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Low-carbon energy scenarios and the role of Fusion

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Abstract

In the global context of a progressive commitment towards decarbonization of human activities, the electricity system plays a pivotal role in policies for the transformation of energy uses and energy sources exploitation, and in the consequent reduction of greenhouse gas related to these activities. Nuclear energy is an energy source compatible with a decarbonized generation mix, but as of today there is no widespread commitment towards a major nuclear fission technology deployment, mainly due to concerns about operation safety, environmental sustainability of decommissioned power plants and spent fuel management. Nuclear fusion technology, on the other hand, may be a crucial step forward in the utilization of nuclear reactions and solve all those critical issues. However the deployment of a significant installed capacity of fusion power plants is to be expected, in all likelihood, during the second half of the century, therefore after the time window set by the main industrialized countries for their decarbonization targets. As for now, decarbonization policies focus mainly on renewable generation from variable sources, like solar photovoltaic and wind power. These generation technologies experienced a huge cost reduction in recent years, but still pose many questions about the cost and requirements of a power system entirely, or mainly, based on them.

In this perspective this thesis presents Italian energy scenarios for the electricity system in which power system forced to fully rely on renewable energy are compared to power system where both fusion and renewable energy can be part of the energy mix. The aim is to assess if fusion availability and deployment brings with it an improvement in an electricity power system: this improvement can be measured in terms of system costs, as well as in terms of any other feature of the power system design or operation that may be considered relevant.

The scenarios presented are generated with the model COMESE (Electricity System Mean Cost - Costo Medio del Sistema Elettrico). COMESE was developed in the context of the energy scenarios research activities carried out at RFX Consortium in Padua. The aim of the code is to represent effectively the features, costs and requirements of an electricity power system based on a major, or at least relevant, share of renewable sources. To do so it performs an hourly simulation of all the generation and storage technologies included in the power system, as well as simulating power flows between different system

zones, in order to assess how the generators siting and the transmission grid capacity influence the system operation.

The current version of COMESE, developed in MATLAB language, is the result of an overall upgrade and restructuring of the code carried out as a central part of this PhD activities. A complete description of the code itself is included in the thesis. The aim of the work on COMESE was to deepen the degree of detail achievable from a system simulation, while keeping the tool as versatile as possible, in order to be able to tune it accordingly to the specific issues that may need to be assessed from time to time. This made COMESE a useful tool for a vast kind of analyses on the power system operations, beyond the ones involving fusion deployment. Moreover, fusion deployment scenarios themselves can be easily generalized, in order to assess the role of capital intensive baseload technologies in a decarbonized power system.

The opening chapter of this thesis covers briefly the context of research on sustainable energy scenarios, the role of the electricity system on decarbonization policies, and a description of the models for the analyses on energy systems.

Chapter 2 consists of a general description of thermonuclear fusion technology.

Chapter 3 includes a detailed description of COMESE: its inputs and outputs, the logic, the assumptions adopted to simulate the system operations, and the different ways it can be used.

Chapter 4 includes the description of the analyses carried out with COMESE on the economic burden of flexible generation, storage systems and the power transmission infrastructure in a future fully decarbonized electricity system. The impact of the availability of a baseload nuclear fusion generation fleet on the overall system costs, as well as on the requirements on the three power system assets just listed, is investigated.

Chapter 5 includes the description of the analyses carried out with COMESE on the availability of a long term storage system based on hydrogen infrastructure, of fusion power generation, and of the possible interaction between these two assets.

Sommario

Nel contesto globale di un progressivo impegno verso la decarbonizzazione delle attività umane, il sistema elettrico ricopre un ruolo primario nelle politiche di modifica degli usi energetici e di sfruttamento delle fonti energetiche, e nella conseguente riduzione dei gas serra legati a questi ambiti. L'energia nucleare è una fonte energetica compatibile con un mix di generazione decarbonizzato, ma ad oggi la tecnologia a fissione nucleare non è al centro delle strategie di decarbonizzazione con un ruolo prioritario e condiviso, principalmente a causa delle preoccupazioni sulla sicurezza degli impianti, la sostenibilità ambientale delle centrali dismesse e la gestione del combustibile esaurito. La tecnologia a fusione nucleare, d'altra parte, promette di essere un passo avanti cruciale nello sfruttamento delle reazioni nucleari in campo civile e risolvere tutte queste criticità. Tuttavia il dispiegamento di una significativa flotta di centrali a fusione è prevedibile, con ogni probabilità, per la seconda metà del secolo, e quindi oltre la finestra temporale fissata dai principali paesi industrializzati per i propri obiettivi di decarbonizzazione. Per ora, quindi, le politiche di decarbonizzazione si concentrano principalmente sulla generazione rinnovabile da fonti intermittenti, come il solare fotovoltaico e l'eolico. Queste tecnologie di generazione hanno subito un'enorme riduzione dei costi di generazione negli ultimi anni, ma pongono ancora molti interrogativi sui costi e sui requisiti di un sistema elettrico interamente, o in larga quota, basato su di esse.

In questa prospettiva, in questa tesi vengono presentati scenari energetici per il sistema elettrico italiano in cui sistemi che fanno completo affidamento su generazione rinnovabile vengono confrontati con sistemi in cui sia l'energia da fusione nucleare che la generazione rinnovabile possono far parte del mix energetico. L'obiettivo è valutare se la disponibilità e la diffusione della tecnologia a fusione portino con sé dei miglioramenti del sistema elettrico: questi miglioramenti possono essere misurati in termini di costi di sistema, nonché in termini di qualsiasi altra caratteristica della struttra o del funzionamento del sistema elettrico che possa essere considerata rilevante.

Gli scenari presentati sono stati generati con il modello COMESE (Costo Medio del Sistema Elettrico). COMESE è stato sviluppato nell'ambito delle attività di ricerca sugli scenari energetici del Consorzio RFX di Padova. Lo scopo del codice è quello di rappresentare efficacemente le caratteristiche, i costi ed i requisiti di un sistema elettrico basato su una quota maggioritaria, o comunque rilevante, di

fonti rinnovabili. Per fare ciò si basa su di una simulazione oraria di tutte le tecnologie di generazione e accumulo incluse nel sistema elettrico, nonché di una simulazione dei flussi di potenza tra le diverse zone del sistema, al fine di valutare come l'ubicazione dei generatori e la capacità della rete di trasmissione influenzino il funzionamento del sistema.

La versione attuale di COMESE, svluppata in linguaggio MATLAB, è il risultato di un aggiornamento e di una ristrutturazione complessiva del codice, attività che ha ricoperto una parte centrale di questo dottorato. Una descrizione completa del codice è inclusa nella tesi. Lo scopo del lavoro su COMESE è stato quello di approfondire il grado di dettaglio ottenibile da una simulazione di sistema, mantenendo al contempo lo strumento il più versatile possibile, in modo da poterlo tarare in funzione degli aspetti che di volta in volta vogliano essere valutati con maggior grado di dettaglio. Ciò ha reso COMESE uno strumento utile per diversi tipi di analisi sul funzionamento del sistema elettrico, oltre a quelle focalizzate sulla penetrazione della generazione da fusione. Inoltre, gli stessi scenari di implementazione della fusione possono essere facilmente generalizzati, al fine di valutare il ruolo delle tecnologie di generazione baseload ad elevato costo capitale in un sistema energetico decarbonizzato.

Il capitolo introduttivo di questa tesi illustra sinteticamente il contesto della ricerca sugli scenari energetici sostenibili, il ruolo del sistema eletrico nelle strategie di decarbonizzazione, ed una descrizione dei modelli per la simulazione di sistemi energetici.

Il capitolo 2 comprende una descrizione generale della tecnologia di generazione elettrica da fusione termonucleare controllata.

Il capitolo 3 contiene una descrizione dettagliata di COMESE: gli input e gli output, la logica di funzionamento, le ipotesi adottate nella simulazione del funzionamento del sistema elettrico, e le diverse modalità di utilizzo.

Il capitolo 3 comprende la descrizione delle analisi effettuate con COMESE sul contributo al costo complessivo di un futuro sistema elettrico decarbonizzato da parte dei seguenti elementi: i sistemi di generazione flessibile, i sistemi di accumulo energetico e il sistema di trasmissione dell'energia elettrica. In questo modo si è valutato quale impatto abbia la disponibilità di una flotta di impianti di generazione per il carico di base a fusione nucleare sul costo complessivo del sistema, e sui suoi requisiti in termini degli elementi sopra citati.

Il capitolo 4 include la descrizione delle analisi effettuate con COMESE sulla disponibilità di un sistema di accumulo energetico di lungo termine basato su un'infrastruttura ad idrogeno, della penetrazione della fusione nucleare, e delle possibili interazioni tra queste due tecnologie.

Samenvatting

In de wereldwijde context van een progressief engagement om menselijke activiteiten koolstofvrij te maken, speelt het elektriciteitssysteem een centrale rol in het beleid voor de transformatie van energiegebruik en de exploitatie van energiebronnen, en in de daaruit voortvloeiende vermindering van broeikasgassen in verband met deze activiteiten. Kernenergie is een energiebron die verenigbaar is met een koolstofarme opwekkingsmix, maar tot op heden is er geen wijdverspreide inzet voor een grootschalige toepassing van kernsplijtingstechnologie, voornamelijk vanwege zorgen over de operationele veiligheid, de milieuduurzaamheid van ontmantelde centrales en het beheer van verbruikte splijtstof. Kernfusietechnologie kan daarentegen een cruciale stap voorwaarts zijn in het gebruik van kernreacties en al deze kritieke kwesties oplossen. De inzet van een aanzienlijke geïnstalleerde capaciteit van kernfusiecentrales wordt echter naar alle waarschijnlijkheid verwacht in de tweede helft van deze eeuw, dus na het tijdsvenster dat de belangrijkste geïndustrialiseerde landen hebben ingesteld voor hun doelstellingen voor het koolstofarm maken van de economie. Op dit moment richt het beleid voor het koolstofarm maken van de economie zich voornamelijk op hernieuwbare opwekking uit variabele bronnen, zoals fotovoltaïsche zonne-energie en windenergie. De kosten van deze opwekkingstechnologieën zijn de afgelopen jaren enorm gedaald, maar er zijn nog steeds veel vragen over de kosten en vereisten van een elektriciteitssysteem dat volledig of voornamelijk op deze technologieën is gebaseerd.

In dit perspectief presenteert dit proefschrift Italiaanse energiescenario's voor het elektriciteitssysteem waarin elektriciteitssystemen die volledig afhankelijk zijn van hernieuwbare energie vergeleken worden met elektriciteitssystemen waarin zowel fusie als hernieuwbare energie deel kunnen uitmaken van de energiemix. Het doel is om te beoordelen of de beschikbaarheid en inzet van fusie een verbetering van een elektriciteitssysteem met zich meebrengt: deze verbetering kan worden gemeten in termen van systeemkosten, maar ook in termen van elk ander kenmerk van het ontwerp of de werking van het elektriciteitssysteem dat als relevant kan worden beschouwd.

De gepresenteerde scenario's zijn gegenereerd met het model COMESE (Electricity System Mean Cost - Costo Medio del Sistema Elettrico). COMESE is ontwikkeld in het kader van de onderzoeksactiviteiten naar energiescenario's bij het RFX Consortium in Padua. Het doel van de code is om de

kenmerken, kosten en vereisten van een elektriciteitssysteem gebaseerd op een groot, of in ieder geval relevant, aandeel hernieuwbare bronnen effectief weer te geven. Daartoe voert de code elk uur een simulatie uit van alle opwekkings- en opslagtechnologieën in het elektriciteitssysteem, en simuleert de energiestromen tussen verschillende systeemzones om te beoordelen hoe de locatie van de generatoren en de capaciteit van het transmissienet de werking van het systeem beïnvloeden.

De huidige versie van COMESE, ontwikkeld in de MATLAB-taal, is het resultaat van een algehele upgrade en herstructurering van de code die is uitgevoerd als centraal onderdeel van deze PhD-activiteiten. Een volledige beschrijving van de code zelf is opgenomen in het proefschrift. Het doel van het werk aan COMESE was het verdiepen van de mate van detail die haalbaar is uit een systeemsimulatie, terwijl het gereedschap zo veelzijdig mogelijk gehouden wordt, zodat het afgestemd kan worden op de specifieke kwesties die van tijd tot tijd beoordeeld moeten worden. Hierdoor is COMESE een nuttig hulpmiddel voor een groot aantal analyses van de werking van het elektriciteitssysteem, naast de analyses die betrekking hebben op de inzet van kernfusie. Bovendien kunnen fusiescenario's zelf gemakkelijk worden gegeneraliseerd om de rol van kapitaalintensieve basislasttechnologieën in een koolstofarm elektriciteitssysteem te beoordelen.

Het openingshoofdstuk van dit proefschrift behandelt in het kort de context van het onderzoek naar duurzame energiescenario's, de rol van het elektriciteitssysteem in het decarbonisatiebeleid en een beschrijving van de modellen voor de analyses van energiesystemen.

Hoofdstuk 2 bestaat uit een algemene beschrijving van thermonucleaire fusietechnologie.

Hoofdstuk 3 bevat een gedetailleerde beschrijving van COMESE: de inputs en outputs, de logica, de aannames die zijn aangenomen om de werking van het systeem te simuleren, en de verschillende manieren waarop het kan worden gebruikt.

Hoofdstuk 4 bevat de beschrijving van de analyses die met COMESE zijn uitgevoerd naar de economische belasting van flexibele opwekking, opslagsystemen en de infrastructuur voor elektriciteittransport in een toekomstig elektriciteitssysteem dat volledig koolstofvrij is. De invloed van de beschikbaarheid van een kernfusieproductiepark met basislast op de totale systeemkosten, en op de vereisten voor de drie zojuist genoemde assets van het elektriciteitssysteem, wordt onderzocht.

Hoofdstuk 5 bevat de beschrijving van de analyses die zijn uitgevoerd met COMESE over de beschikbaarheid van een langetermijnopslagsysteem gebaseerd op waterstofinfrastructuur, van fusie-energieopwekking, en van de mogelijke interactie tussen deze twee activa.

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Chapter 1

Introduction

Since the last decades of the twentieth century, the impact of anthropic activities on the environment has become a topic of major interest and has entered the public, political and scientific debate with growing relevance. Among the large number of issues linked to this topic, global warming (as a result of the growing atmospheric concentration of greenhouse gases from anthropogenic emissions) has gained a primary importance, leading to the planning and implementation of policies aimed at the containment and the future reduction of this phenomenon, at the hands of countries and supranational entities or organizations [1, 2].

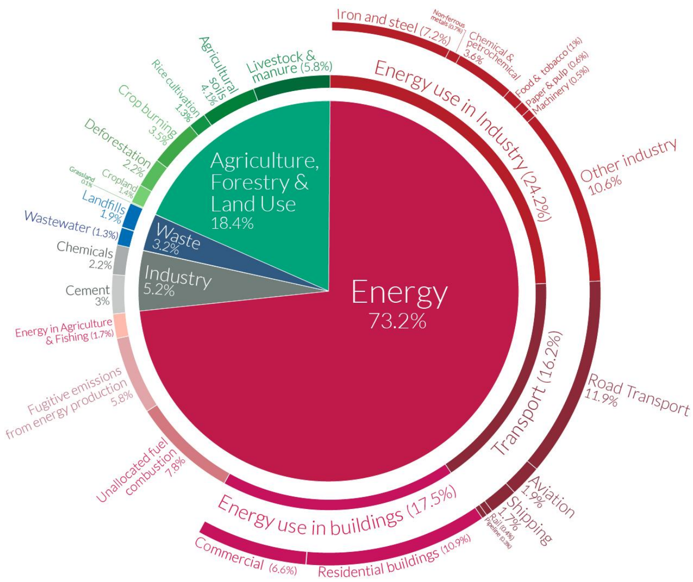


Figure 1.1: Global greenhouse gases emission per sector in 2016, for a total amount of 49 CO2 equivalent tonnes. Source: Climate Watch - The World resource institute (2020).

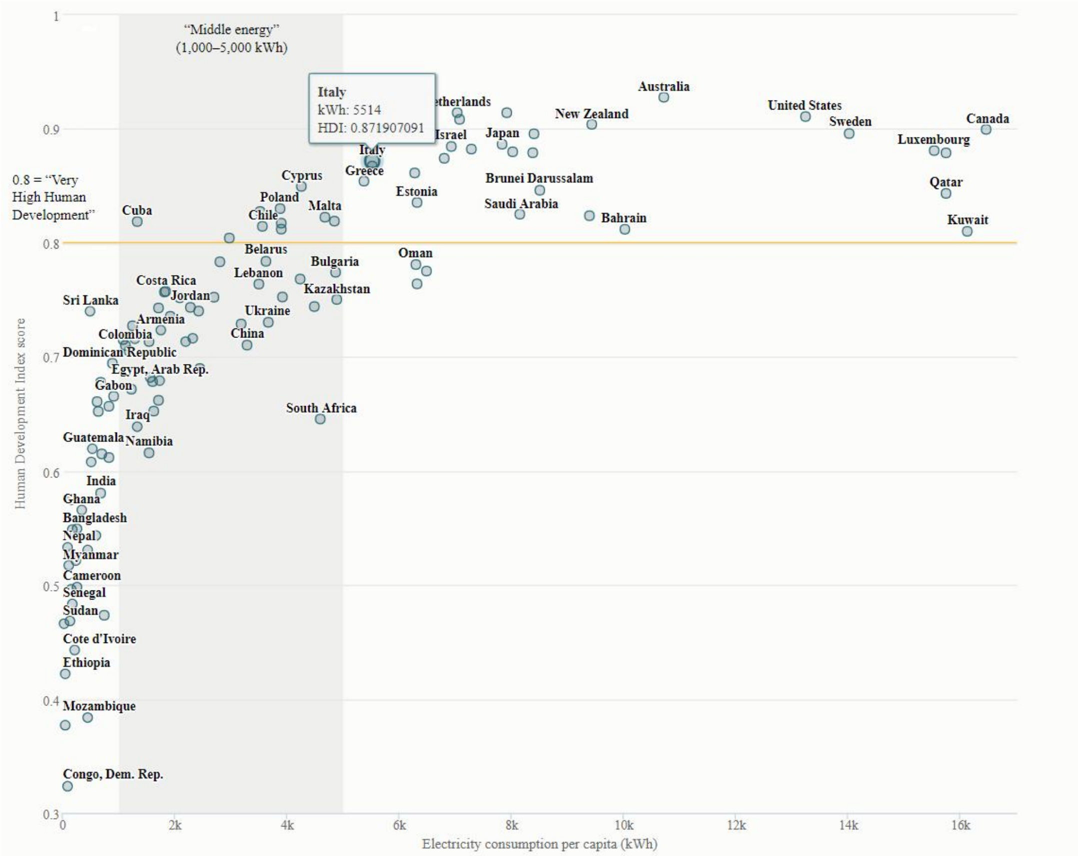


Figure 1.2: Human Development Index vs Electricity consumption per capita. Source: CGD - Center for Global Development.

Among human activities, the ones contributing the most to greenhouse gases emissions are the transformation and utilization of fossil fuels, i.e. coal, natural gas and oil, in the energy sector (transports, heating and electricity). Other sectors that contributes to these emissions with a smaller, but nonetheless relevant, share are the agricultural sector, the industrial one, and the wastes one (Figure 1.1). The exploitation of fossil fuels has been the basis for industrialized countries development since the end of the eighteenth century, and it is still of paramount importance for these societies; indeed, the largest share of the world energy consumption is still satisfied resorting to those resources. A clear correlation can in fact be noticed between the availability and consumption of energy resources and the achievement of development and high standards of living for a society and its population (Figure 1.2). While the per capita energy consumption is linked to the development degree of a society, its overall amount is also linked to the number of people living in it. Up to the end of the twentieth century the world energy consumption was mainly driven by the development of western countries and the increase of their population. Figure 1.3 shows that up to now this causality link never inverted, as the only times that the

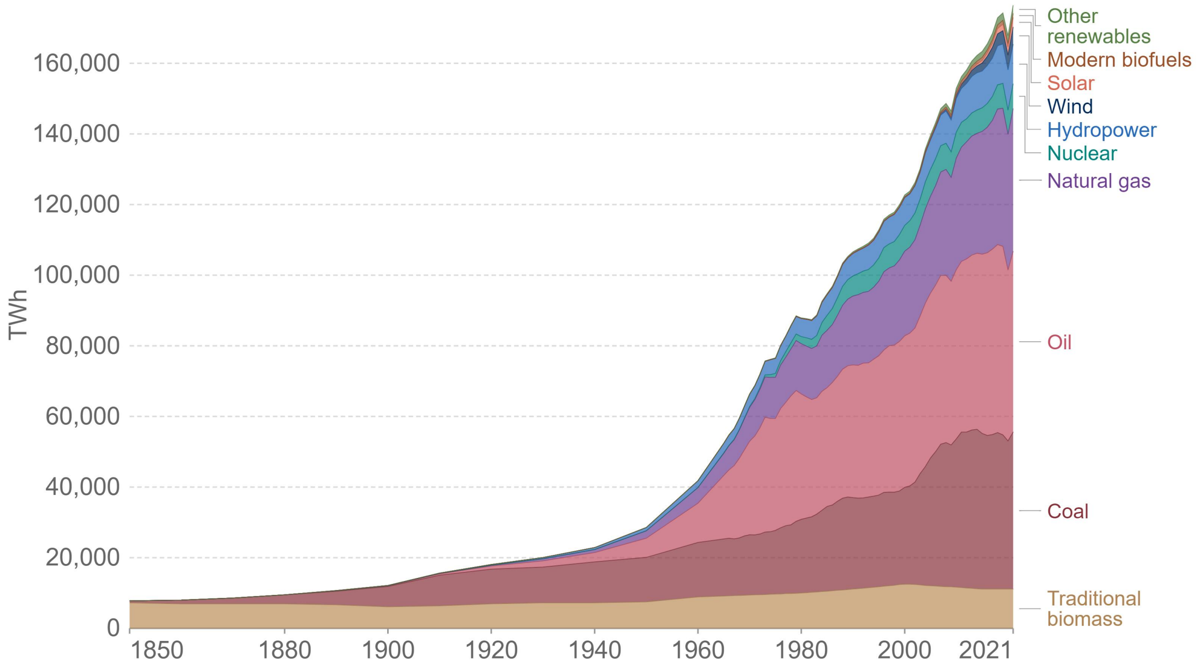


Figure 1.3: Global primary energy consumption by source from 1850. Source: Our World in Data based on Vaclav Smil (2017) and BP Statistical Review of World Energy.

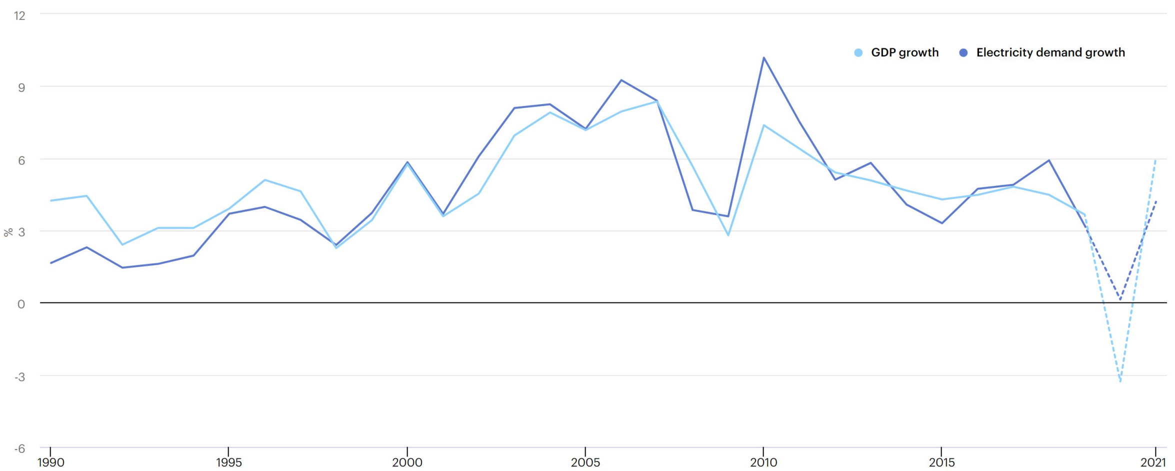


Figure 1.4: Electricity demand and real GDP growth in emerging and developing economies, 1990-2021 IEA data [3].

overall energy consumption stopped or decreased it was due to major socio-economic crisis (1979 Oil crisis, 2007-2010 financial crisis and European debt crisis, 2019 COVID-19 pandemic). While western countries population growth and energy consumption per capita started to stagnate in last decades, other countries are experiencing the same growth now [3, 4], and so the overall growth of energy demand cannot be expected to stop in the following decades as well (Figure 1.4).

Therefore policies affecting energy systems and energy supplies cannot be considered merely environmental issues, but a perfect example of a sustainable development issue. A typical definition of sustainable development is that of a development process consistent with three sustainability aspects: economic, social and environmental sustainability. Economic sustainability is achieved when a measure is implemented coherently with the market and the economy rules that a society adopts. Social sustainability implies that policies and actions have to be carried out respecting democratic rules and equality, freedom and law principles. Environmental sustainability is achieved when a policy allows to maintain quality and reproducibility of natural resources over time. These characteristics are summarized in the report "Our Common Future" [5] (also known as Brundtland Report) of the WCED[1], published in 1987, with the following definition:

> *"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs"*

It is therefore clear that in order to implement energy policies aimed at achieving a sustainable development from the environmental point of view, they must be proven to be economically sustainable as well. This, however, is not trivial, since the energy sector is characterized by a high "inertia": system updates and upgrades usually require a long time, and influence its features and operation for an even longer period. In the electricity sector, for instance, authorization and construction time of new power plants or power lines for the upgrade of the transmission system can take years; moreover, power plants lifetime usually spans over tens of years. However, the electricity sector is not the only example of long characteristic times in the energy sector: upgrades and changes to transports infrastructures (e.g. railways, highways), as well as to the circulating vehicle fleets, also take several years to be implemented. These features enforce today's policies to be formulated in such a manner that they will result coherent, or at least compatible, with the evolution of the energy system during a time span of several tens of years, even in the face of unforeseen. Otherwise there is a risk to miss the targets set, or to build a system with excessively high operation and maintenance costs, coming from structural contradictions that prevents it to operate effectively. This is the context in which energy scenarios are used. As stated in [6]:

> *"Scenarios are alternative views of the future which can be used to explore the implications of different sets of assumptions and to determine the degree of robustness of possible future developments"*

[1]World Commission on Environment and Development

While this definition outlines a set of tools, or more generally an analyses approach, that can be applied to various research fields, the features of the energy sector that has been previously enlisted highlight why scenarios analyses are particularly suited to study this field: energy scenarios are exploited to assess trends in the evolution of the energy system from today to a more or less distant future. Features and outcomes of this evolution are determined on the basis of currently available data about the energy system, and of assessments on their evolution in the years to come (techno-economic features of different technologies, evolution of systems and factors strictly related to the energy system, upcoming energy policies, etc.). Therefore energy scenarios are not forecasts on future features of the energy system; they should instead be considered as indicators of what can be the outcome of specific energy policies and given assumptions. We can divide scenarios in two cathegories:

Reference Scenarios: These scenarios investigate the evolution of the energy system under the assumption that current energy policies are kept unchanged. They can be used as benchmark in order to see how significant would be the outcomes of new policies, with respect to the current ones, over a certain time span.

