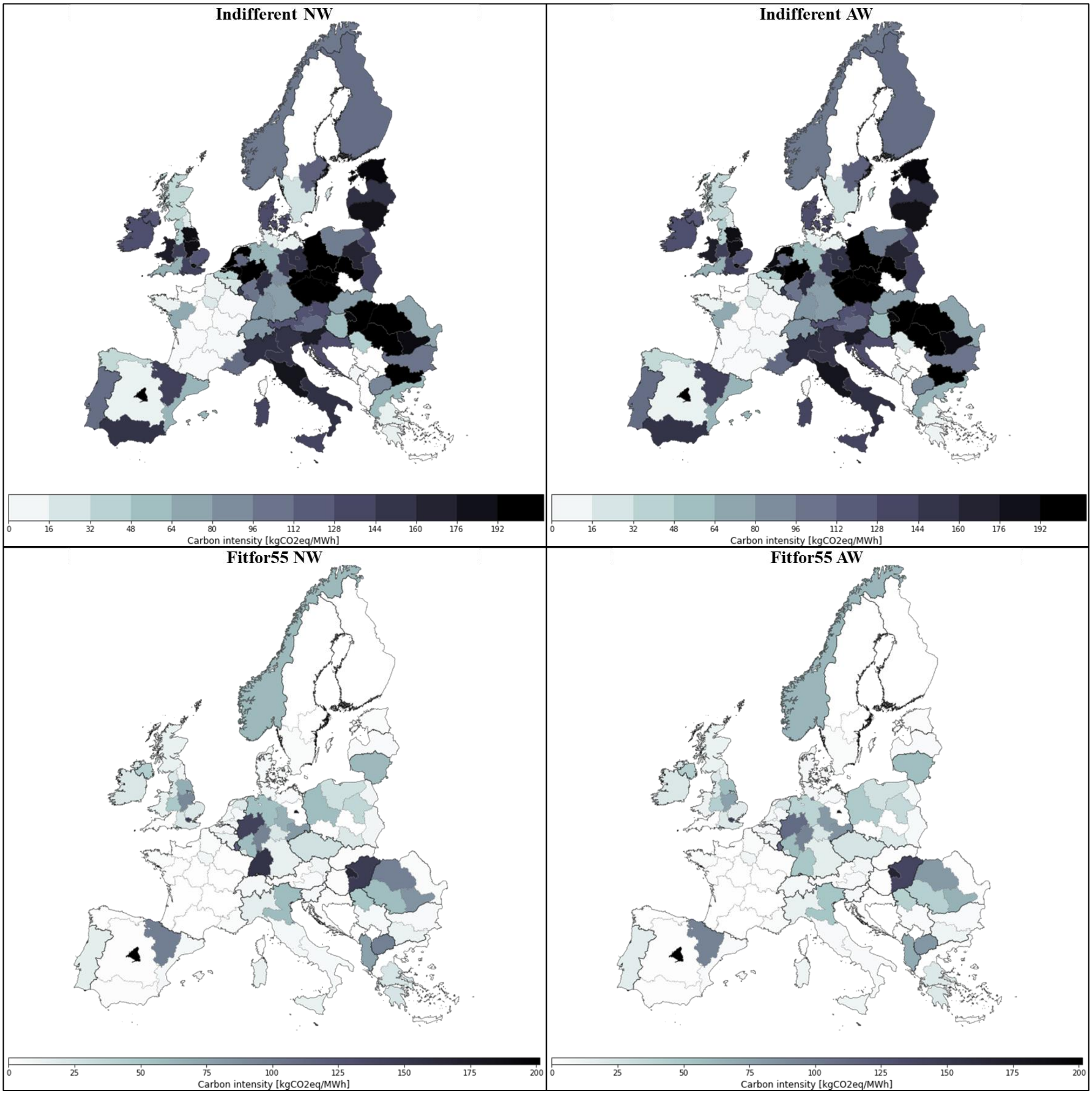


Figure 9.2. Scenario comparison – Carbon intensity of electricity generation by region (Indifferent and Fitfor55 scenarios)