Policy Scenarios: Scenarios that simulate the introduction of a specific policy (or a mix of them), assessing its outcome and if it is coherent with the expected goals, set with respect to a reference scenario features.

1.1 The role of the electricity system towards decarbonization

Several measures can be put in place to reduce GHG emissions from the energy sector [7], including:

1 Reduction of the energy demand: to directly reduce the final energy consumption, for example encouraging practices such as car sharing or the use public transports, or improving the level of thermal insulation of buildings.

2 Improving energy efficiency: to increase the efficiency of devices and energy transformation processes, in order to exploit less energy resources for a given final energy demand.

3 Carbon free sources penetration: to promote the use of energy sources whose exploitation is not linked to GHG emissions, like renewable sources (Solar energy, Wind energy, Hydropower, etc.) or nuclear power.

4 CCUS exploitation: Carbon Capture, Utilization and Storage (sometimes Sequestration) refer to techniques with which carbon dioxide is separated, treated and stored. Carbon dioxide can be captured from a large point source and later stored, in order to lower, or completely cancel its carbon footprint, but it can also be used to produce a synthetic fuel, whose emissions will then be balanced by the CO2 captured and used for its realization, to the same effect [8].

The electric power system play a vital role in putting in place these measures, since it's particularly fit to implement them: on one hand the exploitation of renewable energy sources has taken hold mainly in the electricity sector, with the commercialization of economically competitive technologies in several parts of the world (electric generation from photovoltaic generators, wind farms and hydroelectric power plants). On the other one the increase of electricity penetration, i.e. the final energy demand satisfied with electricity, would allow to increase the energy services powered by electricity from carbon free generators. In addition, electricity conversion in energy services usually takes place with much higher efficiencies with respect to alternatives powered by fuels. Finally, CCUS techniques can be used to treat the emissions of conventional generators or to generate synthetic fuels for electricity generation. These are the reasons why, in current policies, the electric power sector is the most relevant asset to be exploited to reduce GHG emissions.

The European roadmap “ROADMAP2050” [9], published in 2010, has been the main reference for the European decarbonization policies in the last decade. It set an overall goal of 80% emissions reduction with respect to the 1990 levels, with different objectives per sector: specifically, a 95% reduction in the electric power sector, compensating for less challenging targets for other sectors (sea and air transports, industry and agriculture). Following the outcomes of the 2015 United Nations Climate Change Conference (COP21), the 196 participating countries signed the so called “Paris Agreement”, stating that the members agreed to reduce their carbon output "as soon as possible" and to do their best to keep global warming "to well below 2 degrees C", and possibly at 1.5 degrees C [10]. While it can be pointed out that this statements are qualitative, and that every country has been left the choice on what measures it considers more suited to tackle the problem, and with what time schedule, it certainly boosted the efforts of lot of them in proposing related energy policies. Indeed, in 2020 the European Union updated its long term strategy with the so called “European Green Deal”, with the goal of making Europe a climate neutral continent, i.e. with net-zero emissions. Anyway this doesn't necessarily involve to level the decarbonization efforts in all sectors: the power sector is still suited to have a main role, as it can include measures to exceed the zero-emissions target and reach “negative emissions”, such carbon capture and storage (CCS) from biomass generation or synthetic fuels, in order to balance sectors in which complete emissions cut seems too difficult -or expensive- to achieve. Especially in view of the major role that electricity generation, transmission and distribution systems will have in the decarbonization process, in the following decades it will undergo deep changes in its components, features, and management logics. This means that it's mandatory to take into account these changes, and try to assess at the best of our ability what will be their impact on the operation of the system, focusing both on challenges and chances that will arise.

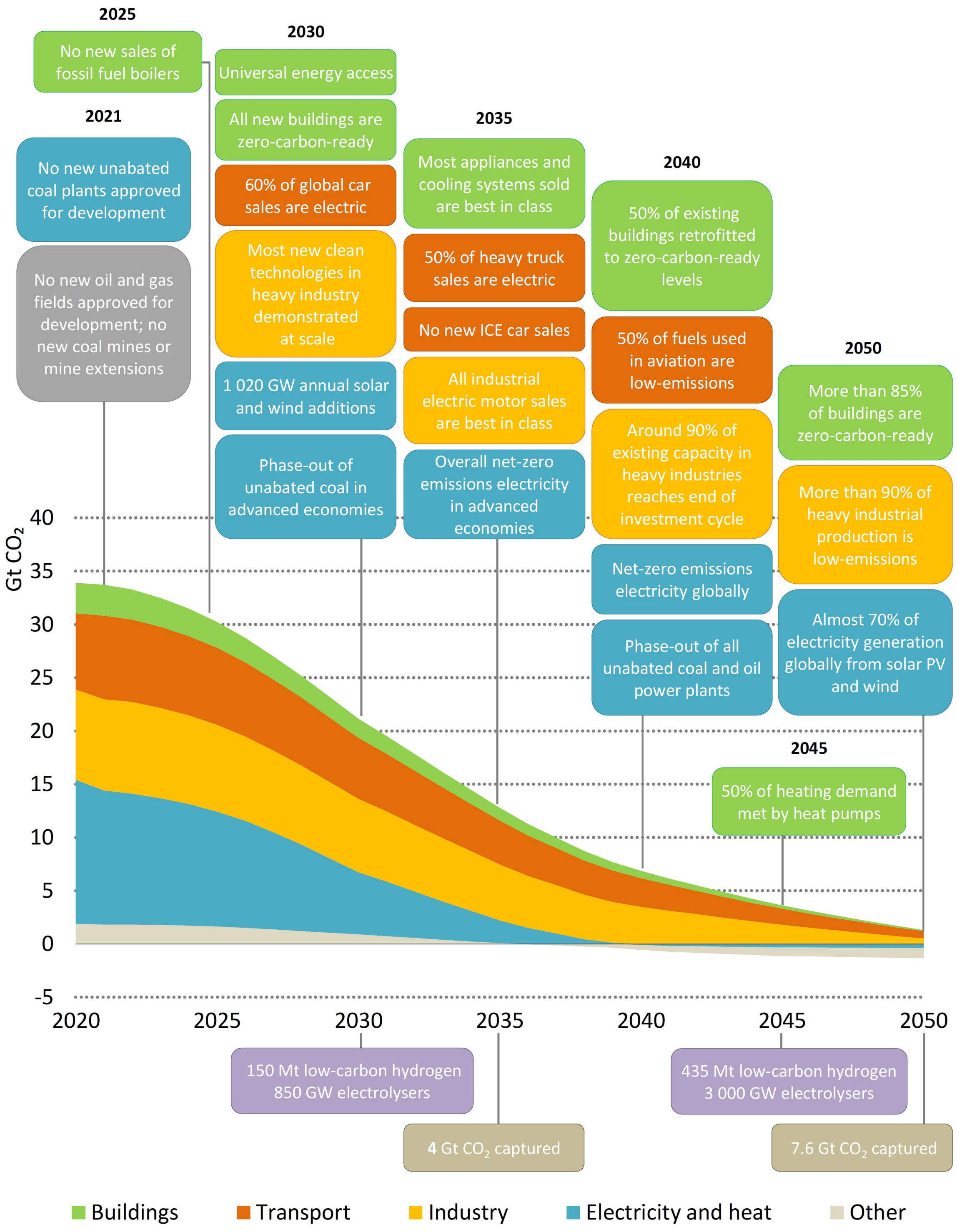


Figure 1.5: Key milestones in the parthway towards a net zero system [1]. Source: IEA.

1.2 Features of a future decarbonized power system

There is no single path that can be picked in order to obtain a decarbonized electricity system, but instead several alternatives. The power system configuration is very likely to converge towards the design that will allow to reach the lowest generation cost, both due to the market behavior and in the interest of the national policy makers. Still it's possible to identify some technologies and characteristics that will very likely be part of that future system. Below is a synthetic overview of those elements.

1.2.1 Nuclear Fission

As anticipated, electricity generation in a decarbonized power system will be completely, or almost completely, based on generation technologies that do not emit carbon dioxide. Nuclear fission is an energy source that certainly satisfies that constraint, and one that currently contributes roughly to 10% of the overall world electricity production. This technology has proven, and still does, to be an economically viable alternative to fossil fuels, as shown by the high number of nuclear power plants currently operating or under construction. Nuclear fission technology also has the advantage, differently

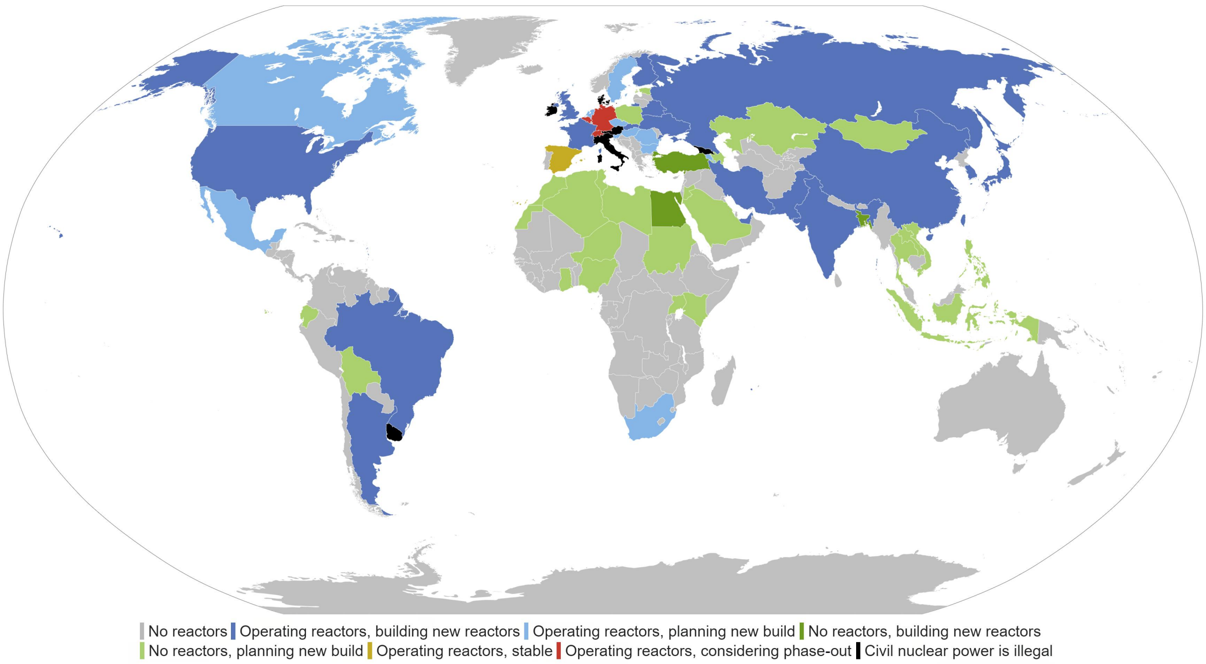


Figure 1.6: Global status of nuclear deployment as of January 2022. Source: World Nuclear Association.

from the main renewable sources, of being programmable and able to deliver constant power generation with high capacity factors. On the other hand Nuclear fission power plants exploit Uranium, a limited resource, as a fuel [11, 12]. And that means that it cannot be a durable solution for energy generation, even if the development of breeding reactors and Thorium reactors could largely increase the time window during which we could rely on nuclear energy [13]. Still, while global energy scenarios usually envisage a substantial increase in the nuclear fleet, with a share of the electricity generation at least equal to the current one, in the face of a bold increase of electricity demand, national policies are very heterogeneous on the matter, and a substantial number of countries either have built their energy mix completely excluding nuclear energy, or are planning a complete phaseout of their nuclear fleet. Nuclear energy is indeed a topic that polarizes public opinion, with arguments concerning operation safety, environmental impact (beyond the GHG emissions topic, mainly concerning plant decommissioning and fuel disposal), economic feasibility and effectiveness as a resource in the fight against climate change. Figure 1.6 summarizes the current policies concerning nuclear fission generation around the world.

The first argument that can arise from this view is that such a wide set of stances on a techno-economic topic cannot possibly be the result of objective considerations, and that should remind us of the weight of social sustainability on the matter. While this is certainly true, it should be also kept in mind that the electricity system and its components cannot only be related to the environmental problem, and specifically to the GHG emissions one. The design of the system is basically an optimization problem with more than one objective: some of them can easily be quantified (costs, emissions, land occupation, etc.), while other are more linked to intangible human needs and their perception (security of supply, visual impact, ethics, etc.). Either way, a single solution cannot be defined, even if the problem is correctly approached from every technical point of view.

1.2.2 Penetration of renewable energy sources

Renewable energy sources is a definition that includes a lot of different devices and concepts, whose common feature is that they rely on natural phenomena to harvest primary energy and convert it into electricity. That primary energy all rely, more or less directly, on the solar irradiation of earth, with the sole exception of geothermal energy: the fact that the energy needs of humanity are merely negligible when compared to the overall amount of energy linked to these phenomena, and the foreseen lifetime of the sun (5 billion years, which is anyway the time window available for human life on earth), lead to the conclusion that given an economic way of exploiting these sources, they can be a durable and sustainable resource on which humanity can rely for its energy needs. A first practical division can be made in three categories of renewable sources: hydropower, mature intermittent technologies, and other technologies. Hydropower is the renewable energy source that has been exploited for the longest time: electricity generation from hydropower dates back to the second half of the nineteenth century, but it has been used for centuries before that to extract and exploit mechanical energy. Hydroelectric power is a mature technology, economically sustainable, and, differently from other renewable sources, is also extremely versatile in terms of ramp-up and ramp-down rates, even more than conventional fossil fueled generators. Drawbacks of hydropower are mainly two: the first one is the exploitable potential. Suitable sites for hydropower plants are limited [14], and are already extensively exploited in developed countries. Developing countries can, and most certainly will, increase their share of hydropower, but reasonably to an extent comparable to the one currently reached by developed countries. Also, hydropower, especially when dealing with large scale projects, is likely to have a high social and environmental impact, linked mainly to the creation of the artificial basin, the modification of the water stream and the flow of water through the turbines [15, 16]. Wind turbines and solar photovoltaic panels are both mature technologies that were subjected to a strong cost reduction in the last two decades [17], as testified by the relevant increase of installed power and energy generation: following hydropower, with a generation share of 17%, wind and solar generation currently accounts for, respectively, 8.2% and 5.2% of the global electricity generation (2022 data from [18]). All of the other renewable energy sources, namely geothermal, biomass, waste, waves and tidal, together account for a remaining 3% of the electricity generation. If we exclude breakthrough advances in their development, they are not ready or suited for large deployment, whether it's because of insufficient exploitable potentials, technical limits or too high costs. In this context, renewable sources on which the vast majority of electricity scenarios and energy policies rely are solar and wind power. The following features, shared by these sources, are the more relevant to be taken into account to plan their integration in a future electricity system, regardless of the obvious differences between these generation technologies.

1.2.2.1 Variability

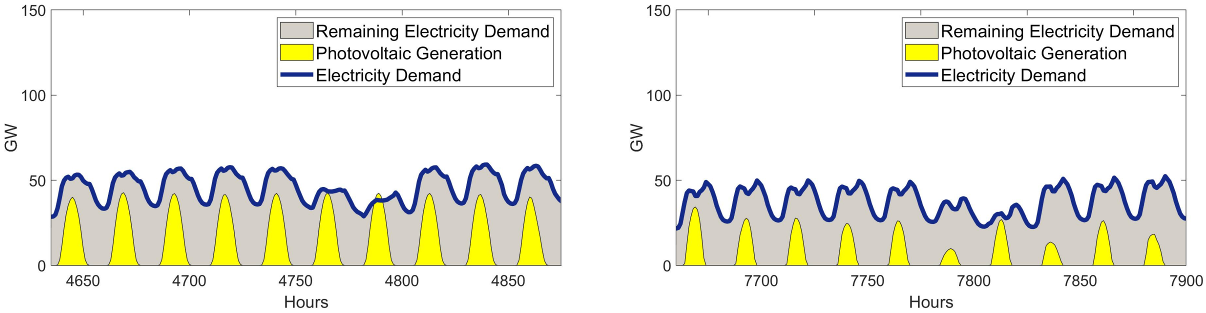
The power output of wind and photovoltaic farms cannot be regulated in order to match the time evolution of the electricity demand; it's instead a function of meteorological phenomena and their intensity. If we exclude scenarios in which the installed power is sufficiently low, i.e. the nominal power is lower than the negative peak of demand all over the year, and consider instead cases where a major share of electricity must be supplied by variable generation, every hour of the year will be divided in two categories: "surplus" hours, during which the power output exceeds the demand, and the excess energy must be either stored, or curtailed, and "deficit" hours, during which the power output is not sufficient to meet entirely the electricity demand, and other generators must be activated. Figures 1.7, 1.8, 1.9 and 1.10 qualitatively show the non programmability significance. The current Italian profile is compared to renewable generation (photovoltaic and wind generators) during intervals of high generation and low generation. Two meaningful cases are shown: a case in which the generation capacity is matched to the peak demand, and a case in which the generation capacity is such that the yearly renewable generation matches the yearly electricity demand.

1.2.2.2 Intermittency

Not only the power output of variable generators is out of human control, but it's also not entirely knowable. In order to know the power output of these generators in a time different from the present (i.e. to forecast it), two tools are needed: a model of the generator, representing the power output as a function of the climatic variable involved in the energy conversion process (solar irradiation, wind speed, temperature, etc.) and a weather forecast tool able to deliver us those whether variable. Whether forecast tools have been developed in time for a wide range of reasons, and can be adapted with little effort to this aim. Still, they do not guarantee perfect forecast: their accuracy decrease with the distance in time, and they can also be subjected to unexpected meteorological events or human errors. The power system cannot be operated hour by hour: some of its components needs to program their activity hours or days ahead, and this means that a sufficient degree of confidence must be achieved in forecasting renewable generation power output. Also, from the opposite point of view, the power system must be sufficiently resilient to be able to cope with partially inaccurate forecasts, without compromising the quality of the service delivered to users.

1.2.2.3 Seasonality

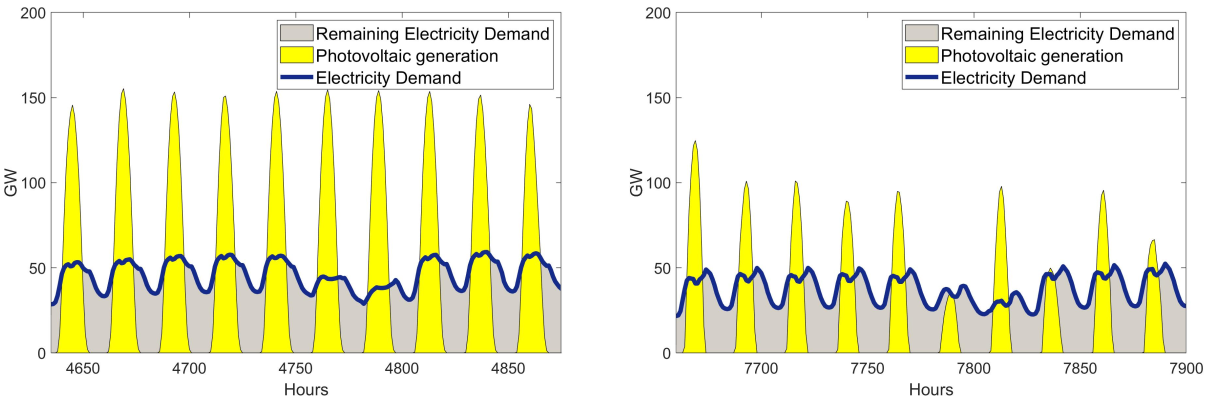
Earth climate is subjected to cyclical conditions induced by the different positions and distances that the planet assumes with respect to the sun during its orbit around it. These changes are continuous, but can be approximately described with the alternation of seasons. Even if weather events can substantially modify the power output of variable generation in the same hour of different years, aggregated values of energy generation show common patters for the same season. On one hand this behavior can help in planning the system operation, allocating limited resources to the periods of the year when they are most needed, on the other one it also impose to check the reliability of the system during all year: a system designed to deliver effectively energy only during the most favorable moment of the year could be unable to do the same in other time intervals, and result unreliable, or severely more expensive to be operated. Figures 1.11 and 1.12 show the monthly trend of renewable generation in Italy for photovoltaic generation and wind power generation, respectively. Mean trends show the common seasonal trend, while single years trends are reported to highlight the fluctuations to which also seasonal trends are subjected. Specifically, it can be noticed how the seasonal trend is more stable in the case of wind power, but with higher fluctuations with respect to the mean values. On the other hand, photovoltaic generation varies in a wider range of values, but with smaller fluctuations with respect to the mean trend. Figures 1.13 and 1.14 show, for comparison, the fluctuations in the Italian monthly electricity demand. The first one shows Italian electricity demand in 2015, while the second one shows a possible behaviour for electricity demand in a 2050 Italian scenario. The assumptions used to build the latter are detailed in Chapter 4 and Chapter 5.



(a) Ten summer days time window. From the 12th to the 21th of July.

(b) Ten winter days time window. From the 14th to the 23th of November.

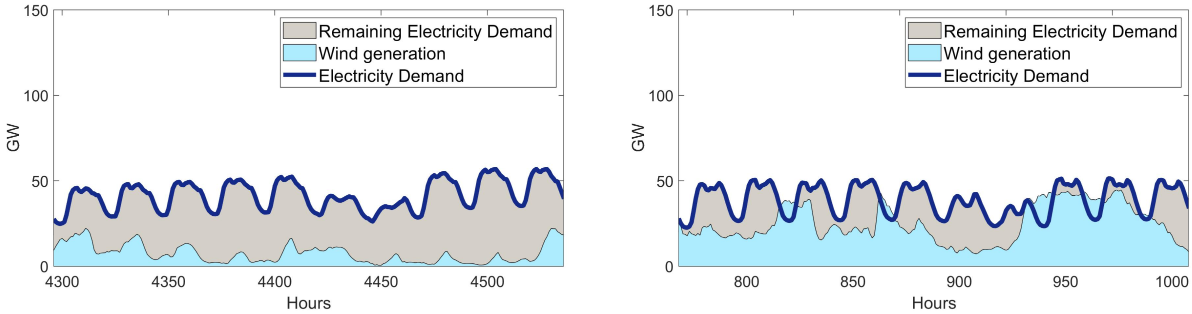
Figure 1.7: Photovoltaic generation vs current italian electricity demand, assuming to match peak power demand and photovoltaic rated power (60 GW). Data on demand and photovoltaic generation are from 2015.



(a) Ten summer days time window. From the 12th to the 21th of July.

(b) Ten winter days time window. From the 14th to the 23th of November.

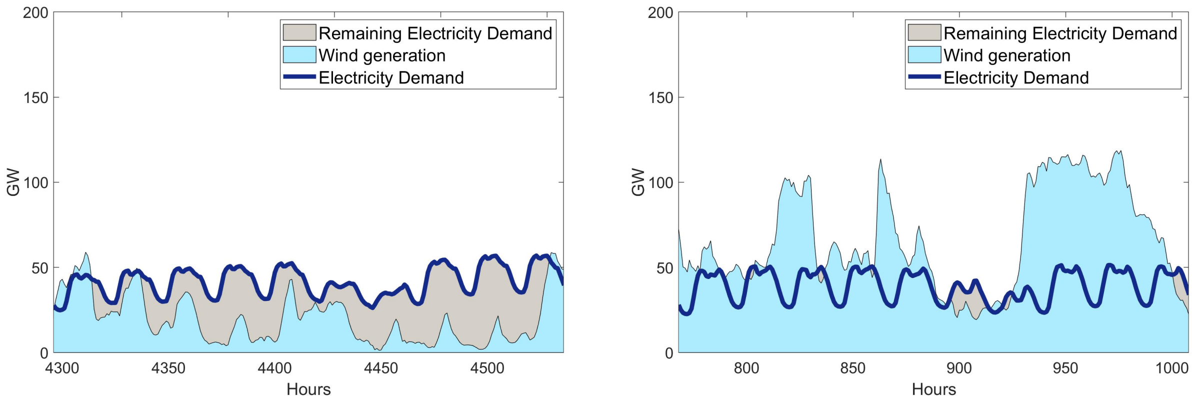
Figure 1.8: Photovoltaic generation vs current italian electricity demand, assuming to match the yearly electricity demand and the yearly photovoltaic generation (320 TWh). Data on demand and photovoltaic generation are from 2015.



(a) Ten summer days time window. From the 28th of June to the 7th of July.

(b) Ten winter days time window. From the 1st to the 10th of February.

Figure 1.9: Wind turbines generation vs current italian electricity demand, assuming to match peak power demand and wind generators rated power (60 GW). Data on demand and wind turbines generation are from 2015.



(a) Ten summer days time window. From the 28th of June to the 7th of July.

(b) Ten winter days time window. From the 1st to the 10th of February.

Figure 1.10: Wind turbines generation vs current Italian electricity demand, assuming to match the yearly electricity demand and the yearly wind turbines generation (320 TWh). Data on demand and wind turbines generation are from 2015.

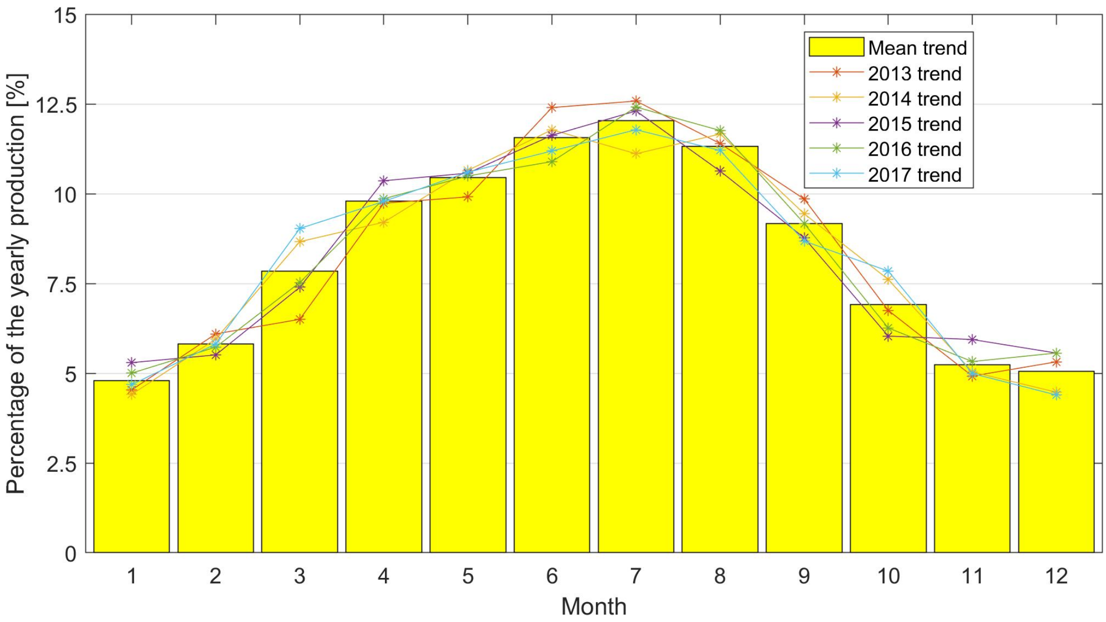


Figure 1.11: Monthly photovoltaic generation in Italy. Trends from 2013 to 2017 and mean trend.

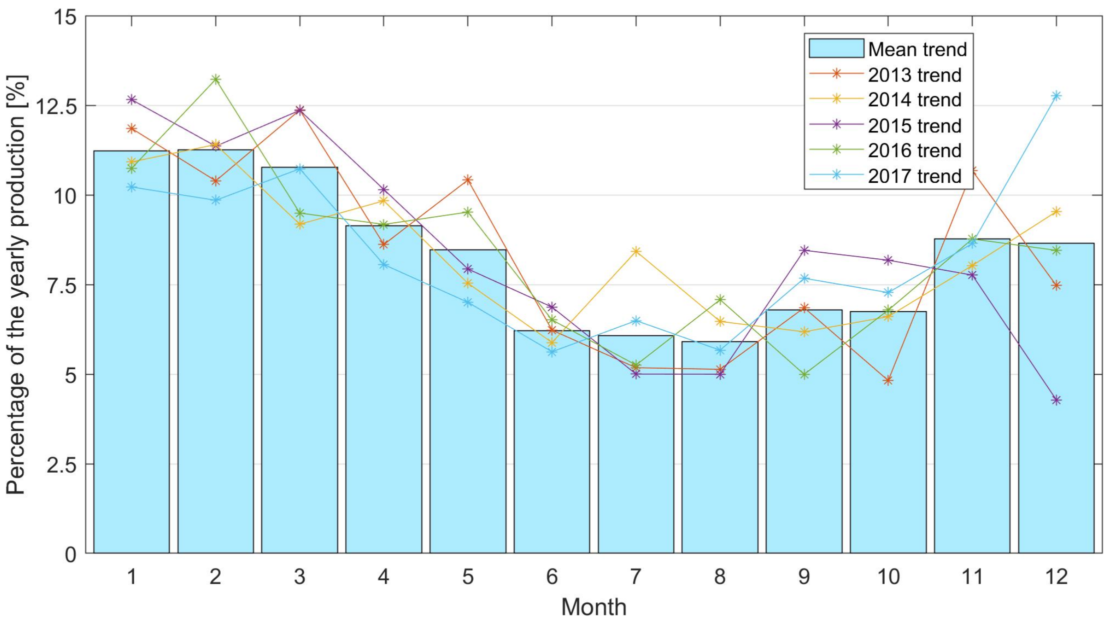


Figure 1.12: Monthly wind turbines generation in Italy. Trends from 2013 to 2017 and mean trend.

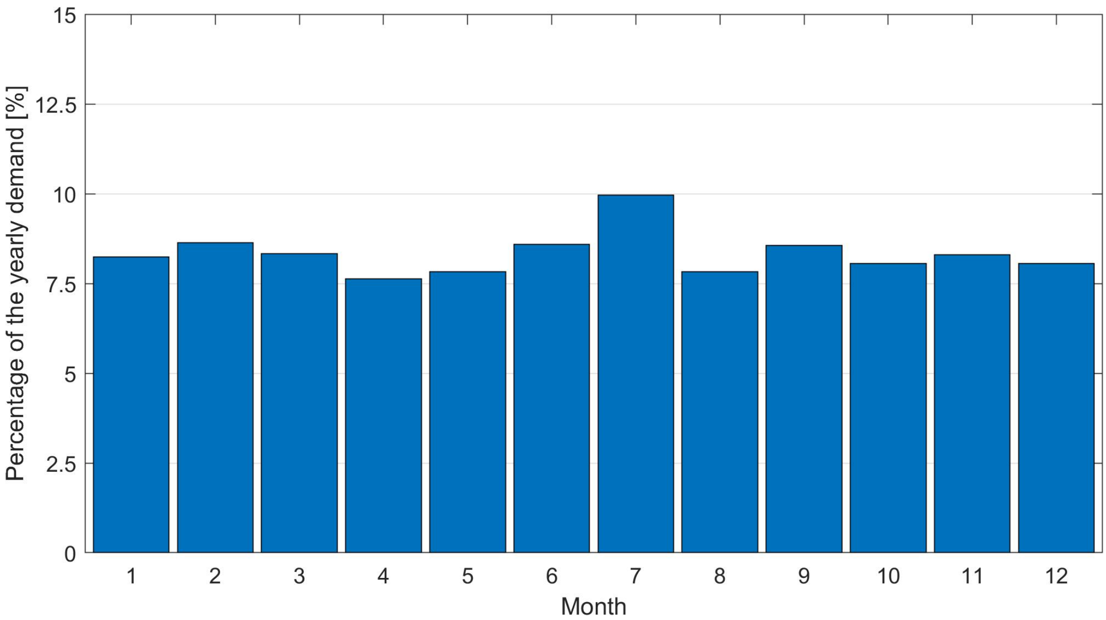


Figure 1.13: Montlhy electricity demand in Italy in 2015.

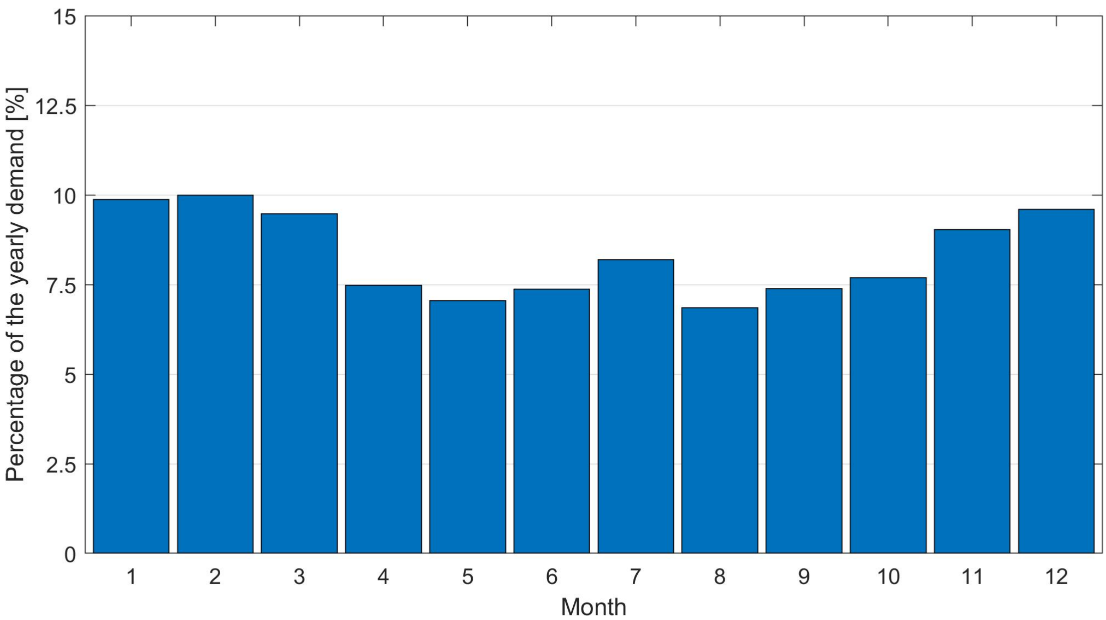


Figure 1.14: Possible montlhy electricity demand in Italy in 2050.

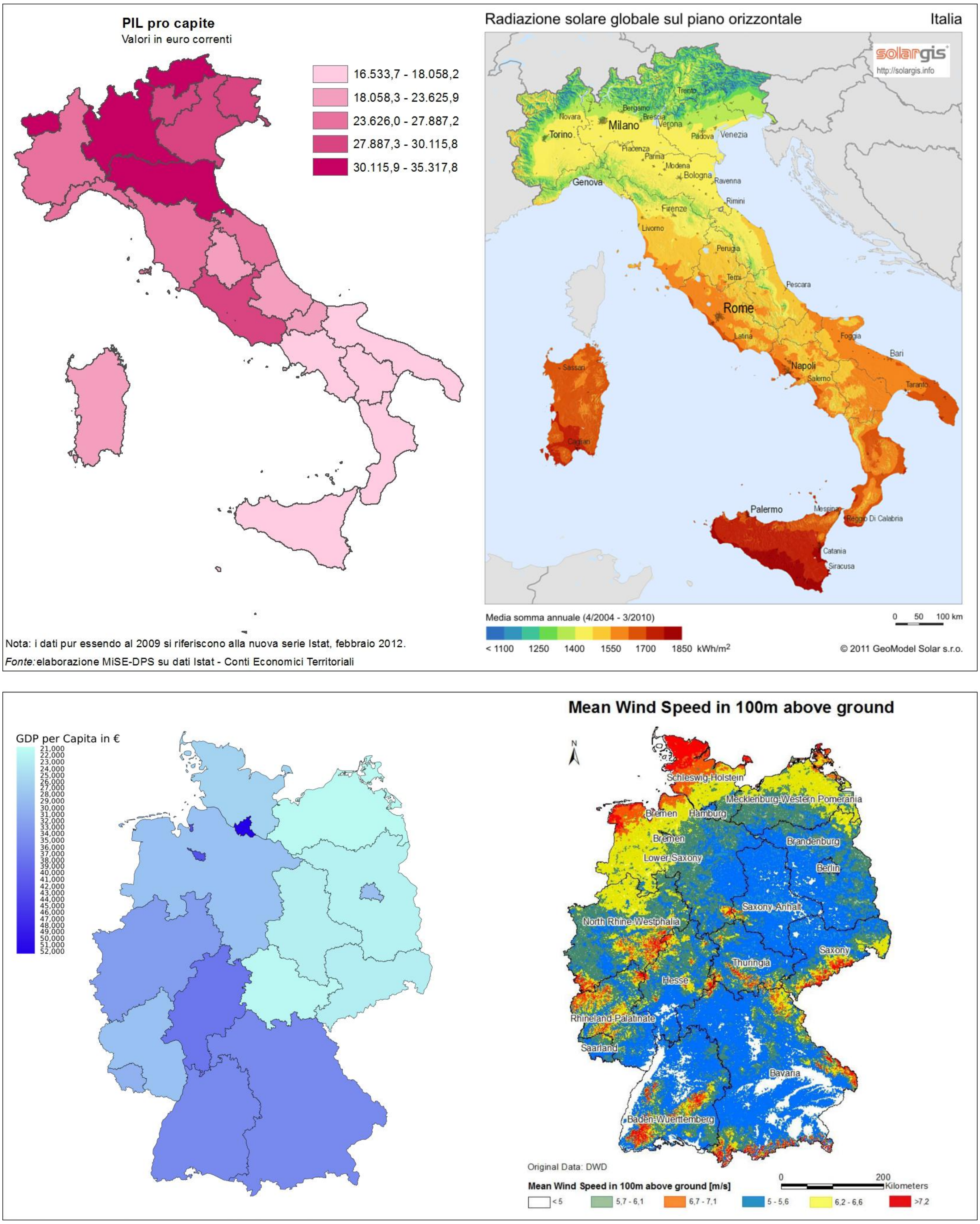


Figure 1.15: GDP distribution (left) and Renewable potential (right) for Italy and Germany.

1.2.2.4 Generators siting

Renewable generators siting is another critical aspect for their deployment. The amount of energy that can be collected and converted by renewable generators is strongly linked to their geographical location. For solar generators, it is mainly function of latitude and of the horizon profile. Wind speed at a specific location is function of air temperature and pressure gradient, but also of the orography characteristics of the site. Moreover, orography and transport infrastructure (streets, roads, bridges) can heavily influence the installation and maintenance costs and feasibility. If the location chosen for renewable generation parks does not match the zones with the heavier electricity loads, the transmission power grid will have to allow the transit of high amount of energy, with the related installation and maintenance costs. Figure 1.15 shows, as an example, the situation of Italy and Germany. On the left side it's shown the GDP distribution in the country regions, which provides a good approximation of the most energy consuming areas. On the right side the potential for the exploitation of the most abundant renewable source for the two countries, respectively solar and wind energy. Its easy to see how in both cases the high demand zones (north for Italy and south for Germany) are not geographically matched with the high generation potential zones (south for Italy and north for Germany). If on one hand an investor should seek, for the same cost, the location that grants the highest capacity factors, a policy maker should try to drive the choice of installation sites setting appropriate market rules, in order to obtain a siting coherent with the location of loads and the transmission grid capacity and topology.

1.2.3 Energy storage systems

Energy storage systems are another element that is very likely to be crucial in a future electricity system, and are often present in energy policies and strategies. The most intuitive use of this resource is to store the excess energy from renewable generators during surplus hours, thus avoiding its curtailment, and instead be able to postpone its use to following deficit hours, when renewable generation is not sufficient to entirely meet the load, avoiding (or reducing) the need for backup programmable of flexible generation. Considering this way of using storage systems, we can identify two quite different operating options:

> **Short term storage**: a storage systems designed to supply the energy after a limited number of hours with respect to when it was absorbed. These systems have a limited storage duration (the ratio between the energy capacity and the rated input or output power), i.e. the number of hours necessary to completely charge or discharge the system at the rated power. Given the limited storage duration, it would be uneconomical to keep the energy stored for long periods, as it would result in low usage and high costs per unit of stored energy. They are instead suited to balance frequent fluctuations in the mismatch between generation and demand. Batteries and pumped hydro stations are the most common devices suited to be exploited as short term storage systems.

Long term storage: a storage system designed to supply the stored energy long after it was stored inside of it. These systems need a cheaper reservoir in order to achieve much greater values or storage duration. In this way, they become suited to balance a seasonal mismatch between electricity generation and demand without being uneconomical. The technologies aforementioned are not suited to reach sufficiently high values of storage duration; instead different solutions are being evaluated, as power-to-gas or power-to-power systems.

Beyond their use to exploit surplus energy, energy storage systems could have a relevant role -from both economic and operational perspectives- in the electricity system management, with a vast number of uses, often referred to as "Energy Storage as a Service" (ESaAS) [19]. The analyses described in this thesis do not focus on these services, but for the sake of completeness they are here briefly enumerated: Coincident Peak Management, Demand Response, Power Factor Correction, Power Quality, Back-up Power, Peak Shaving, Energy Arbitrage, Market Ancillary Services, Transmission Support.

1.2.4 Dispatchable generators

The management of electricity generation and its flows in the transmission and distribution grid, with the aim of balancing energy demand from the loads and energy generated, net of line losses and regulation requirements, is called dispatching. Every generator whose power output is programmable is defined as dispatchable. During system operation planning, conventional dispatchable generators power output is programmed with an advance of hours or days in order to match the energy demand, relying on forecasts on non-programmable generation and energy demand. Still, it's often necessary to rely on flexible dispatchable generators to correctly match the actual values of generation and demand, due to forecasts errors or unpredictable faults or contingencies, both on generation and demand side. Differently from conventional generators, flexible dispatchable ones have very short ramp-up and ramp-down times, i.e. the rates with which their power output can be varied without compromising their operation. The need for flexible dispatchable generation is currently satisfied mainly using basin or reservoir hydropower and natural gas fueled turbines. As it's already been said the first ones have a limited growth potential, while the second ones will not be compatible with major generation contributions due to emissions constraints. It then becomes mandatory to focus on the following issues:

- To what extent, both taking into account installed power and generated energy, will a future power system have to rely on flexible dispatchable generation?
- Will hydropower plants capacity be sufficient to entirely meet the demand for flexible dispatchable generation?
- Will alternative non emitting fuels (hydrogen, biogas, biomethane, syngas, etc) be available to fuel either new plants, or the ones that are currently fueled with natural gas?
- What impact will these technologies have on the overall system cost?

1.3 Energy system modelling

What was argued in sections 1.1 and 1.2 motivates the need for energy systems analysis and adequate energy systems analysis tools, yet the study of the these systems is subjected to some peculiarities and limitations that makes this effort non trivial.

To begin with, let us remind that an energy system operation is not a natural phenomenon: its behaviour is a function of well known principles of electromagnetism and thermodynamics that govern its components, as well as the result of arbitrary human operational choices, dictated by both operators and users' needs and resources. Specifically, unless considering a centralized planned economy and a non-democratic system, the human factor cannot be considered a unique, well defined and constant input in the system management. It's actually the result of at least four actors, with non-aligned or even conflicting interests: users, producers, system operators and regulators. The criteria guiding these actors are heterogeneous as well and sometimes contradictory, spanning from social and economic needs, to geopolitical relations and technical constraints, such as: abundance and affordability of energy, environmental sustainability, resource availability, service continuity and power quality.

Such nature of the energy systems alone would imply the impossibility to carry out proper scientific experiments on them, but that is also technically impossible: first of all the energy system cannot be reproduced both from a structural point of view, obviously due to its physical dimensions and the cost of its components, but also with respect to the human factors just mentioned. On the other hand, the energy system itself cannot be used to conduct major experiments, due to the primary importance that its normal operation plays in daily life of societies, with very rare and specific exceptions [20]. Moreover, the energy system design cannot be modified (perturbated) at will, due to what has been previously defined as high "inertia". Finally, analyses involving energy systems, and in particular scenario analyses, often include elements that are not yet commercialized, mature, or even available.

In this context, the analyses of energy systems are mainly carried out by means of computational models that try to reproduce the behaviour of an energy system. It is clear that given the material extension of the system studied, the number of phenomena influencing its behaviour, and the number of significant variables that feature it, a rather strong level of approximation is necessary to handle the problem computationally. This also entails that different models may adopt different approaches, assumptions and degrees of detail or approximation with respect to the same aspects of the energy system, so as to simulate in as much detail as possible the features that are object of the analyses.

1.3.1 Energy system models

Given the importance and the urgency of the problem assessed, in recent years a high number of energy models have been proposed and adopted to perform scenario analyses. If on one hand the availability of a diverse set of tools is for sure beneficial to deepen the understanding of energy systems from diverse point of views, on the other hand such a variety of models could make it difficult to choose the most appropriate tool for a specific kind of analyses, as well as making it difficult to correctly interpret the results of a simulations, if the model assumptions are not completely available or understood by the user.

A brief description of the most relevant features and properties that characterize energy models is presented in the remaining part of this section, in order to provide the reader with a set of information useful to categorize an energy model, as well as to use them to classify the COMESE code, that will be described accurately in Chapter 3. For a more complete description and classification of these tools, the reader can consult [21, 22, 23].

Finally the features of some particularly relevant energy models are recalled, namely: the MARKAL/ TIMES model, the PRIMES model and EnergyPLAN. EnergyPLAN is also classified following the criteria enumerated in the following section, since it was used for a comparison with COMESE, described in section 3.6.

1.3.1.1 Energy models features and properties

Bottom-up and top-down approach: Top-down models are based on macroeconomics relationships and long-term changes. They try to describe the energy system evolution relying on the simulation of market behaviour. They allow a highly detailed simulation of interactions across different sectors and regions. On the other hand they impose a rather coarse representation of the energy sector, with a low detail of the technical and operational features of its components. They are also strongly dependant on hystorical, or exogenously defined behaviour patterns, and do not comply well with technological advancements, policy changes and shifts in attitudes. Bottom-up models, on the contrary, are based on a detailed technological representation of the energy system, of its components and its operations, and is more suited to account for radical changes in its design and management. Still, they represent the energy system as an isolated one, and fail to capture how its influenced by macro-economics, and in turn what is its impact on them.

Forecasting and backcasting method: Most energy scenario studies delivered up to approximately 2010 were based on the “forecasting method”: future energy mixes were deterministically extrapolated from historical trends, with different assumptions on energy sources availability and costs acting as constraints. From 2010 on, there was a sharp change in the approach, thus most of the current energy scenario studies are based on the “back-casting” method, adopted for the first time by the European Commission in 2011 [9]: keeping the desired future energy system set-up as basis, the viable paths towards its achievement are identified and their economics assessed a posteriori. The reason for this change to happen was the increasing commitment to decarbonization targets (as described in 1.1) and the need to simulate radical policies and prompt changes in habits and attitudes.

Purpose: As it was anticipated, the purpose of energy models can be to assess, analyse and deepen the knowledge of several aspects of a the energy systems operation and design. Three overall categories can be outlined, bearing in mind that a single model can fit more than one: a) Power system analyses. These tools analyse the energy system operation with a high degree of detail, usually relying on a high time resolution and on small spatial scales, focusing on the integration and correct operation of its components from a technical point of view, and addressing problems like power flows, fault levels, frequency and voltage control, etc. b) Operation analyses. The aim of these tools is to optimize the operation of the energy system, addressing problems like dispatch, unit commitment and balance of energy supply and demand. They are suited for the analyses of wider regions over time windows relevant for aggregated energy balances (days, months, years). c) Investment and capacity planning. Relying on energy market simulations, these models represent the evolution of an energy system in order to optimize the investment and plan the most cost-effective capacity deployment in the time window considered.

Methodology: Three main categories can be identified. a) Simulation. The model (usually a bottom-up model) represents the energy system based on specific equations and relying on detailed representation of the system elements. They aim at exploring different operation strategies or assessing the correct operation of the system and its reliability. b) Optimization. The model optimize a given quantity that can be related to the system operation and design, like renewable generation share, GHG emissions, land occupation, investment and operation costs, etc. c) Equilibrium. In this case the model is strongly based on an economic approach. Equilibrium models represents the energy sector as a part of the whole economy and simulates its relations with other economy sectors, trying to evaluate the total impact and effectiveness of energy policies.

Single-sector and multi-sector models: Single-sector models focus on just one energy sector (e.g. the power sector, transports, heat) neglecting the possible interactions with the other ones. On the contrary, multi-sector tools represents these interactions simulating energy transformations and energy vectors that can link them, exploiting possible synergies.

Unit commitment strategy: The unit commitment problem is the choice of which generators to exploit during each hour to correctly meet the demand and the supply of energy, in order to satisfy all of the constraints and the rules set by the regulator and the transmission system operators, and to deliver energy in the most secure and economic possible. Unit commitment, net of the rules and constraints just mentioned, is regulated by the energy market [24]. Some models rely on a simulation of unit commitment based on the current energy market rules. Other rely on a user defined priority order to decide which generators should be activated to meet the demand. The reason is that energy systems with a markedly different structure from the current one, like the ones simulated in future what-if scenarios, could be not suited for current market rules. A significant example is the electricity market: to good approximation, suppliers currently offer electricity at its marginal cost. This can be problematic (not only concerning simulations, but also the actual future market operation) considering that not only renewable generation has often zero marginal cost, but even more considering that in scenarios based on major shares of renewable energy it's quite common that the entire electricity demand can be satisfied entirely by renewable generation.

Time-scale and time window: The time-scale is a parameter generally suited to describe models that simulate the evolution of the system, like the ones with investment and capacity planning purpose. Even if no unique classification is present, an effective one can be: a) Short-term: up to five years. b) Medium-term: from 5 to 15-20 years. c) Long-term: several decades. Energy models for operation and power systems analyses could be classified as models with a time-scale up to one year long, but the classification itself is not completely appropriate since they do not simulate any evolution of the system: in this case the "time window" term is more appropriate.

Target year: A definition somehow overlapping to the timescale one. For investment and capacity planning simulation it's the final year of the simulation. For power system and operation analyses the year assumed for the ongoing simulation: it affects costs, technology availability and policy constraints assumption in future what-if scenarios studies.

Time resolution: The name is self explanatory. Every model analyse the energy system with a given time resolution. It can span from one or more years for investment and capacity planning models, from minutes to a year for operational analyses and below minutes for power system analyses. Some models allow to modify the time resolution in a given range to tune the model from time to time. Other models rely on a mixed approach, with a coarser resolution for the main analyses and a higher resolution on a limited number of specific time intervals, during which operational feasibility checks are performed.

Spatial resolution: The energy system can be modelled as a single entity where all the plants and devices of a given technologies are represented as a single device. The same goes for the users, while the constraints given by the transmission infrastructure through which energy supply and demand meet are neglected. This assumption is called "single node" assumption or sometimes, especially in power system models, it goes by the name of "copper plate" assumption. On the other hand, some models allow to divide the simulated system with several degrees of detail. Power system analyses tool may allow a dedicated representation for each user and generator, operation analyses tools may represent nations, divided in administrative regions or power system zones, or supranational entities, divided in nations. Investment and capacity planning models can even simulate the entire world, as divided in major macroeconomic entities. IEA-ETSAP scenarios, for example, are based on a global MARKAL/TIMES model, where the world is divided in 15 macro-regions. The PRIMES model, used by the European Commission, produce European scenarios where each nation of the Union plus the candidate states are singularly represented as a region. It must be pointed out that even model that allow a regional representation can adopt the single node assumption. In this case transmission constraints are equally neglected but the system design is defined with a higher degree of detail.

Transmission and distribution constraints: Transmission and distribution, i.e. the delivery of energy from the supplier to the user over long and short distances, respectively, can be modelled in models that allow a zonal representation, with as much detail as the spatial resolution allows.

Myopic and perfect foresight: Models can adopt two approaches in simulating the system operation during each on of the time slices (as long as the temporal resolution) that divide the time window covered by the analysis. Under the perfect foresight assumption the operation (or the evolution) of the system is optimized and solved simultaneously for all the time slices. That means to assume that in every moment, and especially at the beginning of the time window considered, the evolution of the input parameters is completely known. The alternate approach is to assume myopic foresight, which can rely only on information about the current time slice considered and the previous ones.

Forecast: The concept of forecast is partially overlapping to the foresight one. Simulations including forecasts have the ability to analyse a time slice including information about a limited subsequent time interval. This forecast can be perfect, but also try to represent to some extent the inaccuracies that characterize the exploitation of forecasts in real life system operations (forecasts on energy demand, renewable generation, climate dynamics, market behaviour, etc).

1.3.1.2 MARKAL/TIMES

MARKAL (MARKet and ALlocation) [25] is a bottom-up model, simulating both the energy supply and demand sides of the energy system, developed in the context of the Energy Technology Systems Analysis Programme (ETSAP) of the International Energy Agency. TIMES (The Integrated MARKAL-EFOM System) [26] is the evolution of MARKAL: it's a linear programming model generator suitable for investment optimisation over a long time horizon. MARKAL/TIMES is the name commonly used to refer to the analysis carried out with this two tools. As reported in [21], the MARKAL/TIMES model is currently the most widely used to simulate energy systems at a national and regional level (in the literature it has been adopted over a range between 20 and 100 years); however it represents daily and seasonal variations in a rather coarse way by using time-slices; hence, they are not perfectly suitable to accurately simulate the dynamics associated with the integration of variable renewables and storage technologies in almost 100% renewable energy systems. Nevertheless MARKAL/TIMES is currently used by more than 70 countries, often through customised versions in order to include a more detailed national characterisation. This approach is used in the European Union with the European TIMES model (ETM-UCL) [27] to simulate the energy systems of 11 European regions covering the EU member States plus Norway, Iceland and Switzerland. In terms of spatial resolution, multi-regional versions of MARKAL/TIMES have been developed; in addition, MARKAL/TIMES models can be integrated with other modelling tools, able to take into account zonal features of the power system.

1.3.1.3 PRIMES

The PRIMES model (Price-Induced Market Equilibrium System) [28] is used at EU level to develop low-carbon energy scenarios until 2050. Primes is a bottom-up partial equilibrium modelling framework that simulates energy demand and supply systems in the EU and in each member States, and it was developed by E3Modelling, a spin-off of the E3MLab at National Technical University of Athens. It normally analyses whole-year time periods, although the power sub-model can be solved with higher time resolution, which is however not so detailed to allow an accurate analysis of energy systems with high share of variable renewable. In terms of spatial resolution, Primes can model a regionalized energy system, allowing to evaluate strongly regional-dependent parameters such as demand, availability of resources and capacity of renewable energy sources.