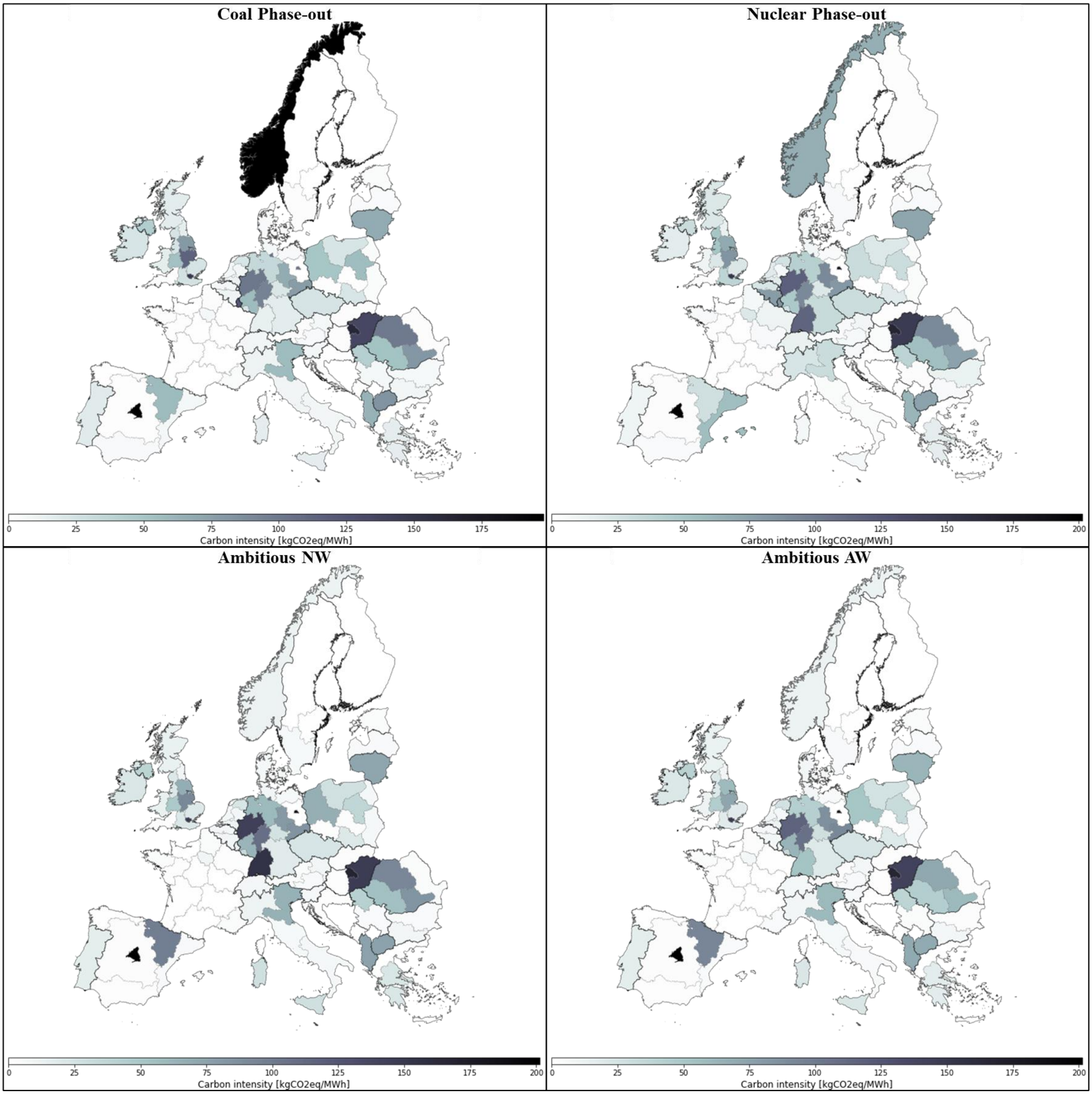


Figure 9.3. Scenario comparison – Carbon intensity of electricity generation by region (Phase-out and Ambitious scenarios)

Appendix 2

This appendix contains the information on the main sources of information used for the creation of the database and the setup of FINE. It is divided into five parts: the *key data sources* section shows the main sources used for the creation of the reference and study database. *Specific sources by countries* gives an overview of extra sources of information to complement the key data sources to match the reference capacity at country level. *Sources for techno-economic parameters* shows the sources for commodities price and techno-economic parameters of power plants. *National targets* provides an overview of the sources used for the 2030 national targets at country level. Finally, *emissions factors* shows the reference used for the emission factor of the fossil power plants.

Key data sources

- IRENA [29] [30]
- IAEA – Power Reactor Information System (PRIS) [31]
- Powerplantmatching [32]
    - ENTSO-E transparency platform
    - World Resource Institute
    - Open Power System Data
    - Global Energy Observatory
    - Europe Beyond Coal
- The Wind Power[42]
- Global Energy Monitoring (GEM) [43]
    - Global Solar Power Tracker [44]
    - Global Coal Plant Tracker [45]
    - Global Gas Tracker [46]
- IEA – Biomass global database [47]
- Ember [38]

Specific sources by countries

Albania

Hydropower

- Regional Strategy for Sustainable Hydropower in the Western Balkans [48]
- Mapping of hydropower plant in Albania, using Geographic Information System [49]
- National Agency of Natural Resources – Hydro-energetic potential of Albania [50]
- Energy Regulatory Authority: Hydro energy production 2007-2021 [51]

Austria

Hydropower

- Verbund data [52]

Solar

- STAT atlas [53]

Belgium

General

- ELIA [54]

Solar

- Study of PV park in Brussels capital region – 2019 [55]
- Flemish Energy and Climate Agency – PV capacity per municipality [56]
- Wallonia dynamic map [57]

Natural gas

- Brugel – Report on green electricity [58]

The Czech Republic

Solar

- Capacity of photovoltaic power plants in the Czech Republic [59]
- List and map of solar power plants in the Czech Republic [60]
- List Solar [61]

Finland

Solar

- Optimization of rooftop photovoltaic installations to maximize revenue in Finland based on customer class load profiles and simulated generation [62]

France

General

- Open Data Energy Networks – National register of installations of electricity production and storage [63]