1.3.1.4 EnergyPLAN

EnergyPLAN [29] is another modelling tool widely used in the EU context. EnergyPLAN is developed and maintained by the Sustainable Energy Planning Research Group at Aalborg University, in Denmark, and is thoroughly described in [30]. Following the criteria enumerated in section 1.3.1.1 this tool can be classified as a bottom-up model for the operation analyses of the energy sector. It's a simulation model that analyse the system over a one year time window, with an hourly time resolution and adopts the single node assumption for what concerns the spatial resolution. Since the single node assumption is used, no transmission constraint is simulated. EnergyPLAN is a multi-sector model, including in its simulations the electricity, heating, cooling, industry, and transport sectors. Finally, EnergyPLAN adopts a myopic foresight approach with no forecasting ability in the simulation of the energy system during the target year, and can handle unit commitment with both a market simulation strategy and a fixed priority order, called "technical simulation strategy". EnergyPLAN purpose, quoting [29], is "*to analyse the energy, environmental, and economic impact of various energy strategies. The key objective is to model a variety of options so that they can be compared with one another, rather than model one 'optimum' solution based on defined pre-conditions. Using this methodology, it is possible to illustrate a palette of options for the energy system, rather than one core solution*". Due to its features and to the comprehensive description of its functioning EnergyPLAN was deemed an appropriate choice to make a comparison with the code presented in this thesis, and described in Chapter 3: COMESE.

Chapter 2

Nuclear Fusion

Nuclear fusion is an energy source currently unavailable, to which a vast research activity has been dedicated since the fifties of the twentieth century, currently involving worldwide partners including the European Union, Russian Federation, People's Republic of China, Japan, Republic of Korea, Republic of India, Canada, and the Unites States of America. Moreover, beyond academic and public research centers, in recent years also the private sector has gained interest in fusion technology [31, 32, 33, 34, 35, 36]. The widening of the research activities, with complementary or alternative approaches and designs, will surely widen our knowledge of plasma and other fusion relevant aspects, increasing the chance of breakthrough results that could speed up the time schedule for an operating fusion power plant prototype. Still, under current conditions, there is wide consensus on forecasting the availability of operating fusion power plants only in the second half of this century.

This is the reason why decarbonization is very unlikely to be achieved exploiting fusion power, given that the majority of decarbonization policies set the target for zero emissions around the year 2050, or shortly after. Nonetheless nuclear fusion features, which will be briefly exposed in this section, would make of it a resource of primary importance in a decarbonized energy mix, once commercially available.

2.1 Nuclear fusion reaction

Nuclear fusion is the reaction for which two light atom nuclei fuse together, usually producing one heavier atom and releasing kinetic energy in the process. It is possible to notice that the nuclear mass of any atomic species does not match the sum of the mass of the nucleons (protons and neutrons) that belong to their nucleus. This mismatch derives from the fact that part of the nucleons mass is converted in binding energy when they form a nucleus, according to the well-known mass-energy equivalence:

$$E = mc^2 \tag{2.1}$$

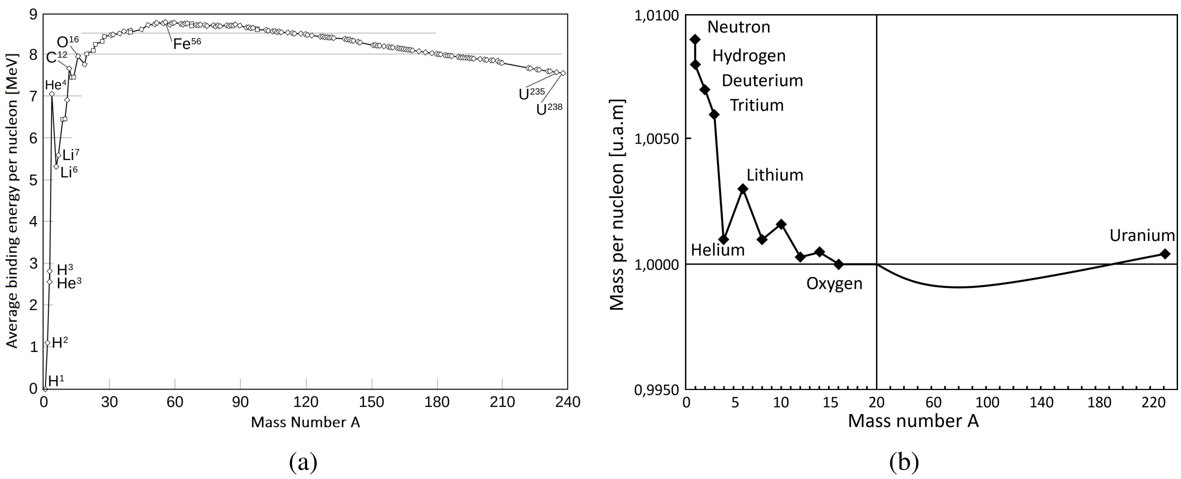


Figure 2.1: (a) Binding energy per nucleon as a function of the Mass Number. (b) Mass per nucleon as a function of the Mass Number.

For which, in this context, the following form is more suited:

$$\Delta E = \Delta mc^2 \tag{2.2}$$

In order to compare the binding energy of different atomic species it's useful to divide the mass of the atom by its mass number, thus obtaining its mass per nucleon: it becomes then clear that as the mass number increases (starting from neutron, proton towards heavier nuclei) the mass per nucleon first decreases, with few exceptions, until it reaches a minimum for iron($\mathbf{^{56}Fe}$), and then it starts increasing again (Figure 2.1a). If we apply equation (2.2) to the data on atomic mass we can instead derive the binding energy per nucleon, for which we get a specular trend (Figure 2.1b). In the low mass-number region (A< 56) the fusion of two light nuclei involves the creation of a heavier nucleus with lower mass per nucleon, therefore with higher binding energy, with a consequent release of energy. Likewise, in the high mass-number region (A> 56) splitting a heavy nucleus into two lighter nuclei with lower mass per nucleon, implies the release of energy. This phenomena is known as nuclear fission, and is currently the only process available to exploit nuclear reactions for the generation of energy in the civil sector, mainly exploiting the fission of Uranium isotope $\mathbf{^{235}U}$.

In order for two atomic nuclei to fuse, having both positive electric charge, they need to reach a relative distance small enough that the repulsive Coulomb force is overcome by the nuclear attraction force, i.e. they need to gain a kinetic energy higher than the so-called Coulomb Barrier, which in turn is a function of the nuclei involved in the reaction. In nature these conditions can be found only in stars, thanks to extremely high temperatures, pressures and densities, where they induce two kind of reactions:

the *pp-chain*[1], that dominates in stars with masses less or equal than that of the Sun:

$$2\,\mathrm{p} + \mathrm{e}^- \longrightarrow {}^2_1\mathrm{D} + \nu_e \qquad {}^2_1\mathrm{D} + \mathrm{p} \longrightarrow {}^3_2\mathrm{He} + \gamma \qquad 2\,{}^3_2\mathrm{He} \longrightarrow {}^4_2\mathrm{He} + 2\,\mathrm{p} \tag{2.3}$$

Or the *CNO-cycle*, that dominates in stars more than 1.3 times as massive as the Sun. Involving isotopes of Carbon ($^{12}\mathbf{C}$,$^{13}\mathbf{C}$), Nytrogen ($^{13}\mathbf{N}$,$^{14}\mathbf{N}$,$^{15}\mathbf{N}$) and Oxygen ($^{15}\mathbf{O}$) as cathalysts, with the following net reaction:

$$4\,\mathrm{p} + 2\,\mathrm{e}^- \longrightarrow {}^4_2\mathrm{He} + 2\,\nu_e + 7\,\gamma \tag{2.4}$$

2.2 Controlled Thermonuclear Fusion

Controlled thermonuclear fusion refers to all the strategies that can be put in place to induce fusion reactions, collect the energy released, and covert it for civil uses, in contrast to uncontrolled thermonuclear fusion, which refers to the exploitation of fusion reactions for military purposes. A reactor able to exploit fusion reactions to generate energy must be able to confine for a sufficient time, and at specific conditions, the reactants, in order to extract more power from fusion reactions than the one spent to trigger them. The ratio between these two quantities is called gain factor Q. The condition when $Q = 1$, when the external power fed to the reactants is matched by the power generated by fusion, is referred to as "breakeven". $Q > 1$ corresponds to the aforementioned condition, when we have a net production of energy from the entire process, while $Q = \infty$ refers to the condition when no external power is required to maintain self-sustaining fusion reactions, that is called “ignition”.

The chance to induce fusion reactions with a net gain of energy depends on three parameters: temperature T [keV], density n [m^{-3}] and energy confinement time τ_E [s]. Temperature must be high enough to allow the reactants to overcome the Coulomb barrier and trigger the fusion reaction; more specifically it must be in a range where the cross section(the probability that the nuclear reaction will occur) is high enough. Density increases the chances of interaction between two particles, while energy confinement time is a measure of how fast the energy content of the plasma tend to escape the reaction environment: the longer the reactants remain in fusion relevant conditions the higher the chance of interaction grows.

Since it’s impossible to reproduce on earth the environmental conditions typical of stars, it’s necessary to exploit different reactions from the ones that take place in nature (2.4,2.3). Figure 2.2 shows the cross section for three fusion reactions potentially exploitable on earth:

[1]Four possible "branches" can take place as final step of the *pp-chain*, depending on temperature. Equation (2.3) shows the so-called Branch-I(the most common in the Sun), that takes place for temperatures between 10 and 18 MK.

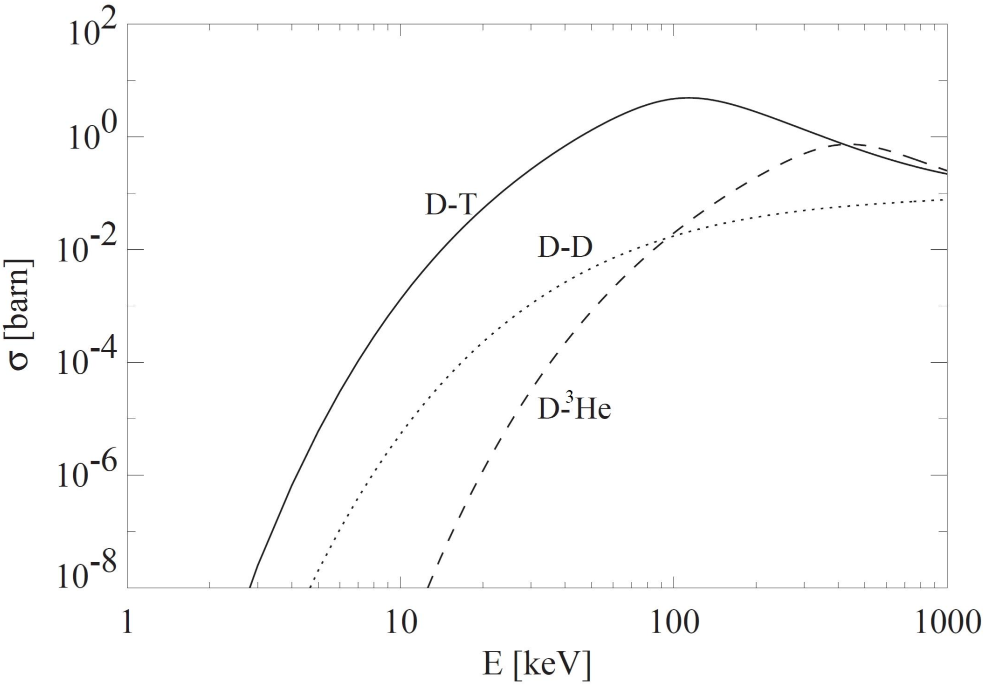


Figure 2.2: Cross section

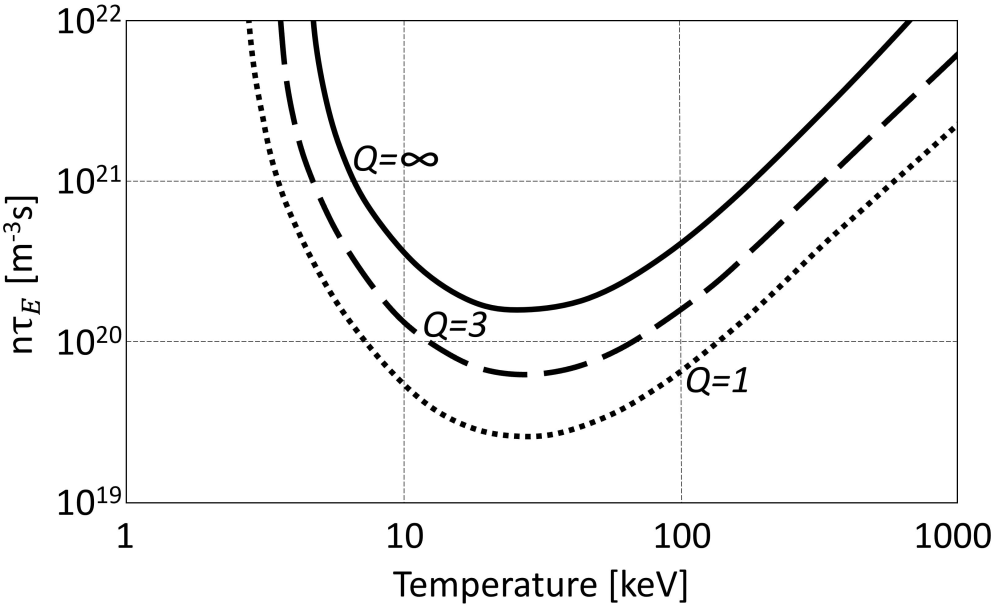


Figure 2.3: Trend of the $n \cdot \tau_E$ product required to reach breakeven (Q = 1), Lawson's criteria (Q = 3) and ignition ($Q = \infty$) as function of temperature.

- **D-T**

$$ {}^{2}_{1}\mathrm{D} + {}^{3}_{1}\mathrm{T} \longrightarrow {}^{4}_{2}\mathrm{He} + \mathrm{n} + 17.6\,\mathrm{Mev} \tag{2.5} $$

Deuterium–Tritium reaction is the most promising options for first generation fusion power plants, and the one studied in all current research lines. It's the easiest reaction to initiate, since it reaches cross section values up to two order of magnitude greater than other reactions, for lower temperatures (Figure 2.2), and it produces a high amount of energy: 3.52 MeV per nucleon, equivalent to $338 \cdot 10^6$ MJ per kg of fuel. While Deuterium is available in nature Tritium is not, but can be artificially produced.

- **D-D**

$$ {}^{2}_{1}\mathrm{D} + {}^{2}_{1}\mathrm{D} \longrightarrow {}^{3}_{2}\mathrm{He} + \mathrm{n} + 3.27\,\mathrm{MeV} \tag{2.6a} $$

$$ {}^{2}_{1}\mathrm{D} + {}^{2}_{1}\mathrm{D} \longrightarrow {}^{3}_{1}\mathrm{T} + \mathrm{p} + 4.03\,\mathrm{MeV} \tag{2.6b} $$

Deuterium–Deuterium reaction takes place, almost with equal likelyhood, with the two different branches reported above. Even if it produces a considerably lower amount of energy (0.82 or 1.01 MeV per nucleon, equal to $78 \cdot 10^6$ or $96 \cdot 10^6$ MJ per of fuel, depending on the branch) it would be the most desirable reaction, since it relies only on Deuterium, which is virtually unlimited and easy to extract. However it's not a primary candidate for first generation fusion power plants since it's the most difficult reaction to initiate.

- **D-${}^{3}_{2}$He**

$$ {}^{2}_{1}\mathrm{D} + {}^{3}_{2}\mathrm{He} \longrightarrow {}^{4}_{2}\mathrm{He} + \mathrm{p} + 18.3\,\mathrm{MeV} \tag{2.7} $$

Deuterium-Helium-3 is worth considering as well, since it produces a high amount of energy (3.66 MeV per nucleon, equivalent to $351 \cdot 10^6$ MJ per kg of fuel), all of its products are charged particles, and only a small number of neutrons would be produced via D-D secondary reactions and next generation D-T reactions. Still it's not considered in current research lines due to the low **^{3}He** availability (it's absent in nature and has actually to be produced using Tritium) and the difficulty to initiate the reaction (slightly easier than D-D but harder than D-T).

The condition to reach a desired value of Q with a specific reaction can be expressed with the so called triple product, defined by John D. Lawson in 1957:

$$ T_p = T \cdot n \cdot \tau_E \quad [\mathrm{keVm^{-3}s}] \tag{2.8} $$

The three quantities involved in the triple product are not independent: for every choice of Q it is possible to calculate the trend of the required value of $n \cdot \tau_E$ as a function of temperature. By doing so, and considering the cross section values for the D-T reaction, we obtain the trend that is shown in Figure 2.3 for three different conditions: $Q = 1$, $Q = 3$ and $Q = \infty$. As already said the first and the third correspond respectively to breakeven and ignition conditions, while $Q = 3$ is the value originally calculated by Lawson for an operating reactor, assuming a conversion efficiency of the extracted energy equal to 33%.

The trends shown in Figure 2.3 also highlight that the product $n \cdot \tau_E$ reaches a minimum for temperatures around 25 [keV]. That is the region of temperatures where a reactor should work in order to reach the desired value of Q with the most favorable requirements in terms of n and τ_E. In turn, the technical constraints on the maximum achievable density in the reaction environment will set a requirement in terms of confinement time. For the three values of Q reported in figure the curves reach, respectively, a minimum of $2.5 \cdot 10^{19}$ [m^{-3}s], $6 \cdot 10^{19}$ [m^{-3}s] and $1.5 \cdot 10^{20}$ [m^{-3}s].

2.3 Magnetic Confinement Fusion

Fusion reactants must, as explained above, be confined in an environment where they can reach the required conditions on temperature and density for a time long enough to trigger the fusion reactions. The extremely high temperatures needed impose that no conventional vessel can be used to contain the reactants, and make plasma confinement one of the most delicate processes to be achieved in a fusion reactor. Two main confinement schemes are considered to achieve controlled fusion reactions:

ICF Inertial Confinement Fusion is an approach based on initiating fusion reactions thanks to the compression and heating of a solid target containing the fusion reactants. In current experiments these targets are small (diameters of millimeters) pellets containing milligrams of Deuterium and Tritium. The outer layer of these pellets is coated with a material designed to absorb high amount of energy, deposited with several high energy beams (currently lasers), so that pressure and temperature inside the pellet is raised enough to trigger fusion reactions.

MCF Magnetic Confinement Fusion is an approach based on keeping the reactants, in a plasma gas state, separated from the chamber of a vessel thanks to magnetic fields. These fields influence the trajectory of the charged particles, keeping them confined. In this section only magnetic confinement fusion will be described, as the main research lines for commercial reactors are based on this scheme.

A charged particle in presence of a uniform and static magnetic field B will be characterized by an helicoidal motion: the component of its motion parallel to the magnetic field -with velocity $v_{\parallel}$- will be affected only by the interactions with the environment, and not by the field itself, while the circular motion on the perpendicular plane -with velocity $v_{\perp}$- will be characterized by a frequency called “cyclotronic frequency” and a radius called “Larmor radius”:

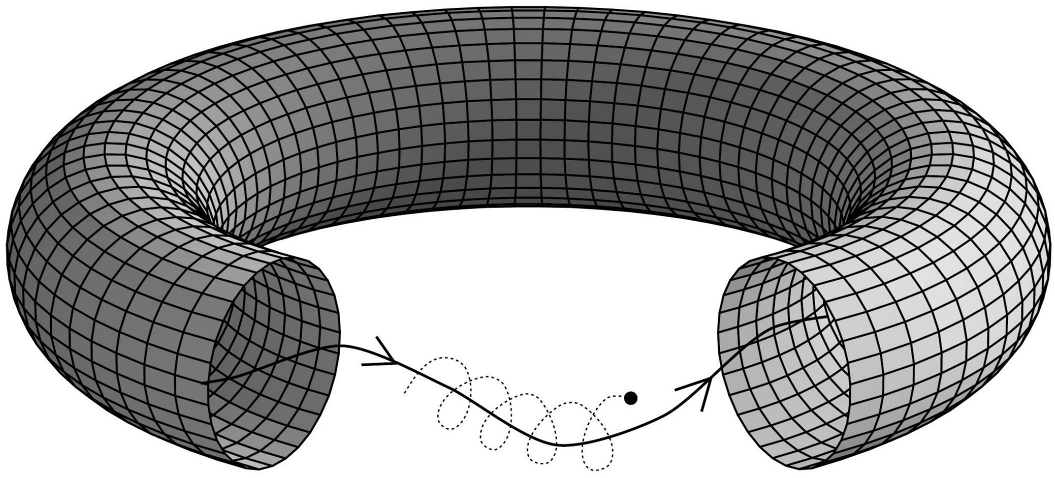


Figure 2.4: Helicoidal motion of a charged particle around a magnetic field line in a toroidal configuration.

$$\omega_c = \frac{q|B|}{m} \qquad r_L = \frac{v_\perp}{\omega_c} = \frac{m v_\perp}{q|B|} \tag{2.9}$$

Where q is the charge of the particle, m its mass, B the magnetic field to which the particle is subjected. The uniform motion along the field lines suggests that a toroidal configuration, allowing field lines to close on themselves, is the more efficient configuration to keep charged particles confined. Still, also exploiting non-uniform magnetic field configurations (Magnetic Mirror), in so called "linear devices", can be conceived. In fact also in a toroidal configuration the magnetic field is non-uniform: it's designed to assume a helical structure by superimposing a toroidal component, along the torus axis, and a poloidal one, on the perpendicular (poloidal) plane. This allows to compensate drift motions linked to possible dishomogeneities of the field and to its curvature (Figure 2.4). Three toroidal configurations for the magnetic confinement, with different geometries and magnetic field features, are currently used in experiments:

Tokamak: In these devices the toroidal field component is induced exploiting external coils closed on the chamber, on the poloidal plane. The poloidal field component is instead generated by a current flowing inside the plasma itself, that acts as a conductor. This current is generated by electromagnetic induction, as in transformers, by concatenating a magnetic flux to the plasma, acting as the second wire (Figure 2.5). The tokamak configuration is the one adopted in most of fusion experiments, and is currently used for the conceptual design of reactors prototypes as well.

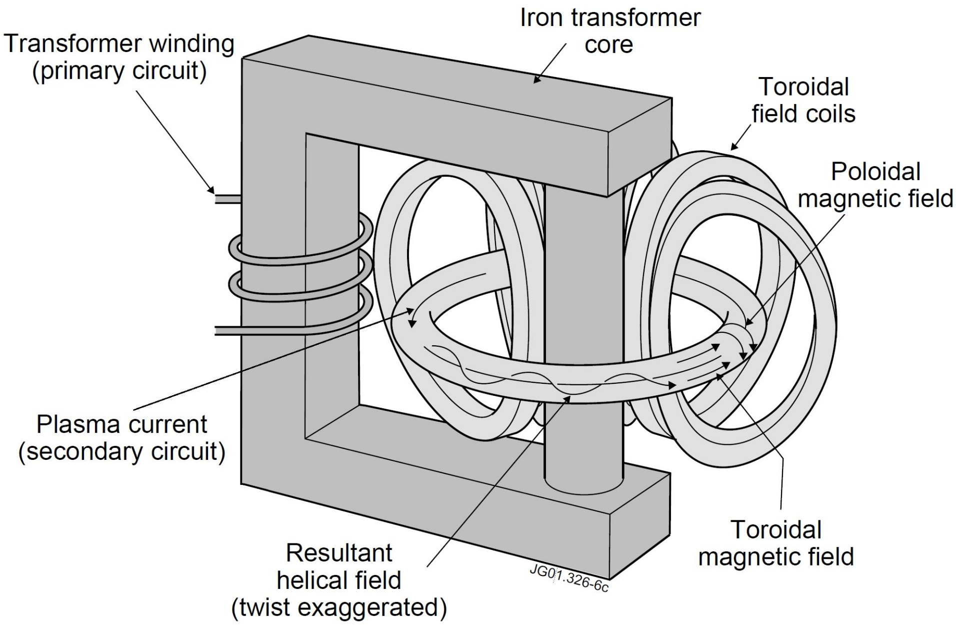


Figure 2.5: Main components in a tokamak configuration.

RFP: The Reversed Field Pinch peculiarity is that the magnetic field is mainly generated by the current flowing inside the plasma and not imposing an external toroiral field as in tokamaks. Toroidal and poloidal field components have similar magnitute, and the first one changes direction in the region near to the plasma boundary, from which the name of the configuration (Figure 2.6).

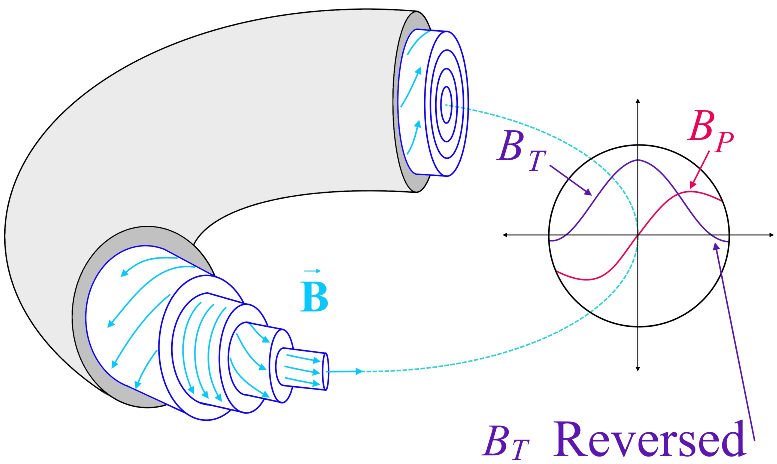


Figure 2.6: Magnetic field components in the Reversed Field Pinch configuration.

Stellarator: A device exploiting a magnetic configuration obtained without any current flowing in the plasma. Both the poloidal and the toroidal field components are generated with external coils. This magnetic configuration is extremely stable but also complex to realize, due to its non-axisymmetricity (Figure 2.7).

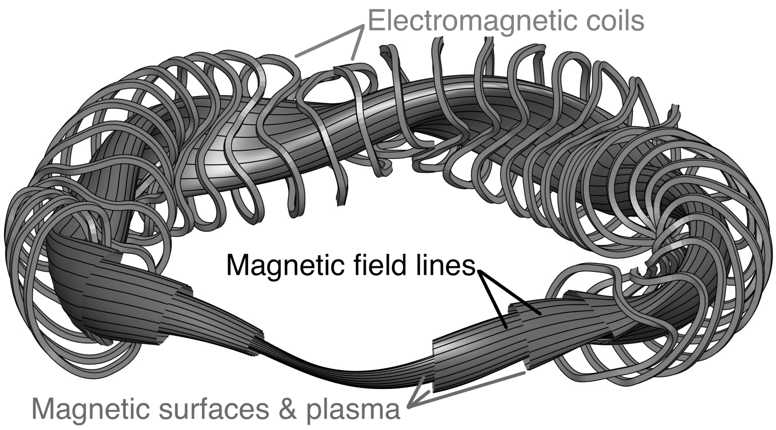


Figure 2.7: Plasma, magnetic field lines and electromagnetic coils shape in a stellarator configuration.

2.4 Assessing the future role of fusion

The following section aims at giving a concise overview of the main features of a future fusion power plant. In a fusion power plant, fusion reactions will take place in the magnetically confined plasma, inside a vacuum vessel: a high vacuum environment is required to accurately control plasma composition and density. The energy generated by fusion reactions is associated to the products ($^{4}\mathbf{He}$ and a neutron) in the form of kinetic energy. Specifically, the energy is distributed with an inverse proportionality with respect to the mass of the products, i.e. 3.5 [MeV] to the alpha particle and 14.1 [MeV] to the neutron. Since alpha particles are charged, they will be confined by the magnetic fields, thus yielding their energy to the plasma itself and keeping it heated. On the other hand neutrons, having no net electrical charge, will escape confinement and impinge on the plasma facing components, that are anchored to the vessel walls. These components are the blanket panels, covering up broadly 80% of the plasma facing surface, and the divertor cassettes, at the bottom of the chamber, devoted to the collection of fusion byproducts and unconfined particles. Their neutron kinetic energy will be yielded to these components, removed with a cooling system, and in the end used to generate electricity with a conventional steam turbine system. Blanket components will have multiple functions in the economy of the reactor: they need to guarantee a low contamination of the plasma, following both expected (neutron deposition) and unexpected (plasma disruptions) particle interactions, to guarantee an efficient heat removal, to shield all the downstream components from neutron damaging (mainly structural materials and magnetic coils), to grant access to the reaction environment for diagnostics and additional heating systems, and most importantly to allow Tritium production. As already stated, Tritium is not available in nature: this is because it's an unstable isotope with a low half-life (12 years). It is then necessary to produce it, and current reactor concepts include on site production solutions: specifically the blanket modules (also called breeding blanket) will have apposite sections contanining Lithium. Tritium will be produced thanks to the interaction of neutrons from nuclear reactions and Lithium, with the following reactions:

$$ {}^{6}_{3}\mathrm{Li} + \mathrm{n(slow)} \longrightarrow {}^{4}_{2}\mathrm{He} + \mathrm{T} + 4.8\,\mathrm{MeV} \tag{2.10a} $$

$$ {}^{7}_{3}\mathrm{Li} + \mathrm{n(fast)} \longrightarrow {}^{4}_{2}\mathrm{He} + \mathrm{T} + n - 2.5\,\mathrm{MeV} \tag{2.10b} $$

The reaction dominating Tritium breeding will be (2.10a), triggered by the neutrons slowed down as they penetrate through the blanket modules, as it's much easier to initiate. Nonetheless also reaction (2.10b), triggered by neutrons not yet slowed down, will have a non-negligible contribution, as natural Lithium contains far more $^{7}\mathbf{Li}$ (92.6 %) than $^{6}\mathbf{Li}$ (7.4 %), and will also contribute as neutron multiplier. The amount of Tritium generated is not only important for the operation of the single plant, but also for fusion technology deployment: Tritium Breeding Ratio (TBR) is defined as the ratio between the Tritium consumed in the chamber and the Tritium extracted from the blanket. While a TBR=1 is necessary to keep a plant operating, a TBR>1 is envisaged in order to make tritium for new plants available. In this regard the achievable TBR will be one of the factors that influence how fast fusion deployment could happen.

As it should be clear from the description of its operations, no CO2 emissions are involved in the generation of electricity from a fusion power plant, and that makes fusion energy a resource compatible with a decarbonized energy mix. Moreover, the operations of a fusion power plant will not involve the production of radioactive high-level wastes (HLW), but only of intermediate-level wastes (ILW), mainly from neutronic activated structural materials. These wastes will have an active life that spans from tens to few hundreds of years, and therefore they will not require deep geological repositories: standard deposits will be sufficient up to the moment of final decommissioning and recycling of these materials. With regards for operation safety, risks concerning radioactivity are quite limited: Tritium will be produced in place, so transport of radioactive material would take place only before the plant activation. In the event of accidents or malfunctions, on the other hand, the chance of a catastrophic event is null, since fusion it's not a chain reaction. If any component should stop working properly, the delicate conditions that keep the plasma confined and at proper conditions would cease to exist, and fusion reactions would just stop. Also, the amount of energy "stored" inside the plasma during regular operations is quite limited, being the single nuclei at very high temperature, but the density quite low: the fusion fuel present in the reaction chamber at every moment is of the magnitude of grams. At last, an important feature concerns fusion reagents availability: both Deuterium and Lithium can be extracted from seawater, while Lithium can also be extracted from minerals, with relevant known reserves mainly in Argentina, Bolivia, Australia, Chile and China. Given the easy access to the required reagents, a penetration of this technology on the energy market would tend to reduce conflicts and instabilities related to resource supply and availability. The described features should answer the question of whether fusion power is a sustainable source of energy from the social and environmental point of view. Nonetheless, also economic sustainability should be proved if we want to state that fusion is a source compatible with sustainable development. Even if it requires considering a very long time horizon (tens of years) it's mandatory to include nuclear fusion in energy scenarios in order to assess its integration in future decarbonized energy systems. These analyses should tell us whether the deployment of nuclear fusion will bring benefits (both technic and economic) with respect to other carbon free technologies, but also which features are the most desirable for a fusion power plant, and aid in choosing among different plant concept which one could be the more suitable for an effective deployment. Comprehensive and detailed data on a future fusion power plant, and specifically on their costs, are obviously not available, but even in their absence we can estimate them by using two elements: data on components for magnetic confinement experiments, and techno-economic features of fission power plants. Indeed, while the energy generation process is radically different, the overall structure of these power plants downstream the heat removal step could be, with a good approximation, the same. Also laws and regulations on nuclear sites safety and security will probably be similar. In general, nuclear fusion, as well as nuclear fission, will be a capital intensive technology, with long construction times, high investment costs and negligible fuel costs.

2.4.1 Scenario research on fusion

Research on nuclear fusion is not limited to a deeper comprehension of plasma physics and the realization of a working fusion reactor. Since the nineties, first in the framework of the Fusion Programme for the European Commission, then in the context of EFDA (European Fusion Development Agreement) and currently under the coordination of the EUROfusion consortium [37], scenario research studies focusing on the future role of fusion have been carried out. The SEAFP project (Safety and Environmental Assessment of Fusion Power) [38] addressed the problem of safety for a future fusion reactor. In doing so it focused on aspect such as radioactivity safety in the case of both normal operation and accidents, the management of radioactive wastes produced by a fusion reactor, the chance of proliferation linked to the existence of a nuclear fusion industry, fusion related non-nuclear hazards and fusion relevant resource availability. The SERF programme (Socio Economic Research on Fusion), through all the first decade of the the twenty-first century, addressed the following topics: the assessment of both direct and external fusion costs, the role of fusion on long term energy scenarios, public perception and opinion about fusion, challenges in the management of large technical systems and experiments. In the context of SERF activities energy systems models were adopted for the analyses of fusion penetration in future energy scenarios. Specifically, first the MARKAL model was used to simulate the penetration of fusion in long term (2100 target year) European scenarios. Then the EFDA-TIMES was created, in order to extend these analyses on a global scale. Currently, scenario research activity on nuclear fusion are carried out in the context of the Socio Economic Studies work package (WP-SES) of EUROfusion. Recent analyses discussed in [39] was carried out by means of the EFDA-TIMES model, focusing on what parameters influence most the extent of fusion deployment (Environmental constraints on CO2 emissions, discount rate) and what technologies are the most likely to be fusion competitors or replacement, in the event that fusion was unavailable (CCS technologies and nuclear fission).

Scenarios discussed in this thesis aim at extending the knowledge about the future role of fusion, by addressing the problem from a partially different point of view, i.e. exploiting a simulation model for the hourly analyses of the power system operation: the model COMESE, described in the following Chapter.

Chapter 3

COMESE

CO.ME.S.E. (Average Cost of the Electric System – COsto MEdio del Sistema Elettrico) is a model for the simulation of a decarbonized electricity power system operations and its economics. COMESE has been developed in the context of the research activities on energy scenarios carried out at RFX Consortium in Padua. At first created as a tool for the comparison of different hourly profiles, COMESE later evolved in more complex model for the simulation of an electricity system under the single node and perfect forecast assumption [40, 41]. The current version of COMESE, developed in MATLAB language, is the result of an overall upgrade and restructuring of the code carried out during this PhD activities, that involved almost every aspect of the code, and especially a zonal system representation, a power flow model, the dropping of the full time-window perfect forecast assumption, the introduction of a short term forecast exploitation and the coupling with an optimization algorithm for the design of a least cost power system under specific constraints.

The purpose of COMESE is to analyze the implications of different choices in the design of a decarbonized power system, representing with an adequate level of detail the features and requirements of a system that relies on a major, or at least relevant, share of variable renewable generation. The power output of variable renewable generators, and more generally their role and impact on the power system operations, strongly depends on three elements: the geographic location of the generators, seasonal climate variations and short term whether events. The more relevant features of COMESE derive from the need to capture the effect of these three factors: COMESE allows to divide the power system in an arbitrary number of zones and to specify the characteristics of all generators with zonal detail, the time window covered by the analyses can be chosen by the user and is usually one year long, while the time resolution, usually hourly, is such to capture effectively the variability and intermittency of renewable generators. This chapter is dedicated to a detailed description of COMESE: its inputs and outputs, the logic, the assumptions adopted to simulate the system operations, and the different ways it can be used.

3.1 Inputs

COMESE inputs can be grouped in three sets: the first one is the “modelling inputs” set. It includes all the variables and the settings that can be set when defining the model functioning, the level of detail of the simulation, and the elements that are themselves represented inside of it. The second one is the “system design inputs” set. It includes all the data that COMESE requires to create a representation of the electric power system and its components, and to simulate their operations. The third one is the “techno-economic inputs” set. It includes all the technical and economic features of the technologies that are part of the system that is represented, whose operation is simulated by COMESE, and that are necessary for the cost analysis that follows the operation analysis.

3.1.1 Modeling inputs

- **Time parameters.** For the sake of simplicity, all the parameters listed below are fed to the model using the hour as unit of measurement, while inside the model they are converted in multiples of the time resolution.
  - Time resolution: the time detail with which the operation of the system is simulated. It’s choice is driven by three factors: the resolution needed to correctly represent the fluctuations of demand and variable generators [figure], the computational cost of the simulation and the time resolution of the available profiles of renewable generation and electricity load. Although it can be set differently, all the analyses carried out with COMESE and presented in this thesis adopt an hourly resolution, and so it shall be considered if mentioned in the following parts of the document.
  - Time window N_h: the temporal extension of the analyses. Any time value multiple of the time resolution can theoretically be set as time window, but choices different from a multiple or a submultiple of one year can hardly be usefull. The most common choice is the analyses of one civil year ($N_\mathrm{h} = 8760\,\mathrm{h}$) while, as anticipated, other choices can be a series of m civil years ($N_\mathrm{h} = m \cdot 8760\,\mathrm{h}$), or conversely, a specific fraction of the year, like a month ($N_\mathrm{h} = 730\,\mathrm{h}$) or a week ($N_\mathrm{h} = 168\,\mathrm{h}$). The latter are usually used to speed up tests and debugging on the model, but they can be exploited as well for analyses focused on limited time intervals of particular interest.
  - Exogenous profile extention N_p: the temporal extension of the generation and load profiles used to simulate vRES generation and electricity demand inside the model (described in Power system design inputs). Every profile fed to the model must have the same extension, which must be equal or greater than the selected time window N_h.
  - Simulation first hour F_h: Input profiles are usually provided with the beginning of the civil

year as a starting point, but various reasons may require to begin the simulation of the power system operations in a different moment. For instance, to separate clearly the four seasons during a year-long simulation, since the civil year begins only ten days after the winter solstice; or to separate the simulation in such a way that a "hot season" (spring and summer) anticipate a "cold one" (autumn and winter), and vice versa. This feature is also clearly required in case the simulation has to involve only a specific fraction of the year.

  - Short term forecast interval h_{FW}: COMESE adopts a short term forecast interval, during which perfect forecast on variable generation and electricity load are assumed. The short term forecast influences the unit commitment: during every hour, data on the following $h_F W$ hours are exploited to decide whether, to be more effective, the use of a certain generation technology should be immediate or postponed in the future. Short term forecast is particularly useful to exploit efficiently short term storage systems and flexible generators with limited energy generation potential. It's also required to exploit them jointly with a synergic logic, as it will be explained in section 3.3.3.
  - Long term forecast interval $h_{\mathrm{FW}}^{\mathrm{LT}}$: a power system can include generators powered by limited resources, whether these limits come from economic feasibility, resource availability or policy constraints. In order to exploit these resources in the best possible way (i.e. when they are needed the most) they cannot just be exploited at will, but it should be estimated which are the intervals of the simulated time window when they can contribute more effectively to the system operations. COMESE does not assume perfect forecast all over the time window considered, but instead exploits rough estimates on variable generation and load aggregated over "long term forecast intervals", which extension usually ranges between two weeks and a month ($h_{\mathrm{FW}}^{\mathrm{LT}} = 365 \div 730\,\mathrm{h}$).

- **Optimization parameters.** COMESE can be coupled with an optimization routine, as explained in 3.5.3. If that's the case, the following inputs must be specified:
  - Optimization Flag: if this flag is activated COMESE enters the section dedicated to the optimization routine, otherwise it performs a single simulation.
  - Decision variables: every element of the system whose installed capacity is subjected to optimization. Not all of the system components (generators, storage systems, high voltage transmission connections) are subjected to the optimization problem. For some among them this could be meaningless, since their potential is too low to have an impact on the final result, or because the scenario is characterized by an arbitrary assumption on the use of a certain technology. More generally, the more the variables involved, the slower and less effective the optimization algorithm becomes; and that entails that the dimensionality of the problem must be kept as low as possible.

- Domain boundaries: for every optimized variable an upper and a lower boundary must be specified. Domain boundaries are usually fed to the model as a percentage variation with respect to a reference value. This means that lower boundaries can at most assume a value equal to -100%, which excludes completely the selected technology, while upper boundaries can theoretically be set as high as desired, and are chosen according to potential data or user assumptions.
- Objective function: the quantity that has to be minimized trough the optimization process. It's usually the LCOTE (see 3.4.1) i.e. the economic figure of merit of a power system simulated with COMESE, but every output of the model can be set as objective function.
- Optimization constraints: just as they can be chosen as objective function, the outputs of the model can also be chosen to set one or more feasibility constraints. An example of constraint can be a maximum number of hours with partially unserved energy, or a maximum amount of energy generated by a specific kind of generator. Any solution that does not meet these constraints, even if with lower values of objective function, shall be discarded.

■ **Other inputs.**

- Unit of measurement UoM: used to convert the input data on power and energy (in GW and TWh) in the desired unit of measurements adopted inside the model (GW-GWh, MW-MWh, etc). This choice is theoretically irrelevant, but if made accordingly to the order of magnitude of power and energy values of the simulated system it can impact the speed and accuracy of the linear systems solving inside the code.
- Power flows analyses Flag: if this flag is activated COMESE includes in the simulation the transmission capacity constraints between zones, by using a simplified power flows model (see PF section).
- Power flows analyses options: power flows analyses allow to include in the model the constraints given by the high voltage connections between zones. Still, it does not simulate in a realistic way the transmission grid when it's not stressed by bottlenecks. Two options, better explained in (see PF section) are available to simulate it with a higher degree of detail, but at cost of an increase of computational burden
- Transmission lines efficiency η_L: the power flows model of COMESE ideally represents the transmission system as lossless. Actually, an accurate calculation of the losses is not compatible with the structure of COMESE, as it involves a quadratic problem, whereas COMESE is based on the solution of linear systems subjected to linear inequalities constraints. Still, it's possible to have a rough estimation of the transmission system losses by assuming a fixed transmission efficiency $\eta_L < 1$. A value of η_L smaller than one automatically sets the systems

in order to account for losses, while setting $\eta_L = 1$ the lossless assumption is preserved.

- Solver choice: hourly unit commitment of every technology in COMESE is the output of the solution of linear systems of equations subjected to constraints and boundaries. In some cases the choice of the a specific solver is mandatory, while in other cases different options can be specified. For each technology (or group of technologies simultaneously analyzed) a different solver can be specified, choosing between a Linear least-squares solver or a Linear programming solver, both with bounds or linear constraints
- Saving options: COMESE is formally a MATLAB function, and as such it produces a limited amount of outputs, usually aggregated quantities. During analysis that require a high number of simulations this is preferable in order to avoid excessive memory consumption. Still, especially when dealing with single simulations, it's possible to save all the workspace at the end of a simulation, in order to be able to analyze the hourly operation of every system component.

3.1.2 Power system design inputs

- **Transmission system inputs.** COMESE is designed to simulate the power system operations of a region, where by region, in the context of energy scenarios, we mean any geographical area who is relevant for aggregated assessments on the energy sector. Countries are a typical example of regions suited for scenario analyses, but also more than one country can be simulated together, up to supranational entities or states confederations (EU, US).
  - Number of zones N_Z: the number of zones in which the system is divided. If $N_Z = 1$ the copper plate (CP) assumption is automatically used, i.e. transmission constraints are neglected and only mean regional values can be used in the simulation. If the region under analysis is a group of countries, the zones in which the system is divided can be the single countries, while if the region is a country, a zones can be administrative regions (or a groups of them). Each zone is identified with an index from 1 to N_Z.
  - Connections matrix $\boldsymbol{C_M}$: an adjacency matrix that is used to set the topology of the transmission system and to determine which zones can exchange energy. Each column and raw corresponds to the zone identified with the same index, i.e. $C_M(i, j) = 1$ means that zones i and j are linked by a branch of the transmission system. This means $\boldsymbol{C_M}$ is symmetric and has a null diagonal.
  - Transmission grid capacities G_C: a matrix of n rows and m columns, where n is the number of transmission technologies considered in the model, and m the number of the transmission system branches. $G_C(i, j)$ is the transmission capacity installed using the i-th technology along the j-th branch of the system.

- Grid branches length G_L: a vector with m elements, where m is the number of branches of the transmission system. $G_L(i)$ is the distance, in km, between the geometric centers of the zones connected by the i-th branch.

- **Demand, generation and storage inputs.**
  - Nominal power input P_{n}: the nominal installed power of a generation or storage technology.
  - Energy input En: the yearly amount of generated energy in the case of generation technologies, of consumed energy in the case of electricity demand, or the nominal energy capacity in the case of storage systems.
  - Equivalent hours number H_{eq}: for generation technologies, the equivalent number of hours of operation at nominal power, i.e. the ratio between generated energy and the nominal power. In the case of storage systems, the storage duration, i.e the time for a complete charge (or discharge) at nominal power, or the ration between nominal energy capacity and nominal power.
  - Hourly profiles: hourly profiles needed to simulate the operation of some of the system elements, i.e. variable renewable generators, electricity demand, or conventional generators with low degree of flexibility and a power output set a priori.
  - Techno economic reference file: the name of the file with the techno-economic features of a certain technology (see following section) needed to characterize that element in the cost analyses.
  - Generator and storage type: (G1) generators with a pre-determined hourly operation profile, such renewable generators and low flexibility baseload generators, (G2) baseload generators with constant power output (G3) high flexibility generators, (S1) short term storage systems, (S2) long term storage systems. The operation of the technologies belonging to each one of these categories is determined with a dedicated function in COMESE.

3.1.3 Techno-economic inputs

- Overnight costs [$€/kW$] or [$€/kWh$]
- Equity capital cost [%]
- Borrowed capital cost [%]
- Debt fraction [%]: fraction of the investments cost covered with borrowed capital
- Construction time [y]
- Efficiency [%]: energy conversion efficiency for generators, charge and discharge efficiency for storage systems.

- Lifetime [y]
- Skewness [$/$]: a measure of the asymmetry of the expenditure time profile during the construction time.
- Operation and maintenance fixed costs [$€/kW \cdot y$]
- Operation and maintenance variable costs [$€/MWh$]
- Lower heating value [MJ/kg] or [MJ/m^3]
- Nuclear fuel burn-up [$MW \cdot d/kg_{U_{natural}}$]
- Natural Uranium consumption for enrichment [$kg_{U_{natural}}/kg_{U_{enriched}}$]
- Fuel cost [$€/kg$] or [$€/m^3$]
- Natural Uranium cost [$€/kg$]
- Enrichment costs [$€/kg$]
- Nuclear fuel disposal [$€/kg$]
- CO2 released per fuel kilogram [-]
- CO2 capture efficiency [%]
- CO2 trasport cost [$€/ton$]
- CO2 storage cost [$€/ton$]
- CO2 emission cost [$€/ton$]
- Decommissioning costs [%]
- Years before decommissioning [y]
- Decommissioning provision return [%]

3.2 Preprocessing

The preprocessing section of COMESE includes all the operations that are carried out before the hourly analysis begins. Beyond the loading of the inputs and the pre-allocation of all the variables needed in the hourly analysis, it is useful to go through the following three operations: profiles scaling and setting, limited resources allocation and power-flows model settings.

3.2.1 Profiles scaling and setting

COMESE exploits exogenous hourly profiles to simulate the power output of variable generators, low flexibility generators and electricity demand. The code is structured so that it can exploit any profile, regardless of its source or its absolute values: normalized profiles per unit of rated power can be exploited, as well as historic profiles referring to registered data and specific rated power. This is obtained by scaling the profiles according to the input values on power, energy and capacity factor fed to the model. Profiles are represented with arrays in COMESE: depending on the needs of the code they can be one-dimensional, two-dimensional or three-dimensional. First dimension is usually assigned to the time variable, second one to the zone variable, and third one, if present, to specify different kind of technologies. In the case of electricity demand, only aggregated energy values referring to one solar year can be fed as input, and the actual demand profile is obtained as:

$$\boldsymbol{D}(h,z,k) = \frac{\boldsymbol{D}_{\mathbf{tot}}(z,k)}{\sum_h \boldsymbol{D}_{\mathbf{ref}}(h,z,k)} \cdot \boldsymbol{D}_{\mathbf{ref}}(h,z,k)\ , \tag{3.1}$$

$$\boldsymbol{D}_{\mathbf{tot}}(h,z) = \sum_{k=1}^{N_d} \boldsymbol{D}(h,z,k)\ . \tag{3.2}$$

Where $\boldsymbol{D}_{\mathbf{ref}}(h,z,k)$ is the reference demand value during the h-th hour, in the z-th zone, for the k-th user category and $D_{\mathbf{tot}}(z,k)$ the overall yearly demand for the k-th user category in the z-th zone. Equation (3.1) scales any profile $\boldsymbol{D}_{\mathbf{ref}}$ so that its aggregated value matches the value of $D_{\mathbf{tot}}(z,k)$. More than one (N_d) user category can be specified in order to be able to vary independently their overall contribution to the total demand, that is subsequently computed with equation (3.2). On the other hand, if just a single profile is sufficient for the analyses ($N_d = 1$), we just get $\boldsymbol{D}_{\mathbf{tot}} = \boldsymbol{D}$ from (3.2).

Differently from electricity demand, electricity generation from renewable generators and low flexibility baseload generators (Generation type G1, see section 3.1.2) can be set both specifying a rated power or an aggregated value of electric energy yearly production. This implies that, since both those values are needed for the hourly analysis and the post processing cost section, also the capacity factor is needed as input, in order to define the missing one, along with the hourly generation profile. The following relations are then used:

$$\boldsymbol{P}_{\mathbf{n}}(z,k) = \frac{\boldsymbol{En}(z,k)}{\boldsymbol{CF}(z,k)\cdot 8760\ \mathrm{h}}\ , \qquad \boldsymbol{En}(z,k) = \boldsymbol{P}_{\mathbf{n}}(z,k)\cdot \boldsymbol{CF}(z,k)\cdot 8760\ \mathrm{h}\ , \tag{3.3}$$

$$\boldsymbol{G}_{\mathbf{tot}}(z,k) = \boldsymbol{En}(z,k)\ , \qquad \boldsymbol{G}(h,z,k) = \frac{\boldsymbol{G}_{\mathbf{tot}}(z,k)}{\sum_h \boldsymbol{G}_{\mathbf{ref}}(h,z,k)} \cdot \boldsymbol{G}_{\mathbf{ref}}(h,z,k)\ . \tag{3.4}$$

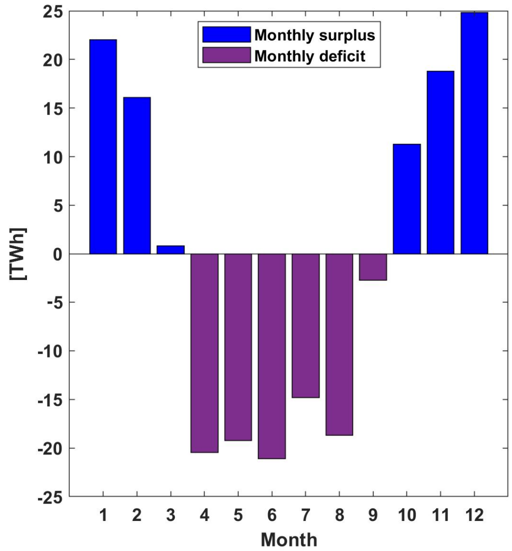
Where $\boldsymbol{P}_{\mathbf{n}}(z,k)$, $\boldsymbol{En}(z,k)$ and $\boldsymbol{CF}(z,k)$ are respectively the rated power, the overall generated energy and the capacity factor that characterize the k-th generation technology in the z-th zone, and $\boldsymbol{G_{ref}}(h,z,k)$ is the reference generation value during the h-th hour, for the k-th generation technology in the z-th zone. Depending on which one between $\boldsymbol{P}_{\mathbf{n}}(z,k)$ and $\boldsymbol{En}(z,k)$ is specified as input, one of the two variants of equation (3.3) is used to calculated the other one, while the actual generation profiles for each of the the k technologies, are calculated with equation (3.4). While in principle equation (3.3) could be used with any combination of two values among P_n, En and CF to derive the third one, it was chosen not to allow the simultaneous setting of P_n and En in order to avoid values of CF greater than 1 as a result of setting incompatible input values. A specific case is given by the generator type G2 (baseload generators with constant power output): in this case equation (3.4) is simplified and does not need any reference profile, simply becoming:

$$\boldsymbol{G}(h,z,k) = \frac{\boldsymbol{G}_{\mathbf{tot}}(z,k)}{8760\ \mathrm{h}} \qquad \forall h\ .$$

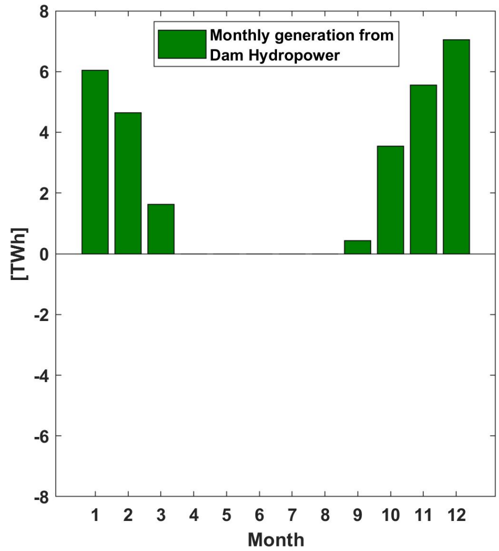
3.2.2 Limited resources allocation in time

During a given time interval of length T [h], a dispatchable generators can, in principle, generate an amount of energy that ranges from 0 to $P_\mathrm{n} \cdot CF_{\max} \cdot T$ [GWh], where $CF_{\max}$ is the maximum capacity factor achievable, i.e. the percentage of hours during which the generator can be kept active, obtained by taking into account the number of hours during which it must be stopped for maintenance. In that range, the amount of energy actually generated during the operation of a plant will be defined by the operator choices, and be influenced on one side by operation, maintenance and fuel costs, and on the other one by the market behavior. In COMESE, where all the generators of a given kind are aggregated and act as a single generator (at least per zone) that could be dealt with just by setting a maximum effective power P_eff exploitable during every hour. That would take into account the maximum achievable capacity factor assuming that maintenance events are evenly distributed among all the generators of that kind, during the analyzed time interval, so that $P_\mathrm{eff} = P_\mathrm{n} \cdot CF_{\max}$. Anyway, there are some kind of generators for which the maximum amount of generation is limited by different kind of constraints: two relevant examples are hydropower and biomass generation. Hydropower generation is function of the flow rate of the water course channeled by the plant. If some kind of reservoir is added to the plant, and water is stored, different generation capacities can be installed following technical requirements or economic choices, in order to modulate the generation of energy in time. Still, that maximum amount of energy that can be generated will remain constant, and eventually, over a certain value of rated power, the higher rated power the lower the capacity factor will be. Biomass energy generation is subjected to a somehow similar problem: beyond cost effectiveness, the amount of biomass exploitable is limited to potential constraints, defined in turn by the availability of resources needed for the biomass production. Different assumptions can be made on that availability, but once set, the maximum amount of energy that can be generated will be fixed, regardless of the rated power of plants exploiting it as a fuel.