Germany

General

- Bundesnetzagentur – Power plants list [64]

Solar

- Bundesnetzagentur – Market Master Data Register (MaStR) [65]

Hungary

Solar

- List Solar [66]
- STS group [67]

Italy

Solar

- National Statistic Office – Statistic report: PV solar 2020 [68]
- Sonnedix [69]

Coal

- Assocarboni [70]

Netherlands

Solar

- Statistics Netherlands (CBS) – solar power; capacity of solar panels in homes, districts and neighbourhoods [71]

Norway

Hydropower

- Norwegian Water Resources and Energy Directorate – Hydropower database [72]

Poland

Solar

- Institute for Renewable Energy – Report Photovoltaic Market in Poland 2022 [73]
- Enerad – The largest solar farms in Poland - Ranking 2022 [74]

Portugal

Solar

- Regional Outlook 2021 - Country notes: Portugal - progress in the net zero transition [75]
- Solar Feeds [76]

Romania

Solar

- Solar Feeds [77]

Slovakia

Solar

- Green Energy Slovakia – Projects portfolio [78]

Spain
General
- Catalan Institute of Energy – Electric energy production installation: Individual data [79]
- Iberdrola – Map of power plants and main operative data [80]

Solar
- Energy from Andalucia Agency – Report on energy infrastructure [81]
- Ministery of economic affairs and digital transformation: Data catalogue – Data on renewable energy in Aragon [82]
- Ministery of economic affairs and digital transformation: Data catalogue – PV installations inventory (Madrid). Data coming directly from Madrid's city hall. [83]

Sweden
General
- Swedish Energy Agency – Energy in Sweden Facts & Figures 2021 [84]

Bioenergy
- Bioenergy power plants map 2021. [85]
-

Hydropower
- Vatenfall [86]
- Skellefteå [87]
- Statkraft [88]
- Fortum [89]

Solar
- Swedish Energy Agency – Grid connected solar instalations [90]

Switzerland
General
- Swiss Federal Office of Energy – Electricity production plants in Switzerland [91]

Hydropower
- Swiss Federal Office of Energy – Large scale hydropower plants list [92]

United Kingdom
General
- Department for Business, Energy & Industrial Strategy – UK Energy in brief 2021 [93]
- Department for Business, Energy & Industrial Strategy – Digest of United Kingdom Energy Statistics (DUKES) [94]
- UK electricity production [95]

Sources for techno-economic parameters

Commodities price

Natural Gas

- 2030 price (2022 forecast): REPower EU forecast [6]
- 2030 price (2021 forecast): IEA World Energy Outlook 2021 [96]
- 2021 price: World Bank Commodities Price Forecast 2021 [97]

Liquified Natural Gas (LNG)

- 2030 price (2022 forecast): REPower EU forecast [6]
- 2030 price (2021 forecast): World Bank Commodities Price Forecast 2021 [97]
- 2021 price: World Bank Commodities Price Forecast 2021 [97]
- *Oil*
- 2030 price (2022 forecast): REPower EU forecast [6]
- 2030 price (2021 forecast): World Bank Commodities Price Forecast 2021 [97]
- 2021 price: World Bank Commodities Price Forecast 2021 [97]

Hard coal

- 2030 price (2022 forecast): REPower EU forecast [6]
- 2030 price (2021 forecast): IEA World Energy Outlook 2021 [96]
- 2021 price: World Bank Commodities Price Forecast 2021 [97]

Lignite

- 2030 price (2022 forecast): TYNDP 2020 Scenario Report – ENTSOE [98]
- 2030 price (2021 forecast): TYNDP 2020 Scenario Report – ENTSOE [98]
- 2021 price: TYNDP 2020 Scenario Report – ENTSOE [98]

Hydrogen

- 2030 price (2022 forecast): Statista [99]
- 2030 price (2021 forecast): Statista [99]
- 2021 price: IRENA – Global Hydrogen Trade Cost[100]

Biomass

- 2030 price (2022 forecast): Danish Energy Agency – Analysis of biomass prices [101]
- 2030 price (2021 forecast): Danish Energy Agency – Analysis of biomass prices [101]
- 2021 price: Rotterdam Biomass Commodities Network – Biomass Market Update [102]

Nuclear

- 2030 price (2022 forecast): TYNDP 2020 Scenario Report – ENTSOE [98]
- 2030 price (2021 forecast): TYNDP 2020 Scenario Report – ENTSOE [98]
- 2021 price: TYNDP 2020 Scenario Report – ENTSOE [98]

Techno-economic parameters

The techno-economic parameters used in this thesis are extracted from three sources:

Levelized cost of electricity renewable energy technologies – 2021 report from the Fraunhofer Institute for solar energy systems ISE. [103]

- Opex per capacity for lignite and hard coal

Demystifying the Costs of Electricity Generation Technologies – 2020 World Bank report. [104]

- Opex per capacity and opex per operation for nuclear power and hydropower.

Technology Data for Generation of Electricity and District Heating – Danish Energy Agency.[105]

- All the other techno-economic parameters.

National targets sources

National 2030 targets

The 2030 targets on RE share and GHG emissions are taken from the National Energy & Climate Plans of each member country of the European Union.

For the countries that are not part of the European Union, the targets are taken from the following sources:

Albania

Even if Albania is not part of the EU, it published its own National Energy & Climate Plan in July 2021 under the standards of the EU.

Montenegro

Development of the National Strategy of Climate Change Until 2030 – 2015 report.

North Macedonia

Even if North Macedonia is not part of the EU, it published its own National Energy & Climate Plan in July 2020 under the standards of the EU.

Serbia

Climate Strategy & Action Plan of the Republic of Serbia. December 2019

Switzerland

Switzerland's Long-Term Climate Strategy. August 2019

Norway

Norway's National Plan related to the Decision of the EEA Joint Committee. October 2019

The United Kingdom

Since The United Kingdom was part of the European Union until 2021, it has its own National Energy & Climate Plan.

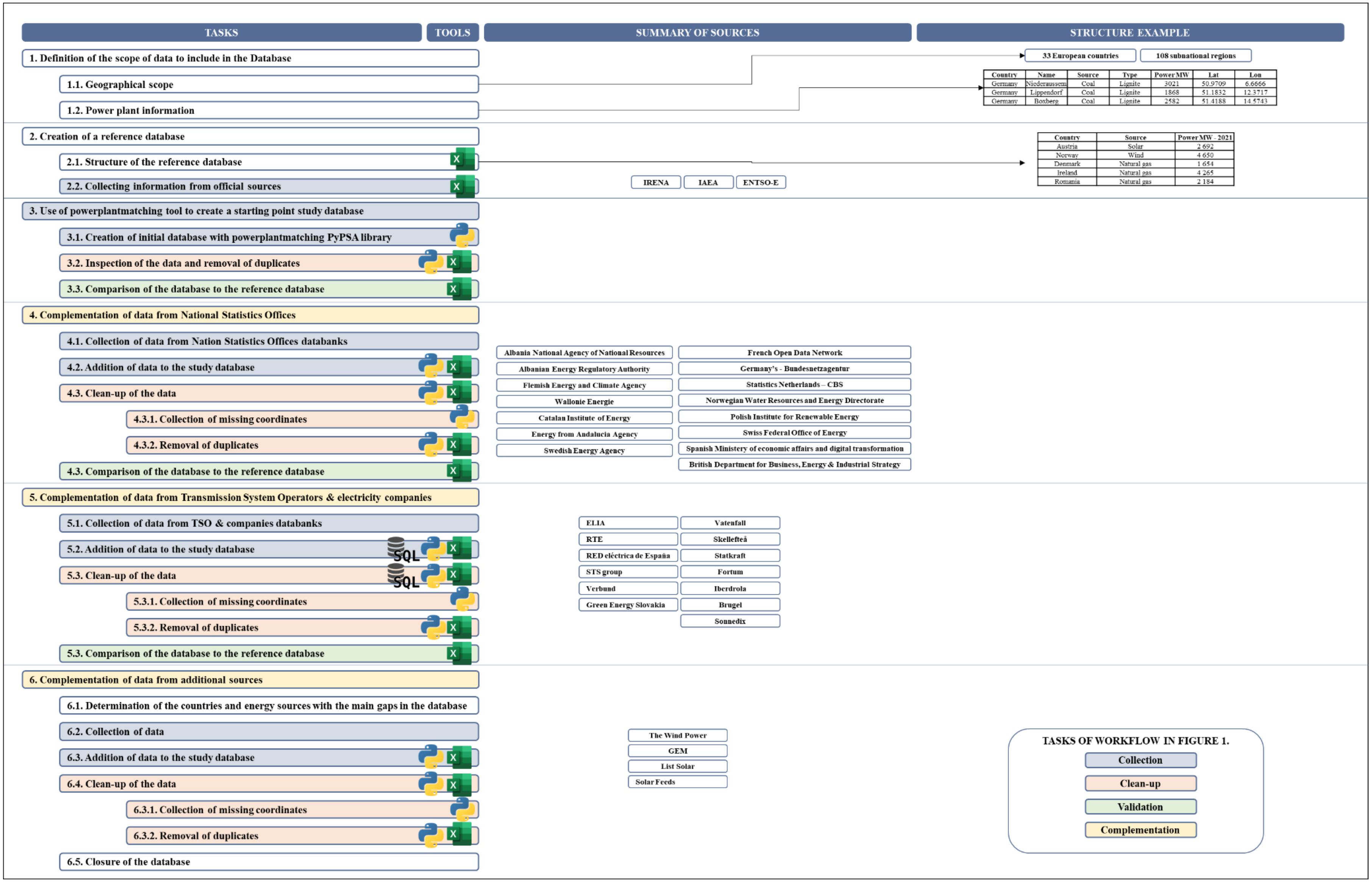
Coal phase-out plans

Europe Beyond Coal [107]

Emissions factors

All the emission factors are taken from the *CoM Default Emission Factors for the Member States of the European Union* report. [106]

Appendix 3. Detailed task flow for the creation of the study database



Country	Name	Source	Type	Power MW	Lat	Lon
Germany	Niederaussem	Coal	Lignite	3021	50.9709	6.6666
Germany	Lippendorf	Coal	Lignite	1868	51.1832	12.3717
Germany	Boxberg	Coal	Lignite	2582	51.4188	14.5743

Country	Source	Power MW - 2021
Austria	Solar	2 692
Norway	Wind	4 650
Denmark	Natural gas	1 654
Ireland	Natural gas	4 265
Romania	Natural gas	2 184

Bibliography

[1] "Techno-economic Systems Analysis (IEK-3)." https://www.fz-juelich.de/en/iek/iek-3 (accessed Sep. 07, 2022).