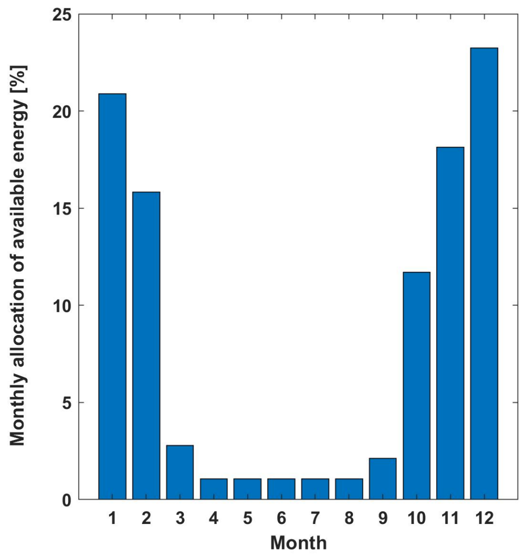
A limited resource exploitation must be optimized, so that it is used in the moments and for the needs that allow to maximize its benefit to the operation of the system to which it belongs. The exploitation of limited energy sources in the power system makes no difference. Once a figure of merit for a scenario has been defined, for example the cost of energy, the problem could be mathematically defined: a system involving every hour of the year can be defined and solved, obtaining an optimized



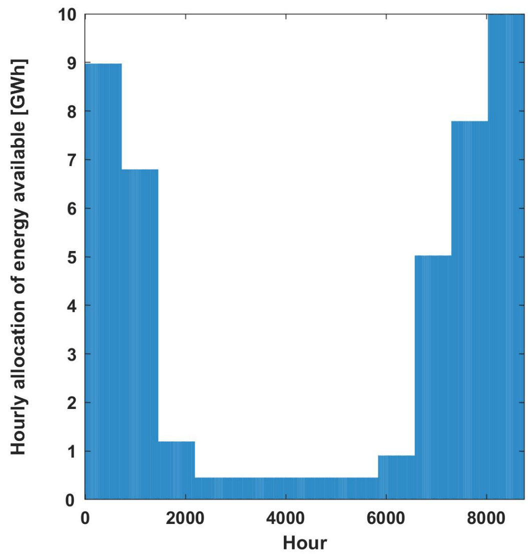
(a) Aggregated surplus and deficit trend over the twelve months.



(b) Generation from Hydropower Dam plants over the twelve months.



(c) Allocation of available energy derived from the surplus/deficit trend.



(d) Hourly allocation of energy matching the monthly trend.

Figure 3.1: Allocation of energy for Hydropower Dam plants in a scenario with major share of photovoltaic generation, using monthly-length long term forecast intervals. Figure (b) shows, for comparison, the monthly generation from Hydropower Dam plants obtained with perfect forecast.

hourly generation profile for the generators considered. This approach is called perfect forecasting, as it involves the simulation of the system operations under the assumption that in any moment (and in particular at the beginning of the considered time window), a complete knowledge of electricity demand and non-programmable generation trends is available.

This approach, however, is clearly at odds with the non-programmable and intermittent nature of renewable generation, and would therefore tend to overestimate the degree of efficiency with which a resource can be exploited: in fact system operators and stakeholders do not have perfect forecast, but deal with the resources allocation by resorting on one hand on historic trends and forecasts prone to errors, and on the other one with risk management and minimization measures. Examples of these elements may be, respectively, multiannual registered climatic data, forecast on the incoming climatic year nature (sunny, rainy, windy, etc.) and fuel reserves build-up.

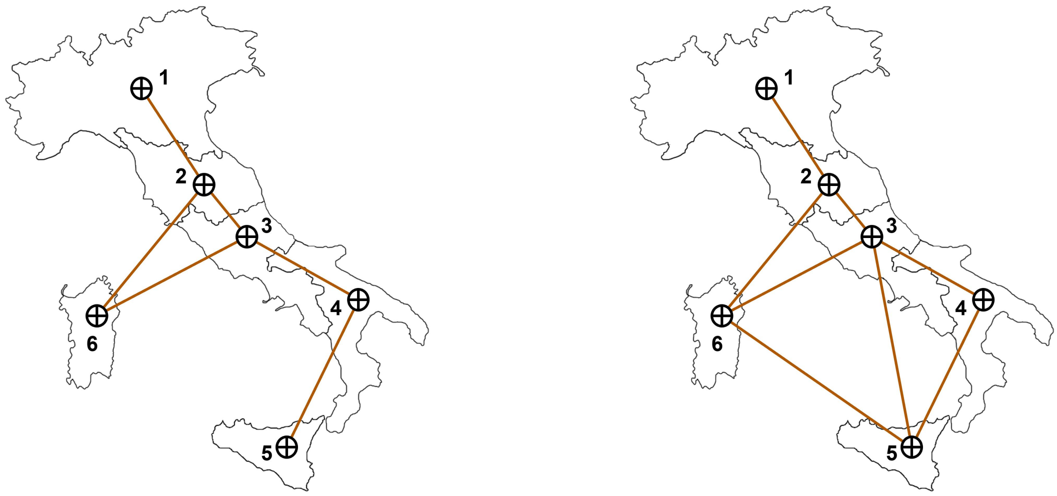
Given these reasons, a different approach is adopted in COMESE, with respect to perfect forecasting. For every hour, dispatching is based on data coming from a limited time interval (short term forecast) following that hour, during which perfect forecasting is used. As for the resource allocation during the whole time window considered, it is estimated at the beginning of the simulation, considering aggregated data on renewable generation and demand, over wide time intervals -at least multiple weeks- that cover the whole time window (long term forecast). Over these “long term” forecast intervals the amount of surplus energy that can be absorbed and re-emitted by storage systems is calculated, net of roundtrip efficiencies, and compared with the amount of generation deficit. The trend of the net between these two values is used to build an availability curve for limited resources. The nature of the energy resource considered influences in different ways its relation with the allocation problem, in particular with respect to the zonal representation of the system: the two examples given at the beginning of these section, biomass and hydropower, are useful also in this case. Hydropower energy potential is linked, as already said, to the water flow channeled by the plant. This would in principle imply that every generator would need an allocation curve tailored for itself. As in COMESE all the generators of a technology are aggregated in a single generator in the eye of the code, this is clearly subjected to an approximation that involves all the hydropower plants. Still, when representing the system as divided in N_z zones, an availability curve is produced per each zone, in order to avoid, in the simulation, what would be an unfeasible resource (water) transfer between zones, and to force hydropower generators to generate energy where it is actually available. On the other hand different resources, like biomass, can be moved, especially if it is refined and transformed in Biogas or Biomethane, involving the methane transmission system. In this case the assumption that the overall national potential can be exploited everywhere is valid, and a single availability curve can be generated ad used as a common constraint for all the zones involved in the analyses.

Figure 3.1 shows an example of energy allocation through the year, using as a long term forecast interval one month. As it can be noticed the available energy distribution does not match exactly the surplus/deficit trend, as a minimum amount of energy is allocated also for months where the trend assumes negative values. This allows to manage short term severe lacks of generation in periods with an otherwise high variable generation. The hourly availability energy curve (figure 3.1d) must not be intended as a strong constraint on generation: as already mentioned dispatchment involves perfect forecast on a short interval of time ($h_{\mathrm{FW}} + 1$ hours). The power output of the considered generator, in the example hydropower dam plants, can assume any hourly profile, as long as the overall energy generated does not exceed the overall amount of energy allocated for the short term forecast interval itself. Any unused energy is redistributed over the rest of the simulation time window, proportionally to the remaining part of the availability curve. The exploitation of short term forecast intervals also helps in smoothing the availability of energy when passing from one long term forecast interval to another, as the overall amount of energy varies gradually.

3.2.3 Power Flows model setting

Dispatchment in COMESE is solved using linear systems defined as an energy balance between generation and demand for each power system zone. Demand is the known term and power output the variables, subjected to constraint on maximum power output and generated energy. If power flows between zones are simulated, the energy balance in a zone can include also a positive energy contribution coming from a linked zone, a negative contribution of energy transmitted to a linked zone, or both (if there is more thank one link). These contribution must be represented in the linear system aforementioned, using as input the connection matrix $\boldsymbol{C}_{\mathbf{M}}$. The structure of matrix $\boldsymbol{C}_{\mathbf{M}}$ depends only on the zone numbering used in the input sheet, which is arbitrary. All its following elaboration in COMESE, described hereafter, are unique.

Figure 3.2 shows two alternative topological configuration of the transmission grid in the case of the Italian system. The system is divided in 6 zones, each one including one or more Italian administrative regions: North (N), Center-North (CN), Center-Shouth (CS), South (S), Sicily (Si) and Sardinia (Sa). This division follows the criteria used by Italian TSO TERNA, until 2021 [43, 44], in order to operate the transmission system and regulate the electricity market, taking into account the more critical transmission connections in the Italian system. Also the numbering used in COMESE for the different zones is reported. In the two cases reported in Figure 3.2 the connections matrix $\boldsymbol{C}_{\mathbf{M}}$ would



(a) Current topology of the transmission grid connections between zones.

(b) Foreseen topology change by 2030, considering the planned upgrades reported in [42].

Figure 3.2: Italian transmission grid topology taking into account current connections (a) and connections expected at 2030, considering [42] (b). The zone numbering used in COMESE is also shown: North (1), Center-North (2), Center-South (3), South (4), Sicily (5) and Sardinia (6).

assume the following form:

$$\boldsymbol{C}_{\mathbf{M}}^{\boldsymbol{a}} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 0 & 1 \\ 0 & 1 & 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 & 0 \end{bmatrix}, \quad \boldsymbol{C}_{\mathbf{M}}^{\boldsymbol{b}} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 0 & 1 \\ 0 & 1 & 0 & 1 & 1 & 1 \\ 0 & 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 1 \\ 0 & 1 & 1 & 0 & 1 & 0 \end{bmatrix}.$$

The first element that can be derived from the matrix $\boldsymbol{C}_{\mathbf{M}}$ is the number of connections between zones N_{PF}, that is equal to half of the matrix non-null entries. Then a numbering and a conventional direction for the power flows must be specified for all the connections. The criteria used in COMESE is to number the connections considering the involved zones: starting from the lower index zone to the higher one. If one zone has more than one connection, then the order is from the lower, to the higher index of the connected zone. The conventional power direction is always from the lower index zone to the higher one. This approach can simply be visualized by scrolling the upper diagonal portion of matrix $\boldsymbol{C}_{\mathbf{M}}$ first along rows, and then along columns, numbering all non null elements following its order of appearence, and setting the conventional direction for element $\boldsymbol{C}_{\mathbf{M}}(i,j)$ from the i-th zone, to the j-th one. Following this approach for topology (a) we would get:

$$\boldsymbol{C}^{\boldsymbol{a}}_{\mathbf{M}}:\begin{bmatrix}0 & \boldsymbol{PF}(1) & 0 & 0 & 0 & 0\\ 0 & 0 & \boldsymbol{PF}(2) & 0 & 0 & \boldsymbol{PF}(3)\\ 0 & 0 & 0 & \boldsymbol{PF}(4) & 0 & \boldsymbol{PF}(5)\\ 0 & 0 & 0 & 0 & \boldsymbol{PF}(6) & 0\\ 0 & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0 & 0 & 0\end{bmatrix},\quad \begin{bmatrix}0 & PF_{12} & 0 & 0 & 0 & 0\\ 0 & 0 & PF_{23} & 0 & 0 & PF_{26}\\ 0 & 0 & 0 & PF_{34} & 0 & PF_{36}\\ 0 & 0 & 0 & 0 & PF_{45} & 0\\ 0 & 0 & 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0 & 0 & 0\end{bmatrix}.$$

While for topology (b):

$$\boldsymbol{C}^{\boldsymbol{b}}_{\mathbf{M}}:\begin{bmatrix}0 & \boldsymbol{PF}(1) & 0 & 0 & 0 & 0\\ 0 & 0 & \boldsymbol{PF}(2) & 0 & 0 & \boldsymbol{PF}(3)\\ 0 & 0 & 0 & \boldsymbol{PF}(4) & \boldsymbol{PF}(5) & \boldsymbol{PF}(6)\\ 0 & 0 & 0 & 0 & \boldsymbol{PF}(7) & 0\\ 0 & 0 & 0 & 0 & 0 & \boldsymbol{PF}(8)\\ 0 & 0 & 0 & 0 & 0 & 0\end{bmatrix},\quad \begin{bmatrix}0 & PF_{12} & 0 & 0 & 0 & 0\\ 0 & 0 & PF_{23} & 0 & 0 & PF_{26}\\ 0 & 0 & 0 & PF_{34} & PF_{35} & PF_{36}\\ 0 & 0 & 0 & 0 & PF_{45} & 0\\ 0 & 0 & 0 & 0 & 0 & PF_{56}\\ 0 & 0 & 0 & 0 & 0 & 0\end{bmatrix}.$$

Finally, taking into account the conventional direction given to each per flow, we can build the transmission matrix $\boldsymbol{M}_{\mathbf{T}}$ (N_{Z}xN_{PF}), in which each row corresponds to a zone, and each column shows the sign of the contribution given by a positive power flow in the corresponding connection:

$$\boldsymbol{M}^{a}_{\mathbf{T}}=\begin{bmatrix}-1 & 0 & 0 & 0 & 0 & 0\\ 1 & -1 & -1 & 0 & 0 & 0\\ 0 & 1 & 0 & -1 & -1 & 0\\ 0 & 0 & 0 & 1 & 0 & -1\\ 0 & 0 & 0 & 0 & 0 & 1\\ 0 & 0 & 1 & 0 & 1 & 0\end{bmatrix},\quad \boldsymbol{M}^{b}_{\mathbf{T}}=\begin{bmatrix}-1 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\ 1 & -1 & -1 & 0 & 0 & 0 & 0 & 0\\ 0 & 1 & 0 & -1 & -1 & -1 & 0 & 0\\ 0 & 0 & 0 & 1 & 0 & 0 & -1 & 0\\ 0 & 0 & 0 & 0 & 1 & 0 & 1 & -1\\ 0 & 0 & 1 & 0 & 0 & 1 & 0 & 1\end{bmatrix}.$$

The matrix $\boldsymbol{M}_{\mathbf{T}}$ will be used to build the linear system to be solved in order to determine the hourly dispatchment of a technology. The transmission model obtained with this approach is a simplified transport model: it just represents active power exchange between zones, neglecting node voltages and line impedance, requiring only power balance [45].

3.3 hourly analysis

The hourly analysis is the core section of COMESE. In this section dispatchment is solved for each technology (generation or storage), that is represented as N_Z plants of rated power equal to the overall installed power of that technology in each zone. A for-loop scans chronologically every hour of the analysed time window: during each hour the different generation and storage technologies are taken into account following a priority list defined by the user; this means that no market simulation is taken into account. The priority list is defined in order to prioritize the exploitation of variable renewable sources and baseload generators, first directly and then via storage systems, and then to resort to flexible generators if there is still a share of unserved energy.

3.3.1 Mathematical formulation of dispatchment

The linear system that has to be solved to determine dispatchment is build up by means of the matrix $\boldsymbol{M_T}$, described in the previous section (3.2.3) and k identity matrices, where k is the number of technologies that we want to consider simultaneously. Let's assume to consider a single technology with the topology (a) used as example in (3.2.3): six zones connected by 6 grid branches. For a single hour, our system would take the following form:

$$-\boldsymbol{PF}(1)+\boldsymbol{P}(1,1)=\boldsymbol{D}(1) \tag{3.5a}$$

$$\boldsymbol{PF}(1)-\boldsymbol{PF}(2)-\boldsymbol{PF}(3)+\boldsymbol{P}(2,1)=\boldsymbol{D}(2) \tag{3.5b}$$

$$\boldsymbol{PF}(2)-\boldsymbol{PF}(4)-\boldsymbol{PF}(5)+\boldsymbol{P}(3,1)=\boldsymbol{D}(3) \tag{3.5c}$$

$$\boldsymbol{PF}(4)-\boldsymbol{PF}(6)+\boldsymbol{P}(4,1)=\boldsymbol{D}(4) \tag{3.5d}$$

$$\boldsymbol{PF}(6)+\boldsymbol{P}(5,1)=\boldsymbol{D}(5) \tag{3.5e}$$

$$\boldsymbol{PF}(3)+\boldsymbol{PF}(5)+\boldsymbol{P}(6,1)=\boldsymbol{D}(6) \tag{3.5f}$$

That is a linear system $\boldsymbol{C}\cdot\boldsymbol{x}=\boldsymbol{d}$, such that:

$$\boldsymbol{C}_{|_{k=1}} = [\boldsymbol{M}_{\mathbf{T}} \quad \boldsymbol{I}_{N_{\mathbf{Z}}}] = \begin{bmatrix} -1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & -1 & -1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & -1 & -1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & -1 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}, \quad \boldsymbol{d} = \begin{pmatrix} \boldsymbol{D}(1) \\ \boldsymbol{D}(2) \\ \boldsymbol{D}(3) \\ \boldsymbol{D}(4) \\ \boldsymbol{D}(5) \\ \boldsymbol{D}(6) \end{pmatrix}, \tag{3.6}$$

$$\boldsymbol{x} = \begin{bmatrix} x_{\mathbf{PF}} \\ x_{\mathbf{Gen}} \end{bmatrix} = \begin{pmatrix} \boldsymbol{PF}(1) & \cdots & \boldsymbol{PF}(6) & \boldsymbol{P}(1,1) & \cdots & \boldsymbol{P}(6,1) \end{pmatrix}^{\top}.$$

Where $\boldsymbol{D}(z)$ is the electricity demand in the z-th zone, and $\boldsymbol{P}(z,1)$ the output power of the first (and in this case only) generation technology considered, in the z-th zone.

This system has infinite solutions, but in order to solve our problem we might have to include some constraints that narrows the solution domain: constraints on the energy generated, on the amount of power exploitable and on the connection capacity between zones. These constraints are in the form of linear systems of inequality constraints ($\boldsymbol{A} \cdot \boldsymbol{x} \leq \boldsymbol{b}$) or boundaries for the values assumed by variables ($\boldsymbol{l}_{\mathbf{b}} \leq \boldsymbol{x} \leq \boldsymbol{u}_{\mathbf{b}}$). The narrowing of the solution domain implies that the system may as well have no solutions. To solve this system, COMESE exploits the MATLAB function lsqlin [46], a linear least-squares solver with bounds or linear constraints. Lsqlin solves the following problem:

$$\min_{\boldsymbol{x}} \left\{ \frac{1}{2} \|\boldsymbol{C} \cdot \boldsymbol{x} - \boldsymbol{d}\|_2^2 \right\} \text{ such that } \begin{cases} \boldsymbol{A} \cdot \boldsymbol{x} \leq \boldsymbol{b} \\ \boldsymbol{A}_{\mathbf{eq}} \cdot \boldsymbol{x} = \boldsymbol{b}_{\mathbf{eq}} \\ \boldsymbol{l}_{\mathbf{b}} \leq \boldsymbol{x} \leq \boldsymbol{u}_{\mathbf{b}} \end{cases}. \tag{3.7}$$

3.3.1.1 Short term forecast

The previous section has been focused on the system that solves dispatchment for a single technlogy and during a single hour. However, as it was already anticipated, COMESE exploits a short term forecast during which the assumption of perfect forecast is used. Thanks to this assumption, programmable technologies (both generation and storage) use can be optimized. The exploitation of short term forecast for each technology will be explained in the following sections; as for its mathematical formulation, it simply involves the simultaneous solution of dispatchment for all of the hours involved in the forecast interval $[h; h+h_{\mathrm{FW}}]$. Keeping the notation used in the previous section, we obtain the system $\boldsymbol{C}^{\boldsymbol{f}} \cdot \boldsymbol{x}^{\boldsymbol{f}} = \boldsymbol{d}^{\boldsymbol{f}}$, with dimension $[(h_{\mathrm{FW}}+1) \cdot N_Z$ **x** $(h_{\mathrm{FW}}+1) \cdot (N_{\mathrm{PF}} + k \cdot N_{\mathrm{Z}})]$, defined in this way:

$$\boldsymbol{C^f} = \begin{bmatrix} \boldsymbol{C} & 0 & \cdots & 0 \\ 0 & \boldsymbol{C} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \boldsymbol{C} \end{bmatrix}, \quad \boldsymbol{d^f} = \begin{pmatrix} \boldsymbol{d^1} \\ \boldsymbol{d^2} \\ \vdots \\ \boldsymbol{d^{(h_{\mathrm{FW}}+1)}} \end{pmatrix}, \quad \boldsymbol{x^f} = \begin{pmatrix} \boldsymbol{x^1} \\ \boldsymbol{x^2} \\ \vdots \\ \boldsymbol{x^{(h_{\mathrm{FW}}+1)}} \end{pmatrix}. \tag{3.8}$$

Inequalities constraints ($\boldsymbol{A^f} \cdot \boldsymbol{x^f} \leq \boldsymbol{b^f}$) and boundaries ($\boldsymbol{l_b^f} \leq \boldsymbol{x^f} \leq \boldsymbol{u_b^f}$) are built with the same logic.

3.3.1.2 Transmission constraints management

Every technology corresponds to the definition of a specific linear system, whose solution determines the dispatchment of that technology. However, this linear systems include the power flow model, that simulate the same transmission system in every case. While these systems are solved with a specific order, they represent a simultaneous energy generation: once the analyses has gone through all the technologies present in the system the overall generation in every zone will correspond to a net power flow distribution in the grid. In order to represent the transmission constraints for a given technology dispatchment it is then necessary to take into account the power flows from the previous steps:

$$\boldsymbol{T_{cap}} = \begin{pmatrix} \boldsymbol{T_{cap}}(1) \\ \vdots \\ \boldsymbol{T_{cap}}(N_{PF}) \end{pmatrix}, \quad \boldsymbol{l^1_{PFb}} = -\boldsymbol{T_{cap}}, \quad \boldsymbol{u^1_{PFb}} = \boldsymbol{T_{cap}}. \tag{3.9}$$

$$\boldsymbol{l^s_{PFb}} = -\boldsymbol{T_{cap}} - \boldsymbol{PF^{s-1}_{Net}}, \quad \boldsymbol{u^s_{PFb}} = \boldsymbol{T_{cap}} - \boldsymbol{PF^{s-1}_{Net}}, \quad \boldsymbol{l^s_{PFb}} \leq \boldsymbol{PF^s} \leq \boldsymbol{u^s_{PFb}}. \tag{3.10}$$

$$\boldsymbol{PF^s_{Net}} = \boldsymbol{PF^{s-1}_{Net}} + \boldsymbol{PF^s}. \tag{3.11}$$

Where $\boldsymbol{T_{cap}}(i)$ is the transmission capacity of the i-th connection, i.e. the maximum amount of power that can flow in the i-th connection, $\boldsymbol{u^s_{PFb}}$ and $\boldsymbol{l^s_{PFb}}$ respectively the upper and lower boundaries to be assigned to the power flow variables when solving the dispatch for the s-th technology considered, $\boldsymbol{PF^s}$ the power flows induced by the s-th technology, and $\boldsymbol{PF^s_{Net}}$ the net power flows obtained in the transmission grid taking into account all the technologies up to the s-th one.

3.3.1.3 Copper plate assumption

Copper Plate (CP) assumption, also called single node assumption, is a modelling approach that neglects the infrastructures and constraints involving the energy transmission. COMESE always rely on the CP assumption at some level: in each zone simulated by the model all the generators and all the loads are supposed to be connected to the same node, without any transport or distribution infrastructure needed to link them. However, for the sake of simplicity, a "CP" simulation in COMESE correspond to a simulation where transmission limits between zones are neglected. A "PF" (Power Flows) simulation, on the contrary, includes the constraints given by the limited transmission capacity between zones.

As a matter of fact, there are two model configuration used to produce CP simulations in COMESE. The first one is by setting just one zone in the system design. In this case the transmission connections are absent by definition: the system (3.6) is reduced to a simple equality $\boldsymbol{P}(1) = \boldsymbol{D}(1)$, as $N_Z = 1$ and the $\boldsymbol{M_T}$ matrix collapses into an empty one. As for the forecast analyses, the approach described in (3.3.1.1) in still valid: matrix $\boldsymbol{C^f}$ is just reduced to an identity matrix $I_{(h_{\mathrm{FW}}+1)}$. The second approach involves the design of the system as divided in zones, and the full use of the power flows model as described before, but removing the constraints on the maximum allowable transmission capacities. The second choice is far more computationally demanding, but can be useful to assess the entities of power flow required to operate a system with a given generation siting.

3.3.2 Operation criteria for generators and storage systems

Generation and storage technologies are divided in different categories in COMESE. These categories influences how they are simulated and the way their operation is defined: from the practical point of view the choice of the category implies specific settings in the solution of the system (3.8), that are hereafter described.

3.3.2.1 Baseload and Must-Run generators

Generators of categories G1 and G2 are considered as non programmable: whether because they are variable renewable generators or low flexibility baseload generators, in the eye of COMESE they feature a predetermined generation profile that sets the maximum allowable power output during each hour of the year. In order to speed up the code and reduce the computation burden of a simulation, they are simulated as a single "Baseload and Must Run" (BMR) generator, with an allowable generation profile resulting from the summation of all the G1 and G2 generation technologies. If part of this energy is non exploitable, and then has to be curtailed, its share among the different technologies can be determined with a post-processing. This means that the matrix $\boldsymbol{C}$ will assume exactly the form described in system (3.6). As for the constraints, only boundaries on the variables will be necessary. Being this the first step of the analyses, the transmission capacity boundaries will be equal (and opposite) to the maximum transmission capacity, as in equations (3.9). The boundaries on hourly generation will be:

$$\boldsymbol{l_{Gen\,b}}(h,z) = 0 \quad \forall h,z, \quad \boldsymbol{u_{Gen\,b}}(h,z) = \boldsymbol{G^{BMR}}(h,z). \tag{3.12}$$

Where $\boldsymbol{l_{Gen\,b}}(h,z)$ and $\boldsymbol{u_{Gen\,b}}(h,z)$ are the lower and the upper boundaries for the power output of BMR technologies in the z-th zone during the h-th hour, and $\boldsymbol{G^{BMR}}$ the cumulative generation profiles for all the BMR technologies. Once the system has been solved, the elements of $\boldsymbol{x}$ will give, for each zone and each hour, the power output from BMR generators and the power flows associated to them. An additional elaboration of the results will provide also the unserved energy (or residual demand) and the excess energy that has not been used:

$$\boldsymbol{rd} = \boldsymbol{d} - \boldsymbol{C} \cdot \boldsymbol{x^{sol}} \tag{3.13}$$

$$\boldsymbol{S^{BMR}}(h,z) = \boldsymbol{G^{BMR}}(h,z) - \boldsymbol{x^{sol}_{Gen}}(h,z). \tag{3.14}$$

Where $\boldsymbol{rd}$ is the residual demand after the exploitation of BMR technolgies, and $\boldsymbol{S^{BMR}}(h,z)$ the unexploited surplus energy from BMR generators during the h-th hour in the z-th zone.