[2] N. Gkonis, "Multi-perspective design of energy efficiency policies under the framework of national energy and climate action plans," *Energy Policy*, p. 18, 2020.

[3] N. Kilinc-Ata, "The evaluation of renewable energy policies across EU countries and US states: An econometric approach," *Energy Sustain. Dev.*, vol. 31, pp. 83–90, Apr. 2016, doi: 10.1016/j.esd.2015.12.006.

[4] European Comission, "COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS: 'Fit for 55': delivering the EU's 2030 Climate Target on the way to climate neutrality." Jul. 14, 2021.

[5] "The European Green Deal & Fit for 55," p. 6, 2021.

[6] European Comission, "COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE EUROPEAN COUNCIL, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS: REPowerEU Plan." May 18, 2022.

[7] J. Thema *et al.*, "The Multiple Benefits of the 2030 EU Energy Efficiency Potential," *Energies*, vol. 12, no. 14, Art. no. 14, Jan. 2019, doi: 10.3390/en12142798.

[8] L. Balode, K. Dolge, P. D. Lund, and D. Blumberga, "How to Assess Policy Impact in National Energy and Climate Plans," *Environ. Clim. Technol.*, vol. 25, no. 1, pp. 405–421, Jan. 2021, doi: 10.2478/rtuect-2021-0030.

[9] K. Wach, A. Głodowska, M. Maciejewski, and M. Sieja, "Europeanization Processes of the EU Energy Policy in Visegrad Countries in the Years 2005–2018," *Energies*, vol. 14, no. 7, Art. no. 7, Jan. 2021, doi: 10.3390/en14071802.

[10] Ł. Sułkowski and Z. Dobrowolski, "The role of supreme audit institutions in energy accountability in EU countries," *Energy Policy*, vol. 156, p. 112413, Sep. 2021, doi: 10.1016/j.enpol.2021.112413.

[11] S. Pfenninger, "Energy systems modeling for twenty-first century energy challenges," *Renew. Sustain. Energy Rev.*, p. 13, 2014.

[12] H.-K. Ringkjøb, "A review of modelling tools for energy and electricity systems with large shares of variable renewables," *Renew. Sustain. Energy Rev.*, p. 20, 2018.

[13] M. G. Prina, G. Manzolini, D. Moser, B. Nastasi, and W. Sparber, "Classification and challenges of bottom-up energy system models - A review," *Renew. Sustain. Energy Rev.*, vol. 129, p. 109917, Sep. 2020, doi: 10.1016/j.rser.2020.109917.

[14] S. Pfenninger and B. Pickering, "Calliope: a multi-scale energy systems modelling framework," *J. Open Source Softw.*, Sep. 2018, doi: 10.21105/joss.00825.

[15] S. Pfenninger, J. DeCarolis, L. Hirth, S. Quoilin, and I. Staffell, "The importance of open data and software: Is energy research lagging behind?," *Energy Policy*, vol. 101, pp. 211–215, Feb. 2017, doi: 10.1016/j.enpol.2016.11.046.

[16] A. Pina, C. A. Silva, and P. Ferrão, "High-resolution modeling framework for planning electricity systems with high penetration of renewables," *Appl. Energy*, vol. 112, pp. 215–223, Dec. 2013, doi: 10.1016/j.apenergy.2013.05.074.

[17] L. Welder, D. S. Ryberg, L. Kotzur, T. Grube, M. Robinius, and D. Stolten, "Spatio-temporal optimization of a future energy system for power-to-hydrogen applications in Germany," *Energy*, vol. 158, pp. 1130–1149, Sep. 2018, doi: 10.1016/j.energy.2018.05.059.

[18] M. Hoffmann, "The Pareto-optimal temporal aggregation of energy system models," *Appl. Energy*, p. 22, 2022.

[19] P. Capros *et al.*, "Outlook of the EU energy system up to 2050: The case of scenarios prepared for European Commission's 'clean energy for all Europeans' package using the PRIMES

model," *Energy Strategy Rev.*, vol. 22, pp. 255–263, Nov. 2018, doi: 10.1016/j.esr.2018.06.009.
[20] J. P. Deane, "An integrated gas and electricity model of the EU energy system to examine supply interruptions," *Appl. Energy*, p. 12, 2017.
[21] S. Collins, "Adding value to EU energy policy analysis using a multi-model approach with an EU-28 electricity dispatch model," p. 15, 2017.
[22] P. Fragkos, "Energy system impacts and policy implications of the European Intended Nationally Determined Contribution and low-carbon pathway to 2050," *Energy Policy*, p. 11, 2017.
[23] H. T. J. Henke, F. Gardumi, and M. Howells, "The open source electricity Model Base for Europe - An engagement framework for open and transparent European energy modelling," *Energy*, vol. 239, p. 121973, Jan. 2022, doi: 10.1016/j.energy.2021.121973.
[24] L. Coppens, M. Gargiulo, M. Orsini, and N. Arnould, "Achieving −55% GHG emissions in 2030 in Wallonia, Belgium: Insights from the TIMES-Wal energy system model," *Energy Policy*, vol. 164, p. 112871, May 2022, doi: 10.1016/j.enpol.2022.112871.
[25] M. Blesl, "Effects of climate and energy policy related measures and targets on the future structure of the European energy system in 2020 and beyond," *Energy Policy*, p. 15, 2010.
[26] T. Tröndle, J. Lilliestam, S. Marelli, and S. Pfenninger, "Trade-offs between geographic scale, cost, and infrastructure requirements for fully renewable electricity in Europe," *Joule*, vol. 4, Sep. 2020.
[27] "Background - NUTS - Nomenclature of territorial units for statistics - Eurostat." https://ec.europa.eu/eurostat/web/nuts/background (accessed Sep. 07, 2022).
[28] D. S. Ryberg, "The future of European onshore wind energy potential: Detailed distribution and simulation of advanced turbine designs," p. 17, 2019.
[29] IRENA (2022), "Renewable Energy Statistics 2022." The International Renewable Energy Agency.
[30] "PxWeb - Select table." https://pxweb.irena.org/pxweb/en/IRENASTAT?_gl=1*1i0rfml*_ga*NDgzMTQ0OTIyLjE2NDkyNTgyMzA.*_ga_7W6ZEF19K4*MTY2Mjg0ODA1NS4yLjEuMTY2Mjg0ODMxMC4wLjAuMA.. (accessed Sep. 11, 2022).
[31] "PRIS - Home." https://pris.iaea.org/PRIS/home.aspx (accessed Sep. 11, 2022).
[32] F. Gotzens, "Performing energy modelling exercises in a transparent way - The issue of data quality in power plant databases," *Energy Strategy Rev.*, p. 12, 2019.
[33] F. Ise and P. P. GmbH, "Photovoltaics Report," p. 52.
[34] M. Z. Jacobson and V. Jadhav, "World estimates of PV optimal tilt angles and ratios of sunlight incident upon tilted and tracked PV panels relative to horizontal panels," *Sol. Energy*, vol. 169, pp. 55–66, Jul. 2018, doi: 10.1016/j.solener.2018.04.030.
[35] "Statistics | Eurostat." https://ec.europa.eu/eurostat/databrowser/view/nrg_ti_gasm/default/table?lang=en (accessed Sep. 11, 2022).
[36] "eXtremOS." https://extremos.ffe.de/#status_quo (accessed Sep. 11, 2022).
[37] "Eurostat - Data Explorer." https://appsso.eurostat.ec.europa.eu/nui/submitViewTableAction.do (accessed Sep. 13, 2022).
[38] Ember, "Yearly electricity data." https://ember-climate.org/data-catalogue/yearly-electricity-data/
[39] "Meteorological and hydrological droughts in Europe — European Environment Agency." https://www.eea.europa.eu/data-and-maps/indicators/river-flow-drought-3/assessment (accessed Sep. 13, 2022).
[40] "File:Development of electricity prices for non-household consumers, EU, 2008-2021 v2.png." https://ec.europa.eu/eurostat/statistics-