3.3.2.2 High flexibility generators

High flexibility generators (G3 type) are all the generation technologies whose generation profile is not predetermined, and is instead the output of the hourly analysis itself. They usually are used in the last steps of the hourly analysis, after the direct use of BMR generators and the exploitation of storage systems. These technologies have usually a well defined priority order determined by their costs, fuel (or energy source) availability, and emissions: because of that they are considered in separate subsequent steps one at the time. Still, if needed, it's possible to solve dispatchment for k flexible technologies simultaneously, as described in (3.3.1). For these technologies, the constraint on hourly generation is simpler than BMR generators: since they are programmable, the upper boundary will simply be equal to the rated power of the generator for every hour:

$$\boldsymbol{l_{Gen\,b}}(h,z) = 0 \quad \forall h,z, \quad \boldsymbol{u_{Gen\,b}}(h,z) = \boldsymbol{P}_{\mathbf{n}}(z) \quad \forall h. \tag{3.15}$$

On the other hand, these generators may be subjected to limits on the overall amount of energy that they can generate, a problem that was explained in section (3.2.2), along with the criteria for the energy allocation all over the time window analysed. A generator of the G3 type can be operated with the following three approaches:

1 **Unlimited energy source availability:** the most general case. The linear system is not subjected to any additional constraint. The amount of energy generated is not subjected to any constraint and it's purely an output of the model.

2 **Limited energy source availability:** the overall amount of energy that can be produced over the time window analyzed is limited and specified as an input. That energy can be exploied in every zone of the system with no geographical limitation. A single hourly availability curve is then generated, as described in (3.2.2). The following constraint is added to the system, under the form of an inequality equation:

$$En^{max} = \sum_{i=h}^{i=h+h_{\mathrm{FW}}} \boldsymbol{En^{avail}}(h), \tag{3.16}$$

$$\sum_{h,z} \boldsymbol{x^{sol}_{Gen}}(h,z) \leq En^{max}. \tag{3.17}$$

Where $En^{avail}(h)$ is the hourly profile of the available energy.

3 **Limited and localized energy source availability:** when generators whose energy availability is influenced also by the geographical location, and the primary energy source cannot be moved between regions, N_z availability curves are generated (one for each zone) and the constraint is differentiated per zone:

$$En^{max}(z) = \sum_{i=h}^{i=h+h_{\mathrm{FW}}} \boldsymbol{En^{avail}}(h,z), \tag{3.18}$$

$$\sum_{h} \boldsymbol{x^{sol}_{Gen}}(h,z) \leq \boldsymbol{En^{max}}(z) \quad \forall z = 1,\dots,N_z. \tag{3.19}$$

3.3.2.3 Storage systems

COMESE allow to simulate two kind of storage systems: short term storage systems (S1) and long term storage systems (S2). A single description is sufficient to explain how the code simulates these two options, as one (S2) is treated just as a particular case of the other (S1). Storage systems are simulated after BMR generators, as in COMESE they are mainly considered as tools for the management of generation surplus. Surplus energy has the priority with respect to energy from flexible generators, as it's cheaper, carbon free (provided BMR generation also is), and its use allow to make storage capacity available for further energy storage.

Storage systems involve both charging and discharging energy: if dispatchment were solved for just a single hour and a single zone this feature would not be relevant: every hour would univocally be either an hour of surplus or an hour of deficit, during which, respectively, storage have to be charged or discharged. Since in COMESE multiple zones are considered simultaneously for several hours, a specific approach is defined to deal with this problem. The forecast interval $[h; h+h_{\mathrm{FW}}]$ is divided, for each zone, in deficit and non-deficit intervals: a deficit interval is a time interval during which there is continuously unserved energy in a given zone, while non-deficit intervals are defined as complementary. Once this partition has been made, the analyses can be divided in a charge section and a discharge one:

Charge:
The aim of the charge section is to assess, for each zone, how much energy can be absorbed by the storage systems during the surplus intervals. A non-deficit interval is the basic unit of this analyses because it defines the moment (at its end) when a new amount of energy is available inside the storage systems and can be used to meet some residual demand, in the following deficit interval. In a given zone, during a non-deficit hour, any available surplus energy can be stored without the risk of preventing the direct use of that energy to meet electricity demand: if that energy could have reached the unserved loads, it would not be available as surplus. On the other hand, during a deficit interval, energy can be retrieved from storage systems, without risking to use it instead of directly available energy from BMR generation: if that was possible, the zone would not be experiencing a generation deficit situation. It must be noted that in order for this approach to work it is fundamental to correctly define the deficit and non-deficit intervals, and to not miskate the second one with surplus intervals. A zone might not experience any energy surplus but have zero unmet energy because energy is absorbed from a connected zone that is experiencing a surplus, and in the same way its storage systems can be charged. The mathematical formulation of this problem is the definition of an equation for each non-deficit interval and for each zone: the aim is to minimize the unused surplus. Each equation will be an energy balance between the power input of all the storage systems, net of their charge efficiency, and the cumulative capacity. The desirable solution of the system would be the complete charge of storage during a non-deficit interval:

$$\sum_{s=1}^{s=N_\mathrm{S}}\left(\sum_{h=h^\mathrm{n}_\mathrm{begin}}^{h^\mathrm{n}_\mathrm{end}} \boldsymbol{P_{ch}}(h,z,s)\cdot\boldsymbol{\eta_{ch}}(s)\right)=\sum_{s=1}^{s=N_s}\boldsymbol{Cap}(z,s),\quad \forall n=1,\dots,\boldsymbol{N_{\mathbf{int}}}(z),\quad \forall z=1,\dots,N_\mathrm{Z}. \tag{3.20}$$

Where $\boldsymbol{\eta_{ch}}(s)$ and $\boldsymbol{P_{ch}}(h,z,s)$ are the charging efficiency and the power input charging the s-th storage technology, respectively, during the h-th hour in the z-th zone, N_S is the number of storage technologies simultaneously considered, $h^\mathrm{n}_\mathrm{begin}$ and $h^\mathrm{n}_\mathrm{end}$ are the beginning and end hour of the n-th non-deficit interval for the z-th zone, respectively, and $\boldsymbol{Cap}(z,s)$ the installed capacity of the s-th storage technology in the z-th zone. Finally, $\boldsymbol{N_{\mathbf{int}}}(z)$ is the number of deficit intervals happening in the z-th zone. Boundaries are set for the charge power input:

$$\boldsymbol{l_{Chb}}(h,z,s)=0\quad\forall h,z,\quad \boldsymbol{u_{Chb}}(h,z,s)=\boldsymbol{P_{\mathbf{n}}}(z,s)\quad\forall h. \tag{3.21}$$

Where $\boldsymbol{P_{\mathbf{n}}}(z,s)$ is the nomial power for the s-th storage techonolgy in the z-th zone. Also two inequalities systems must be speficied: the first one ($\boldsymbol{A^f_1}\cdot\boldsymbol{x^f}\le\boldsymbol{b^f_1}$) assures that each storage system, in each zone and during each deficit interval, is not charged beyond its maximum capacity. It's built in a similar fashion to system (3.20), but separately for each storage system:

$$\sum_{h=h^{\mathrm{n}}_{\mathrm{begin}}}^{h^{\mathrm{n}}_{\mathrm{end}}} \boldsymbol{P_{ch}}(h,z,s)\cdot\boldsymbol{\eta_{ch}}(s) \leq \boldsymbol{Cap}(z,s), \quad \forall n=1,\ldots,\boldsymbol{N_{\mathrm{int}}}(z), \quad \forall z=1,\ldots,N_{\mathrm{Z}}, \quad \forall s=1,\ldots,N_{\mathrm{S}}. \tag{3.22}$$

The second one can be build similarly to system (3.5), in order to set the maximum energy that can be fed to the storage systems in a given zone as smaller or equal to the surplus available in that zone and the surplus that can be transferred from connected zones. For $N_S = 1$ we would get:

$$-\boldsymbol{PF}(1)+\boldsymbol{S^{BMR}}(1) \geq \boldsymbol{P_{ch}}(1) \tag{3.23a}$$
$$\boldsymbol{PF}(1)-\boldsymbol{PF}(2)-\boldsymbol{PF}(3)+\boldsymbol{S^{BMR}}(2) \geq \boldsymbol{P_{ch}}(2) \tag{3.23b}$$
$$\boldsymbol{PF}(2)-\boldsymbol{PF}(4)-\boldsymbol{PF}(5)+\boldsymbol{S^{BMR}}(3) \geq \boldsymbol{P_{ch}}(3) \tag{3.23c}$$
$$\boldsymbol{PF}(4)-\boldsymbol{PF}(6)+\boldsymbol{S^{BMR}}(4) \geq \boldsymbol{P_{ch}}(4) \tag{3.23d}$$
$$\boldsymbol{PF}(6)+\boldsymbol{S^{BMR}}(5) \geq \boldsymbol{P_{ch}}(5) \tag{3.23e}$$
$$\boldsymbol{PF}(3)+\boldsymbol{PF}(5)+\boldsymbol{S^{BMR}}(6) \geq \boldsymbol{P_{ch}}(6) \tag{3.23f}$$

Considering that the known terms are the surplus, the variables the charging power and the power flows, and that the system must be expressed in the form ($\boldsymbol{A}\cdot\boldsymbol{x} \leq \boldsymbol{b}$), we can rearrange it as it follows:

$$-(-\boldsymbol{PF}(1))+\boldsymbol{P_{ch}}(1) \leq \boldsymbol{S^{BMR}}(1) \tag{3.24a}$$
$$-(\boldsymbol{PF}(1)-\boldsymbol{PF}(2)-\boldsymbol{PF}(3))+\boldsymbol{P_{ch}}(2) \leq \boldsymbol{S^{BMR}}(2) \tag{3.24b}$$
$$-(\boldsymbol{PF}(2)-\boldsymbol{PF}(4)-\boldsymbol{PF}(5))+\boldsymbol{P_{ch}}(3) \leq \boldsymbol{S^{BMR}}(3) \tag{3.24c}$$
$$-(\boldsymbol{PF}(4)-\boldsymbol{PF}(6))+\boldsymbol{P_{ch}}(4) \leq \boldsymbol{S^{BMR}}(4) \tag{3.24d}$$
$$-(\boldsymbol{PF}(6))+\boldsymbol{P_{ch}}(5) \leq \boldsymbol{S^{BMR}}(5) \tag{3.24e}$$
$$-(\boldsymbol{PF}(3)+\boldsymbol{PF}(5))+\boldsymbol{P_{ch}}(6) \leq \boldsymbol{S^{BMR}}(6) \tag{3.24f}$$

For a single hour we obtain a system ($\boldsymbol{A_2}\cdot\boldsymbol{x} \leq \boldsymbol{b_2}$), that will have then to be expanded for every hour of the forecast interval as in (3.8), equal to:

$$\begin{gathered}
\boldsymbol{A_2}|_{N_S=1} = [-\boldsymbol{M_T} \quad \boldsymbol{I_{N_z}}], \quad \boldsymbol{b_2} = \begin{pmatrix} \boldsymbol{S^{BMR}}(1) & \cdots & \boldsymbol{S^{BMR}}(6) \end{pmatrix}^\top, \\
\boldsymbol{x} = \begin{bmatrix} \boldsymbol{x_{PF}} \\ \boldsymbol{x_{Ch}} \end{bmatrix} = \begin{pmatrix} \boldsymbol{PF}(1) & \cdots & \boldsymbol{PF}(6) & \boldsymbol{P_{ch}}(1) & \cdots & \boldsymbol{P_{ch}}(6) \end{pmatrix}^\top.
\end{gathered} \tag{3.25}$$

Discharge:
Once for every deficit interval the maximum amount of chargeable energy has been determined, discharge can be taken into account. The logic is the following: for each zone, the energy charged during a non-deficit interval can be exploited in all of the following deficit intervals, but not the previous ones. In this case the storage systems appear just as standard generation technologies in the linear system (3.6). The maximum power output is bounded between 0 and the rated power of the storage system, as in equations (3.15). Also in this case linear inequalities are taken into account via two systems. The first one ($\boldsymbol{A_1^f} \cdot \boldsymbol{x^f} \leq \boldsymbol{b_1^f}$) requires that for a given deficit interval, the cumulative power output of a storage system up to that interval cannot exceed the energy charged during all of the previous non-deficit intervals:

$$\begin{gathered}\sum_{h=1}^{h^{\mathrm{n}}_{\mathrm{end}}} \boldsymbol{P_{dch}}(h,z,s) \leq \sum_{h=1}^{h^{\mathrm{n}}_{\mathrm{end}}} \boldsymbol{P_{ch}}(h,z,s) \cdot \boldsymbol{\eta_{ch}}(s) \cdot \boldsymbol{\eta_{dch}}(s), \\ \forall n = 1,\ldots,\boldsymbol{N_{\mathrm{int}}}(z), \quad \forall z = 1,\ldots,N_{\mathrm{Z}}, \quad \forall s = 1,\ldots,,N_{\mathrm{S}}.\end{gathered} \tag{3.26}$$

Where $\boldsymbol{P_{dch}}(h,z,s)$ and $\boldsymbol{P_{ch}}(h,z,s)$ is the power output -and input- of the s-th storage system, during the h-th hour in the z-th zone, during charge and discharge, respectively. $\boldsymbol{\eta_{dch}}(s)$ and $\boldsymbol{\eta_{ch}}(s)$ the respective efficiencies, $h^{\mathrm{n}}_{\mathrm{end}}$ is the end hour of the n-th deficit interval and $\boldsymbol{N_{\mathrm{int}}}(z)$ is the number of deficit intervals happening in the z-th zone.

The second one ($\boldsymbol{A_2^f} \cdot \boldsymbol{x^f} \leq \boldsymbol{b_2^f}$) requires that during each deficit interval, the power output cannot exceed the overall capacity of the storage system:

$$\sum_{h=h^{\mathrm{n}}_{\mathrm{begin}}}^{h^{\mathrm{n}}_{\mathrm{end}}} \boldsymbol{P_{dch}}(h,z,s) \cdot \boldsymbol{\eta_{ch}}(s) \leq \boldsymbol{Cap}(z,s), \quad \forall n = 1,\ldots,\boldsymbol{N_{\mathrm{int}}}(z), \quad \forall z = 1,\ldots,N_{\mathrm{Z}}. \tag{3.27}$$

By imposing these two conditions, we allow the storage systems to keep some energy through a non-deficit interval, if its exploitation is more useful for following deficit intervals, but at the same time avoiding the chance that keeping energy stored prevents more surplus to be wasted.

Once charge and discharge operation has been assessed, unexploited surplus energy and unserved demand are calculated, with an approach similar to the one described with equations (3.14) and (3.13). Residual surplus is needed for any other storage technology, or to estimate the curtailed energy. Residual demand is needed both for following storage technologies or to solve dispatchment for flexible generators.

3.3.2.4 Zonal and hourly priority coefficients

The mathematical formulation of the dispatch problem described in section 3.3.1 intrinsically assigns a higher priority to the solution of the energy balance in equations with higher known term, since their contribution to the norm of the residual has a greater weight, and the solver minimizes the residual in the least-square sense. Depending on the case, it can be useful to eliminate this phenomenon or to exploit it in a controlled fashion. This can be done in COMESE by setting an array of N_Z priority coefficients $\boldsymbol{K}$, that multiply element-wise every equation of system (3.6), transforming system $\boldsymbol{C} \cdot \boldsymbol{x} = \boldsymbol{d}$ in system $\boldsymbol{C_K} \cdot \boldsymbol{x} = \boldsymbol{d_K}$, with:

$$\boldsymbol{C_K} = \begin{bmatrix} -K_1 & 0 & 0 & 0 & 0 & 0 & K_1 & 0 & 0 & 0 & 0 & 0 \\ K_1 & -K_2 & -K_3 & 0 & 0 & 0 & 0 & K_2 & 0 & 0 & 0 & 0 \\ 0 & K_2 & 0 & -K_4 & -K_5 & 0 & 0 & 0 & K_3 & 0 & 0 & 0 \\ 0 & 0 & 0 & K_4 & 0 & -K_6 & 0 & 0 & 0 & K_4 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & K_6 & 0 & 0 & 0 & 0 & K_5 & 0 \\ 0 & 0 & K_3 & 0 & K_5 & 0 & 0 & 0 & 0 & 0 & 0 & K_6 \end{bmatrix}, \quad \boldsymbol{d_K} = \begin{pmatrix} K_1 \cdot \boldsymbol{D}(1) \\ K_2 \cdot \boldsymbol{D}(2) \\ K_3 \cdot \boldsymbol{D}(3) \\ K_4 \cdot \boldsymbol{D}(4) \\ K_5 \cdot \boldsymbol{D}(5) \\ K_6 \cdot \boldsymbol{D}(6) \end{pmatrix} \tag{3.28}$$

Two examples of priority coefficients used in COMESE are reported below: coefficients for the managing of demand meeting priority and coefficients for the managing of storage device charging priority.

Electricity demand priority coefficients

Several criteria can be used to define system zones. Specifically, TSOs often define zones based on criteria such as the transmission grid topology and capacity, as well as geographical features and administrative boundaries of the simulated system. As a result, unless the user is willing to define the zones by himself following this exact rationale, they will usually feature different amounts of electricity demand. Table 3.1 shows as an example the distribution of electricity demand in the six Italian market zones for the year 2015.

As already said, this feature actually implies a priority to the loads of high-demand zones. While in principle there's no need to assume different priority for the electrical loads between different zones, the results obtained can also be misleading, resulting in major shares of unserved energy to be located in low demand zones for any reasons, or in an unjustified stress of the transmission grid. In order to eliminate this imbalance a set of coefficients $\boldsymbol{K_D}$ can be defined with the following criteria:

$$\boldsymbol{K_D}(z) = \frac{\sum_{z=1}^{N_Z} \boldsymbol{D}(z)}{\boldsymbol{D}(z)}, \qquad \forall z = 1, \ldots, N_Z. \tag{3.29}$$

Zone	Electricity load [%]
North	55.5
Center-North	10.6
Center-South	16.1
South	8.6
Sicily	6.2
Sardinia	3.0

Table 3.1: Electricity Load distributions in Italy (2015) according to the zones defined by Italian TSO TERNA. Source: TERNA.

By using these coefficients, all the known terms of system 3.28 assume the value of the overall system electricity demand in the considered hour, giving even priority to all the zones, despite the uneven electricity load distribution among them. If the system to be solved refers to several hours, as described in section 3.3.1.1, instead of a vector we obtain a matrix of coefficients $\boldsymbol{K_D}$, with one raw for each zone and one column for each hour:

$$\boldsymbol{K_D}(z,h) = \frac{\sum_{z=1}^{N_Z} \boldsymbol{D}(z,h)}{\boldsymbol{D}(z,h)}, \qquad \forall z = 1,\ldots,N_Z, \qquad \forall h = 1,\ldots,h_{\mathrm{FW}}+1. \tag{3.30}$$

In this case, the i-th column of $\boldsymbol{K_D}$ will multiply element-wise the elements of the i-th matrix $\boldsymbol{C}$ and the elements of $\boldsymbol{d^i}$ in the known term, of system 3.8. It's crucial to highlight that this approach evens the known term of equations relative to different zones in the same hour, but not for different hours. In fact in this case it's desirable that hours with higher demand benefit from a higher priority. By doing so, for a given amount of exploitable energy, that energy will be preferably used during hours with the higher demand, with the effect of smoothing the profile of residual demand and reducing the requirements in terms of power to cover it.

Storage devices charging priority coefficients

Storage systems charge, described in section 3.3.2.3, is formulated as a minimization problem with respect to the unused storage capacity, as shown in system (3.20). It's clear how also in this case, the larger will be the storage capacity installed in a zone, the higher will be the priority with which it will be charged. In order to even the charging priority in all zones, a vector of coefficients $\boldsymbol{K_S}$ can be defined in a similar fashion to what was done for the demand:

$$\boldsymbol{K_S}(z) = \frac{\sum_{z=1}^{N_Z}\sum_{s=1}^{N_S} \boldsymbol{Cap}(z,s)}{\sum_{s=1}^{N_s} \boldsymbol{Cap}(z,s)} \tag{3.31}$$

Where $\boldsymbol{Cap}(z,s)$ is the capacity of s-th storage technology installed in the z-th zone. If every equation of system 3.20 referring to the z-th zone is multiplied by the z-th element of $\boldsymbol{K}_{\mathrm{S}}$, the priority related to the zonal capacity distribution is evened out.

On the other hand, a user defined charge priority can be useful to investigate different storage operation strategies: an example is a charging strategy driven by the forecast on residual demand from BMR generators. Residual demand from BMR, i.e. the load left unmet after the exploitation of BMR generators (equation 3.13) is covered, as a first attempt, with energy from storage systems. If during overgeneration events energy is charged into the storage systems of the zones that will experience the heavier energy shortage, transmission lines may be either subjected to a lighter exploitation, or free to carry the energy from others generators, enhancing the system flexibility and reliability. In order to do so, an additional set of coefficients $\boldsymbol{K}_{\mathbf{ch}}$ must be defined, and used simultaneously to coefficients $\boldsymbol{K_S}$:

$$\boldsymbol{K^*_{ch}}(z,n) = \frac{\sum_{h=h^n_{begin}}^{h^n_{end}} \boldsymbol{rd}(h,z)}{\sum_{h=h^n_{begin}}^{h^n_{end}} \boldsymbol{D}(h,z)}, \qquad \boldsymbol{K_{ch}}(z,n) = \boldsymbol{K^*_{ch}}(z,n) + \alpha \cdot \max \boldsymbol{K^*_{ch}}(z,n) \tag{3.32}$$

Where coefficient $\boldsymbol{K_{ch}}(z,n)$ multiplies the equation relative to the z-th zone during the n-th non-deficit interval, h^n_{begin} and h^n_{end} are the boundaries of the n-th deficit interval, $\boldsymbol{rd}$ is the residual demand, as defined in equation (3.13), and α is a coefficient arbitrarily chosen to avoid to eliminate equations for which $\boldsymbol{K^*_{ch}}(z,n)$ would go to zero.

There are several approaches that can be used to define the $\boldsymbol{K}_{\mathbf{ch}}$ coefficient, beyond the one described by equation (3.32). It must be kept in mind that non of these can be univocally chosen as the optimal one, as well as that the resulting operation of the storage systems is not optimized: it actually follows an arbitrarily defined user criteria. This is out of the scope of such a feature in COMESE, which aims instead at exploring different possible operation strategies and how they can influence a specific system performances.

3.3.3 Joint action of flexible generators and Storage systems

As stated in the introduction of section 3.3 the hourly analysis scans all the time window hour-by-hour. The multiperiod analyses on the interval $[h; h + h_{FW}]$ is actually needed only to determine the system operation during hour h. Once completed the analyses of the system during hour $h+1$ will be determined with a multiperiod analyses in the interval $[h+1; h+1+h_{FW}]$, and so on. Multipediod optimization however is needed for a specific feature of COMESE: the joint action of flexible generators and storage systems, that is described in this section.

Once the multiperiod analyses for a given hour h is concluded there can be two outcomes: if the electricity demand has been completely satisfied exploiting the available technologies, the operation values for hour h are fixed and the analyses moves to hour $h+1$. On the other hand, if there is some unserved energy, the following feature is activated: flexible generators power output during hour h is checked; if the value of one or more generators is lower than its rated value, their power output may be increased, while the power output of storage systems is decreased accordingly. In this way some energy can be kept inside the storage systems and used in following hours, when it's more needed, but during which flexible generators may be already exploited to their limits. With a similar logic, not only storage systems can be kept charged more than originally planned: they can as well be charged with an even greater power output from flexible generators. The ratio behind this operation strategy is to exploit storage systems during moments when they are poorly charged, and exploit them to shift in time energy that cannot be generated by flexible generators when it's actually needed. For a given feasible system design this approach enhance the reliability of the power system, while for a fixed reliability level it reduces the amount of flexible generators needed power, and then the system costs.

Figure 3.3 shows an example of how the joint action feature can influence the performance of a system. Figure a) shows the hourly operation of a system that's not exploiting the joint action feature, during a time interval in which electricity demand is not completely satisfied and a significant amount of unmet load is present. Figure b), on the other hand, shows the hourly operation of the same system if the joint action feature is active: during several hours (in particular for $h \in [7455 \div 7465]$, $h \in [7480 \div 7490]$ and $h \in [7510 \div 7520]$) flexible generators are generating power, even if the system could meet the load also without their use, reducing consequently the power output of storage systems. Figure c) shows also an additional share of generation from flexible generators (in particular for $h \in [7510 \div 7520]$ and $h \in [7535 \div 7545]$) that's not part of the power balance between generation and loads: it's a share of power dedicated to the additional charge of storage systems. Figure b) shows how, thanks to these measures, an additional amount of stored energy is made available to entirely cover the load for $h \in [7530 \div 7535]$, $h \in [7550 \div 7560]$ and $h \in [7575 \div 7585]$. Even if that additional energy comes from flexible generators, it's clear how without the "Joint Action" feature it would have been impossible to exploit it, since the same generators were already operating at full power during those intervals.