explained/index.php?title=File:Development_of_electricity_prices_for_non-household_consumers,_EU,_2008-2021_v2.png (accessed Sep. 11, 2022).
[41] "Carbon intensity of electricity," *Our World in Data*. https://ourworldindata.org/grapher/carbon-intensity-electricity (accessed Sep. 11, 2022).
[42] The Wind Power, "Global Windfarm Database." Jul. 08, 2022.
[43] "Home," *Global Energy Monitor*. https://globalenergymonitor.org/ (accessed Sep. 11, 2022).
[44] Global Energy Monitor, "Global Solar Power Tracker." May 2022.
[45] Global Energy Monitor, "Global Coal Plant Tracker." Jul. 2022.
[46] "Global Gas Plant Tracker." Jul. 2022.
[47] "Installations | Bioenergy." https://www.ieabioenergy.com/installations/ (accessed Sep. 11, 2022).
[48] Western Balkans Investment Framework, "Regional Strategy for Sustainable Hydropower in the Western Balkans. Background Report No. 1 Past, present and future role of hydropower." Nov. 2017.
[49] L. Lazaj and R. Xhelilaj, "Mapping of hydropower plant in Albania, using Geographic Information System." Apr. 2017.
[50] National Agency of Natural Resources, "Hydro-energetic potential of Albania."
[51] "Enti Rregullator i Energjisë," *ERE*. https://www.ere.gov.al/en/ (accessed Sep. 10, 2022).
[52] "VERBUND run-of-river plants cover majority of consumption." https://www.verbund.com/en-at/about-verbund/power-plants/power-plant-types/run-of-river (accessed Sep. 10, 2022).
[53] "STATatlas." https://www.statistik.at/atlas/?mapid=them_energie_klimafonds&layerid=layer1&sublayerid=sublayer0&languageid=0&bbox=912963,5754341,2087036,6345658,8 (accessed Sep. 10, 2022).
[54] "Generating facilities." https://www.elia.be/en/grid-data/power-generation/generating-facilities (accessed Sep. 10, 2022).
[55] Becquerel Institute – LuciSUN – SUN7 and Brugel, "ETUDE DU PARC PHOTOVOLTAÏQUE EN RÉGION DE BRUXELLES-CAPITALE - 2019." Apr. 06, 2021.
[56] "Home - Energiesparen." https://www.energiesparen.be/ (accessed Sep. 10, 2022).
[57] "WalOnMap." http://geoportail.wallonie.be/walonmap (accessed Sep. 10, 2022).
[58] "Brugel - Rapportage Vert et Greencheck," *BRUGEL*. https://www.brugel.brussels/themes/infos-pour-le-secteur-de-l-energie-13/rapportage-vert-et-greencheck-43 (accessed Sep. 10, 2022).
[59] M. Gallay, J. Kaňuk, and J. Hofierka, "Capacity of photovoltaic power plants in the Czech Republic," *J. Maps*, vol. 11, no. 3, pp. 480–486, May 2015, doi: 10.1080/17445647.2014.935498.
[60] "Seznam solárních elektráren v ČR." https://www.elektrarny.pro/seznam-elektraren.php?kj=&os=&vn-od=0.1&vn-do=&nv=&ml=&le=&zobraz=Search&stranka=4 (accessed Sep. 10, 2022).
[61] "Largest Solar Power Stations in Czech Republic | Photovoltaic Parks in Czech Republic | PV Farms," *List.Solar*. https://list.solar/plants/largest-plants/czech-republic/ (accessed Sep. 10, 2022).
[62] A. Meriläinen, P. Puranen, A. Kosonen, and J. Ahola, "Optimization of rooftop photovoltaic installations to maximize revenue in Finland based on customer class load profiles and simulated generation," *Sol. Energy*, vol. 240, pp. 422–434, Jul. 2022, doi: 10.1016/j.solener.2022.05.057.
[63] "Registre national des installations de production et de stockage d'électricité (au 30/04/2022)." https://odre.opendatasoft.com/explore/dataset/registre-national-installation-production-stockage-electricite-agrege/ (accessed Sep. 10, 2022).

[64] "Bundesnetzagentur - List of Power Plants." https://www.bundesnetzagentur.de/EN/Areas/Energy/Companies/SecurityOfSupply/GeneratingCapacity/PowerPlantList/start.html (accessed Sep. 10, 2022).
[65] "Marktstammdatenregister (MaStR)." https://www.marktstammdatenregister.de/MaStR (accessed Sep. 10, 2022).
[66] "Largest Solar Power Stations in Hungary | Photovoltaic Parks in Hungary | PV Farms," *List.Solar*. https://list.solar/plants/largest-plants/hungary/ (accessed Sep. 10, 2022).
[67] "STS Group." https://stsgroup.hu/en/ (accessed Sep. 10, 2022).
[68] Sistema Statistico Nazionale, "Solare Fotovoltaico - Rapporto Statistico GSE 2020." Jul. 2021.
[69] "Italia," *Sonnedix*. https://www.sonnedix.com/es/countries/italy (accessed Sep. 11, 2022).
[70] "Coal plants in Italy – Assocarboni." https://assocarboni.it/assocarboni/en/il-coal/coal-plants-italy/ (accessed Sep. 11, 2022).
[71] C. B. voor de Statistiek, "Zonnestroom; vermogen zonnepanelen woningen, wijken en buurten, 2018," *Centraal Bureau voor de Statistiek*. https://www.cbs.nl/nl-nl/cijfers/detail/84772NED (accessed Sep. 10, 2022).
[72] "Vannkraftdatabase - NVE." https://www.nve.no/energi/energisystem/vannkraft/vannkraftdatabase/ (accessed Sep. 10, 2022).
[73] Instytut energetyki odnawialnej, BayWa r.e., mBank, and SolTEC, "Raport Rynek Fotowoltaiki w Polsce 2022." May 2022.
[74] "Największe farmy fotowoltaiczne w Polsce – Ranking 2022 | enerad.pl." https://enerad.pl/fotowoltaika/najwieksze-farmy-fotowoltaiczne-w-polsce-ranking/ (accessed Sep. 10, 2022).
[75] OECD, "Regional Outlook 2021 - Country notes. Portugal - progress in the net zero transition."
[76] S. E. Team, "20 Biggest Solar Projects in Portugal," *SolarFeeds Magazine*, Nov. 21, 2021. https://www.solarfeeds.com/mag/biggest-solar-projects-in-portugal/ (accessed Sep. 10, 2022).
[77] S. E. Team, "20 Biggest Solar Projects in Romania," *SolarFeeds Magazine*, Nov. 22, 2021. https://www.solarfeeds.com/mag/biggest-solar-projects-in-romania/ (accessed Sep. 10, 2022).
[78] "Solar power plants," *green energy slovakia*. http://greenenergy.sk/en/slnecna-energia/ (accessed Sep. 10, 2022).
[79] "Instal·lació de producció d'energia elèctrica. Dades individualitzades | Dades obertes de Catalunya." https://analisi.transparenciacatalunya.cat/es/widgets/arbg-m6sq (accessed Sep. 11, 2022).
[80] I. CORPORATIVA, "Mapa de instalaciones y principales datos operativos," *Iberdrola*. https://www.iberdrola.com/conocenos/cifras/principales-datos-operativos (accessed Sep. 11, 2022).
[81] Agencia Andaluza de la Energía, "INFORME DE INFRAESTRUCTURAS ENERGÉTICAS ANDALUCÍA." Dec. 2021.
[82] "Datos de energías renovables en Aragón (IDEARAGON) - Conjunto de datos." http://datos.gob.es/es/catalogo/a02002834-datos-de-energias-renovables-en-aragon-idearagon (accessed Sep. 11, 2022).
[83] "Inventario de instalaciones fotovoltaicas - Conjunto de datos." http://datos.gob.es/es/catalogo/l01280796-inventario-de-instalaciones-fotovoltaicas (accessed Sep. 10, 2022).
[84] "Publications." https://www.energimyndigheten.se/en/facts-and-figures/publications/ (accessed Sep. 10, 2022).
[85] BMH Technology *et al.*, "Bio power plants. Map 2021."
[86] "About our power plants and the production - Vattenfall." https://powerplants.vattenfall.com/#/types=Hydro/countries=Sweden/view=map/sort=name (accessed Sep. 10, 2022).

[87] "Hydropower," *Skellefteå Kraft*. https://www.skekraft.se/english_pages/hydropower/ (accessed Sep. 10, 2022).
[88] "Kvistforsen hydropower plant." https://www.statkraft.com/about-statkraft/where-we-operate/sweden/kvistforsen-hydropower-plant/ (accessed Sep. 10, 2022).
[89] "Hydropower plants," *Fortum*. https://www.fortum.com/about-us/our-company/our-energy-production/hydropower-renewable-and-clean-energy/hydropower-plants (accessed Sep. 10, 2022).
[90] "Nätanslutna solcellsanläggningar." https://www.energimyndigheten.se/statistik/den-officiella-statistiken/statistikprodukter/natanslutna-solcellsanlaggningar/ (accessed Sep. 10, 2022).
[91] B. für E. BFE, "Elektrizitätsproduktionsanlagen in der Schweiz," *Elektrizitätsproduktionsanlagen in der Schweiz*. https://www.uvek-gis.admin.ch/BFE/storymaps/EE_Elektrizitaetsproduktionsanlagen/ (accessed Sep. 10, 2022).
[92] S. F. O. of E. SFOE, "Large-scale hydropower." https://www.bfe.admin.ch/bfe/en/home/versorgung/erneuerbare-energien/wasserkraft/grosswasserkraft.html (accessed Sep. 10, 2022).
[93] "UK Energy in Brief 2021," p. 52.
[94] "Digest of UK Energy Statistics (DUKES): electricity," *GOV.UK*. https://www.gov.uk/government/statistics/electricity-chapter-5-digest-of-united-kingdom-energy-statistics-dukes (accessed Sep. 10, 2022).
[95] "UK Electricity Production." https://electricityproduction.uk/ (accessed Sep. 10, 2022).
[96] "World Energy Outlook 2021," p. 386.
[97] The World Bank, "World Bank Commodities Price Forecast (nominal US dollars)." Oct. 21, 2021.
[98] "Fuel Commodities and Carbon Prices – TYNDP 2020 — ENTSOs." https://2020.entsos-tyndp-scenarios.eu/fuel-commodities-and-carbon-prices/ (accessed Sep. 13, 2022).
[99] "• Europe: green hydrogen costs 2030 | Statista." https://www.statista.com/statistics/1312286/europe-green-hydrogen-production-and-import-costs-2030/ (accessed Sep. 13, 2022).
[100] "Global hydrogen trade to meet the 1.5°C climate goal: Part III – Green hydrogen cost and potential," p. 45.
[101] "Analysis of biomass prices," p. 115.
[102] Rotterdam Biomass Commodities Network (RBCN), "Rotterdam Biomass Commodities Network – Biomass Market Update." 2022.
[103] C. Kost, S. Shammugam, V. Fluri, D. Peper, A. D. Memar, and T. Schlegl, "LEVELIZED COST OF ELECTRICITY RENEWABLE ENERGY TECHNOLOGIES," p. 48.
[104] G. R. Timilsina, *Demystifying the costs of Electricity Generation Technologies*. World Bank, Washington, DC, 2020. doi: 10.1596/1813-9450-9303.
[105] Danish Energy Agency, "Technology Data for Generation of Electricity and District Heating." Jun. 2022.
[106] E. Lo Vullo, "EU Covenant of Mayors (CoM) Default Emission Factors." 2022. [Online]. Available: https://jeodpp.jrc.ec.europa.eu/ftp/public/JRC-OpenData/CoM/Default%20Emission%20Factors/VER-1/
[107] Europe Beyond Coal, "Overview: National coal phase-out announcements in Europe." 2022.