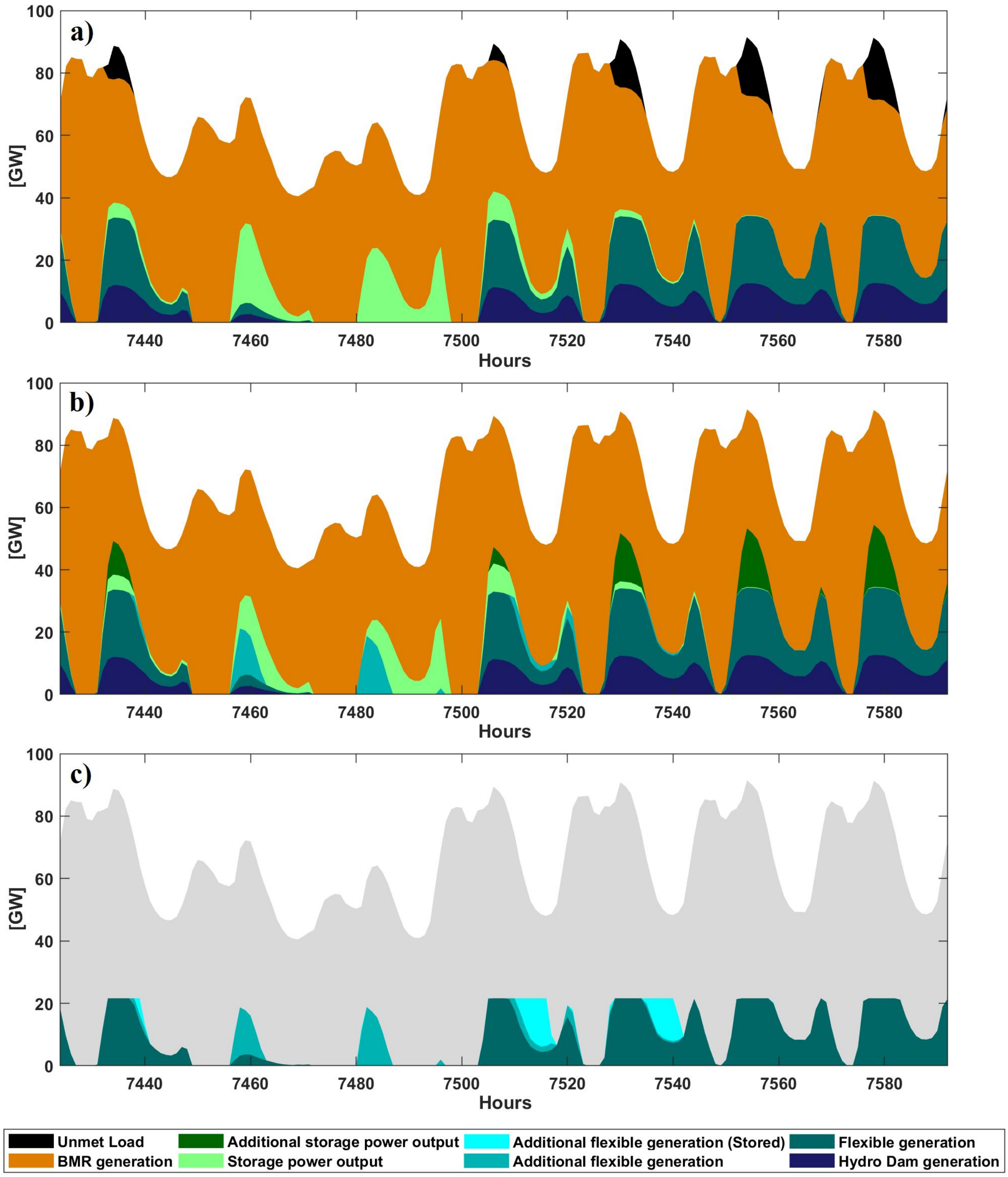


Figure 3.3: Joint action of flexible generation and storage systems. a) Hourly operation of a system that's not exploiting the joint action feature. b) Operation of the same system when the joint action feature is activated. c) Difference in the flexible generators power output.

3.4 Post-processing

In the post-processing section the system operation, i.e. the hourly power output (or input) of generators and storage, can be analysed. Duration curves can be generated for all the involved technologies, as well as it's possible to extract insights on the hourly operations for time intervals of particular interest. The same can be done for the hourly power flows, highlighting bottlenecks events. Unserved energy hourly profile is another output, if a system design results unfit to satisfy entirely the electricity demand. Post-processing includes the calculation of one of the main figure of merit of a scenario produced with COMESE, needed to assess the economic performance of a given system design: the LCOTE.

3.4.1 Costs Calculation: the Levelized Cost of Timely Electricity

The economic performance of a generation technology can be assessed with the so called LCOE (Levelized Cost Of Electricity). The LCOE is computed by discounting all the components of the cashflow of a plant during its lifetime to a present value: the value of energy price that matches the expenditures due to investment costs, fixed operation and maintanance costs, and variable costs, is the LCOE. Therefore the LCOE is an indicator of the cost of energy, as it's the average revenue per unit of energy needed to recover the building and operation costs of a generation plant during its lifetime. For every technology in a power system the LCOE can be computed with the following equation:

$$LCOE_i = \frac{\sum\limits_{j=-k_i}^{j=n_i} I_i(j)\cdot(1+r_i)^{-j} + \sum\limits_{j=0}^{j=n_i} O\&M_i(j)\cdot(1+r_i)^{-j} + \sum\limits_{j=0}^{j=n_i} F_i(j)\cdot(1+r_i)^{-j}}{\sum\limits_{j=1}^{j=n_i} E_i(j)\cdot(1+r_i)^{-j}} \tag{3.33}$$

Where, for the i-th technology:

r_i = Discount rate.

n_i = Expected lifetime of the plant.

k_i = Construction years.

$I_i(j)$ = Investment costs sustained during the j-th year.

$O\&M_i(j)$ = Operation and maintenance costs sustained during the j-th year.

$F_i(j)$ = Fuel costs sustained during the j-th year.

$E_i(j)$ = Energy generated during the j-th year.

However, electricity sale to the final user does not only have to payback the generation expenditures, but also the transmission ones and the costs of energy storage. The latter, in particular, may be a cost term of primary importance in a system largely based on renewable. The task of the hourly simulation in COMESE is exactly this one: to check if a power system is actually fit to satisfy energy demand during each hour of the analyzed time window, taking into account the energy storage requirements and the constraints given by transmission grid capacity and plant siting. The LCOTE (Levelized Cost Of Timely Electricity), is the parameter defined in COMESE to be used as economic figure of merit of a scenario. It's aim is to compute, with the same discount logic that characterize the LCOE, the average cost of a single unit of energy delivered to the user, in a system that is fit to meet the electricity demand during each hour of the analyzed time window. The LCOTE is then defined as the sum of a generation cost term, a storage cost term and a transmission grid cost term, all divided by the entire electricity load covered:

$$LCOTE = \frac{C_{gen} + C_{stor} + C_{grid}}{D_{cov}} \tag{3.34}$$

Where the generation cost term is calculated as:

$$C_{gen} = \sum_{i=1}^{i=N_g} LCOE_i \cdot E_i \tag{3.35}$$

Considering each one of the N_g generation technologies included in the power system. The storage cost term and the transmission grid cost term, being both assets that do not involve the generation of energy, are defined with the following simplified shared formulation:

$$C_{stor} = \sum_{s=1}^{s=N_s} \left[I_s \frac{r_s(1+r_s)^{n_s}}{(1+r_s)^{n_s}-1} + O\&M_s \right], \quad C_{grid} = \sum_{t=1}^{t=N_t} \left[I_t \frac{r_t(1+r_t)^{n_t}}{(1+r_t)^{n_t}-1} + O\&M_t \right]. \tag{3.36}$$

Where, for N_s storage technologies and N_t transmission technologies simulated:

$r_{s(t)}$ = Discount rate.

$n_{s(t)}$ = Expected lifetime of the device.

$I_{s(t)}$ = Investment costs.

$O\&M_{s(t)}$ = Yearly operation and maintenance costs.

Finally the denominator, equal to the overall covered demand, is calculated as:

$$D_{cov} = D_{tot} - E_{uns}. \tag{3.37}$$

Where D_{tot} is the overall electricity demand and E_{uns} the unserved energy. It must be noted that D_{cov}

is used as denominator in order to assure that $E_{uns} > 0$ have a negative impact on the LCOTE. However it can be misleading to compare two systems using the LCOTE in the presence of unserved energy: it could mean to compare two systems with different degree of reliability and effectiveness in meeting the electricity demand. That might be true also in the case of two systems with the exact same amount of unserved energy, depending on how it might be distributed in different ways over the hours analysed and the zones represented.

Finally, it is worth noticing how the definition of $LCOE_i$ (3.33) can be applied for renewable generators both considering the electricity generated gross and net of an eventual curtailment, due to its role in (3.35). However, it's simpler to consider it gross of curtailment, since this makes the definition of curtailed energy among variable technologies an optional step instead of a strictly necessary one. In both cases, the formulation of the LCOTE guarantees that the costs associated to renewable generation are fully taken into account even if curtailment occurs.

3.4.2 Stochastic analysis of the LCOTE

COMESE allows also to adopt a stochastic approach in the calculation of the LCOTE: every technical and economical feature can in principle be fed to the model not only as a deterministic value, but also as a probability distribution. In the latter case the model generates a high number of cases (arbitrary set by the user within the ranges allowed by the hardware used) with a Monte Carlo approach. The LCOTE is then computed for each one of these cases, where all the technical and economical parameters follows the assigned probability distribution.

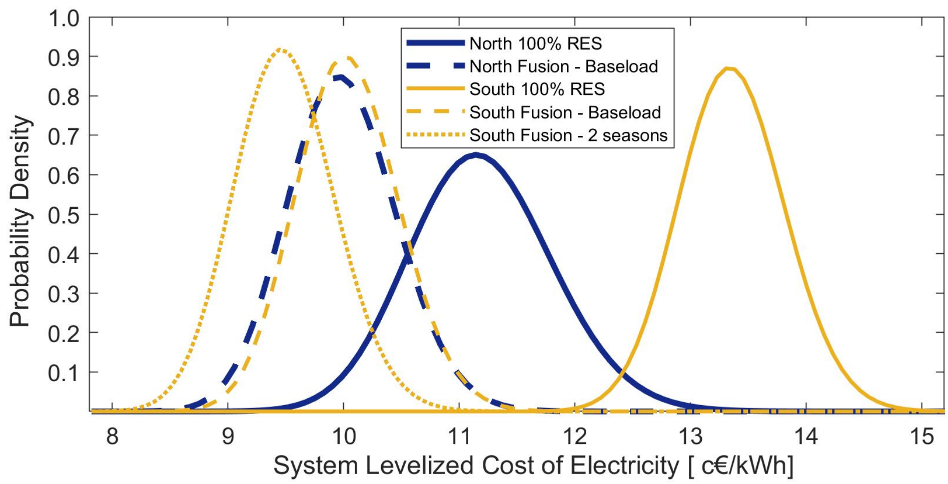


Figure 3.4: An example of the LCOTE calculated with COMESE as probability distribution function. From [41, 47].

The outcome is a probability distribution for the LCOTE itself. This approach can be useful for two reasons: the first one is that it allows to include in the LCOTE computation the information about uncertainties on the technical and economical assumption used, a feature whose importance grows with the time horizon of the analyses. The second one is that it allows to obtain a series of information related to the shape of the probability distribution, often used in policy making and risk assessment for investment planning. These information can make more complete the economic feasibility assessment of future energy scenarios [48].

3.5 How to use COMESE

While the previous part of this chapter was aimed at describing the criteria that COMESE uses to simulate the operation of a power system, this last section describes the different ways in which the model can be used.

3.5.1 Single analyses

A single run of COMESE can simulate the operation of a specific system design arbitrary, whether it is chosen by the user, or exogenously defined, for example if it comes from third party scenario analyses. This approach is particularly useful when dealing with system design and scenarios that have not been defined taking into account a full hourly analysis. COMESE can highlight the datailed operation of each generation and storage tecnology included in the power system, allowing for a detailed cost analyses. Above all it can check whether the system is fit to satisfy the demand in every moment, or otherwise how severe is the lack of power produced by a poorly designed system.

3.5.2 Sensitivity analyses

By choosing an arbitrary number of system elements or features N_v, and assigning them a discrete domain of values, COMESE can be run for any combination of these variables producing sensitivity analyses. The variables can be the capacity of generation, storage or transmission technologies, but also techno-economic features of one or more of these technologies, or even modeling inputs or assumptions. Any output of the model can then be analysed as function of the considered variables, along with an optimal combination (within the domain accuracy) of the considered parameters. It's however clear how, for a given amount of computational resources, this approach force the user to a tradeoff between the number of variables, the domain resolution, and the degree of detail of a simulation (i.e. its computational cost).

3.5.3 Optimization analyses

COMESE can also be coupled with an external optimization routine, that deals with it as a "black box function". Also in this case an N_v number of variable, whose domain can be both continuous or discrete, depending on the approach, can be set. The use of an optimization routine increase the efficiency with which the computational resources are exploited, allowing for a higher number of variables to be considered in the analyses. On the other hand, however, it reduces the informations that we can get about the influence of those same variables on the scenario results: this approach is useful if the only goal of the analyses is the design of an optimized system. However, a mixed approach can also be adopted: a given variable may be analyzed effectively even if with an extremely coarse resolution, with a domain made by a number of elements in the unit magnitude. In this case a specific optimized analyses can be run for each one of this variable choices, assessing how the optimal system configuration varies as a function of the external variable.

3.5.3.1 Differential Evolution algorithm

Until now this approach has been implemented exploiting an optimization routine that is based on the algorithm called Differential Evolution (DE) [49], adapted in order to comply with the analyses of constrained problems as the ones presented in this work. The most common objective function used with this approach is the LCOTE, as it's the economic figure of merit of a scenario, but any output of the model can be set instead. The same applies to for constraints to the system operation: a typical constraint, for the reasons explained in section (3.4.1), is a minimum number of hours during which the electricity delivered does not match (up to a given tolerance) the total electricity demand. DE is a stochastic metaheuristic technique particularly fit, considering its efficiency and robustness, to the solution of computationally demanding problems based on non-differentiable objective functions. This method is based on populations (different electric system configurations in this specific case) evolving as they search for an optimal (least cost) solution, following a sequence of mutation, recombination and selection typical of evolutionary algorithms. Being each run of COMESE independent from another, it was possible to parallelize the problem, which fits particularly well this kind of algorithm. Compared with other techniques of the same family, like evolutionary computation or genetic algorithms, DE stands out with respect to convergence speed. This has made it possible to cope with complex scenarios as the one here presented, with computation time of some tens of hours on low cost hardware.

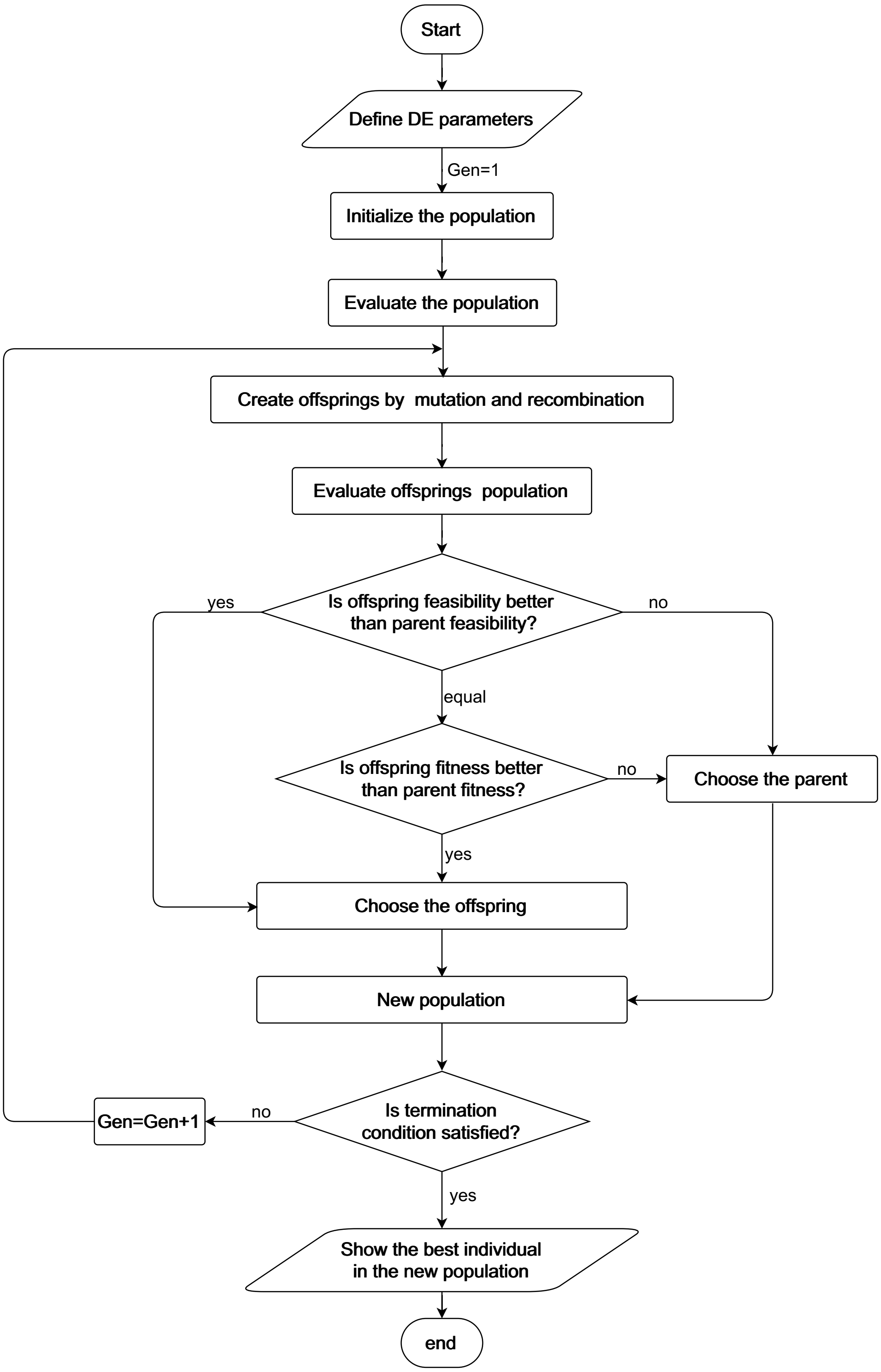


Figure 3.5: Differential evolution algorithm flowchart.

3.6 COMESE validation

If we take into account the description of COMESE given in this chapter, and we rely on the categories proposed in section 1.3.1.1 of Chapter 1, we can classify the mode as follows. COMESE is a bottom-up model for the operation analyses of a power system. However, it also includes an optimization module based on DE algorithm that allows to design an optimized power system, with respect to any selected model output, defining the optimal combination of a set of user defined decision variables. The time window analysed is usually set to one solar year, but given the proper inputs the model can, without any structural modification, analyse shorter (weeks, months) or longer (multiple years). However, as the computational burden of a simulation is directly proportional to the time window extension, long time windows reduce the model versatility, at least in analyses relying on high number of simulations. COMESE normally adopts an hourly resolution, which, anyway, can also be set by the user at will. The same consideration made for the time-window extension holds, in this case for a higher time resolution. With respect with spatial resolution, COMESE allows to divide the system in an arbitrary number of system zones. In this case a power flow analyses based on a transport model can be included in the simulation, as well as a "copper plate" analyses neglecting transmission constraints. On the other hand, if a single zone representation is chosen, the "copper plate" assumption is mandatory. The model simulates only the operation of the power system, hence its a single sector model. However, transport, industrial, cooling and heat sector are included, with dedicated load profils, for what concerns the electricity demand coming from the electrified share of these sectors. COMESE adopts a myopic foresight approach, with a forecast ability. The forecast is assumed to be perfect inside the forecast interval, that it's usually set to 24 hours from the analysed hour, but that can be freely defined by the user. Finally, unit commitment is defined following a user defined priority order, while a simulation of the electricity market is not available as an alternative.

It's easy to see how COMESE shares to a large extent the same approach and purpose of the EnergyPLAN model, which was described in section 1.3.1.4. Since EnergyPLAN is a well established model, its use is documented in a large number of scientific publications, its logic and operation criteria are shared and well documented, and its openly available, it was deemed eligible for a comparison with COMESE, which was carried out by means of the scenarios analyses described in the following section.

3.6.1 A comparison with EnergyPLAN

The scenario analysed in the context of this comparison is a medium term regional Italian scenario focused on the Sardinia region: it has 2030 as target year, and is therefore based on quite conservative assumptions on the electrification and penetration of renewable sources.

3.6.1.1 Model assumptions

Since EnergyPLAN do not allow to simulate system zones, both the models have been exploited relying on the copper plate assumption. Sardinia was then represented as a single zone in COMESE, therefore the same profiles for renewable generation and electricity demand were directly fed to both models. Also, EnergyPLAN simulates a 8784 hours year (i.e. a leap year): the profiles for the analysis have then been adapted repeating the last 24 hours of each profile, and setting the default time-window for COMESE to 8784 hours.

EnergyPLAN storage technologies are limited to pumped hydro storage (PHS). However, the user can add more than one storage, with different values for the capacity, input and output rated power and charge and discharge efficiencies. Thus a first PHS has been set identical to the PHS simulated in COMESE, and a second fictitious PHS has been added, with the features of battery storage. EnergyPLAN also needs the user to specify the priority order between the two systems. Since COMESE deals with this problem with a different approach (section 3.3.2.3) the priority order adopted in the previous version of COMESE [41] was adopted in EnergyPLAN, i.e. the highest priority to the system with the higher storage duration (PHS). This criteria should maximise the amount of energy availability bot in charge and in discharge, as explained in [41].

On the other hand, EnergyPLAN allows to set a fixed share of demand that has to be provided by stable generation, to simulate ancillary services requirements. Since this feature is not present in COMESE, that share has been set to zero. EnergyPLAN also gives the user the option of requiring certain units to have a minimum production at all hours. This feature as well is not present in COMESE, but it was used in EnergyPLAN and handled adopting a specific solution in COMESE, that will be described later. Finally, EnergyPLAN exploits precipitation profiles to simulate the availability of water by basin hydroelectric generators. Since this feature is not present in COMESE, in EnergyPLAN this condition has been replicated by setting a sufficiently high capacity for the basins and a water availability equal to the overall year availability from the first moment of the year.

With respect to overgeneration and unmet demand management, the two models have different approaches. For a given maximum connection capacity with neighbor countries, EnergyPLAN gives a higher priority to energy export and import than to storage charge and discharge, when dealing with overgeneration and unmet demand, respectively. Since COMESE is structured to simulate self-sufficient energy systems, energy import and export have by default the lower priority level. Therefore the maximum connection capacity has been set to zero in EnergyPLAN, and the final results on unexploited overgeneration and final unmet demand have been elaborated a posteriori exploiting the maximum interconnection capacity values.

3.6.1.2 Scenario description

The system configuration for this scenario has been mainly taken from an existing study [50] on decarbonization paths for the Sardinia region in the medium term (2030), with objectives coherent with the Italian PNIEC ("*Piano Nazionale Integrato per l'Energia e il Clima*" - Energy and Climate Integrated Plan). The electricity demand for Sardinia has been set to 8.7 TWh, with a net 3% increase with respect to today, assuming a mild electrification of the transport sector and of heating and cooling demand. Given the moderate increase in demand it was deemed reasonable to use the current (2019) electricity demand profile for Sardinia.

With respect to conventional generation, Sardinia hosts a refinery (Sarlux-SARAS) that relies on a 590 MW IGCC (Integrated Gasification Combined Cycle) power plant. Since this plant is not operating exclusively on the energy market, a constant minimum operation equal to the 30% of the rated power is assumed. In EnergyPLAN this assumption is dealt with the dedicated feature previously mentioned, while in COMESE the plant has been divided in two technolgies: one baseload generator with a rated power equal to 30% of the Sarlux-SARAS plant rated power, and a flexible dispatchable one with rated power equal to the remaining 70

The installed capacity of Dam Hydroelectric plants is 118 MW, with a maximum yearly generation of 0.5 TWh, which is the mean value generated between 2015 and 2018. Even if the current installed capacity of these plants is 72 MW, due to the recent interruption of several plants operations, it was chosen to maintain the same value used in the reference study, for coherence. Photovoltaic generators and wind power capacity, which currently is 787 and 1084 MW, inrease to 1793 and 2135 MW, respectively. The additional capacity comprehends both rooftop mounted panels and utility scale plants for photovoltaic, for a total yearly generation of 2.6 TWh. Wind power capacity expansion, on the other hand, is assumed to happen only thanks to on-shore generators, for a total yearly generation of 5.9 TWh. Run of River hydro, on the contrary, is supposed to maintain its current 100 MW capacity.

Storage systems include pumped hydro storage, with a 790 MW power capacity, a mean storage duration of 10 h and a 90% roundtrip efficiency. These values are based on the assumption of a major increase (more than 200%) for these kind of plants. Battery storage capacity, according to the PNIEC, should reach 417.5 MW, for plants with 8 h duration, and then an overall 3.34 GWh storage capacity.

Finally, taking into account the existing transmission links with the Italian peninsula (SAPEI), the ones undergoing a repowering process (SACOI) and the ones foreseen by the national grid upgrading programmes (T-Link), the overall connection capacity of the region amounts at 2.4 GW

Supplier	Yearly production [TWh]	User	Yearly consumption [TWh]
Sarlux	2.08	Demand	8.7
Dam Hydro	0.26	Pumped Hydro	0.77
Photovoltaic	2.6	Batteries	0.42
Wind power	5.9	Export	2.09
Run of River	0.15	Curtailment	0
Pumped Hydro	0.63		
Batteries	0.36		
Import	0.003		
Total	12	Total	12

Table 3.2: Energy balance in the COMESE simulation - regional Sardinia scenario

Supplier	Yearly production [TWh]	User	Yearly consumption [TWh]
Sarlux	1.92	Demand	8.7
Dam Hydro	0.5	Pumped Hydro	0.91
Photovoltaic	2.6	Batteries	0.1
Wind power	5.9	Export	2.3
Run of River	0.15	Curtailment	0.15
Pumped Hydro	0.74		
Batteries	0.08		
Import	0.12		
Total	12	Total	12

Table 3.3: Energy balance in the EnergyPLAN simulation - regional Sardinia scenario

3.6.1.3 Comparison analysis

Tables 3.2 and 3.3 summarize the yearly energy balances of the Sardinian power system simulated with the two models. While the overall results are quite similar, as one would expect from two rather similar models, some non negligible difference can be pointed out and analysed. The energy balance highlights differences for the voices: import, export, curtailment, dispatchable generation from the IGCC (Sarlux) generator, and for battery and PHS systems, both in charge and in discharge.

First of all let us consider the import voice. This is substantially the amount of demand that the system was not able to deliver to the users, as the import is the only viable way of matching supply and demand in this case, but it's at least within the maximum connection capacity. Anyway, the difference in the two results is relevant, even if the absolute values are quite low: EnergyPLAN estimates that value to be 1.4% of the total yearly demand, while COMESE the 0.03%. These values are more significant if expressed with respect to the average daily electricity demand (0.024 TWh): in the first case we have five times the average daily demand, while in the second one the 12.6%. The two measures given are two extreme representation: the unmet load cannot be assumed to be evenly distributed all over the simulation year, but will also never be concentrated in a continuous time interval. An example of time interval with unmet load can be oserved in Figure 3.8 for $h \in [145 \div 150]$. The comparison between two results can only be qualitative, as two systems can be compared only given the same performance level (i.e. the ability to correctly meet the demand during every hour). If we address the problem from another point of view, we could state that in this case COMESE would assess a much lower need of system improvement with respect to EnergyPLAN in order to design a working system.

Let us then focus on curtailment and export: the sum of the two values is the energy produced but not exploitable by the system users. From this point of view it's quite significant to consider it as a single quantity. COMESE estimates it to be the 24% of the total yearly demand, while EnergyPLAN the 28%. Part of this difference (2%) is not even exploitable by means of energy export: it has in fact to be curtailed.

The reason for that is a different operation in storage systems. Specifically we can point out two relevant facts: the overall amount of energy charged by storage systems is higher in COMESE simulation (+18%) but it's also allocated differently between the two systems. In the EnergyPLAN almost all of it is absorbed by PHS systems, while in COMESE there is roughly a 2:1 ration between the two quantities. The reason for that can be found observing the hourly profiles on figures 3.6 to 3.9. The fixed priority given to PHS, coupled with the absence of a forecast on the subsequent hours, limits the amount of chargeable energy. This is particularly evident for $h \in [10 \div 30]$ in Figures 3.6 and 3.7.

Storage system operation is also one of the reasons why the unmet demand reaches different levels in the two simulations: as it can be observed especially in the winter plots, COMESE simulates the two storage systems always operating together, while EnergyPLAN sequentially. Moreover, a gradual

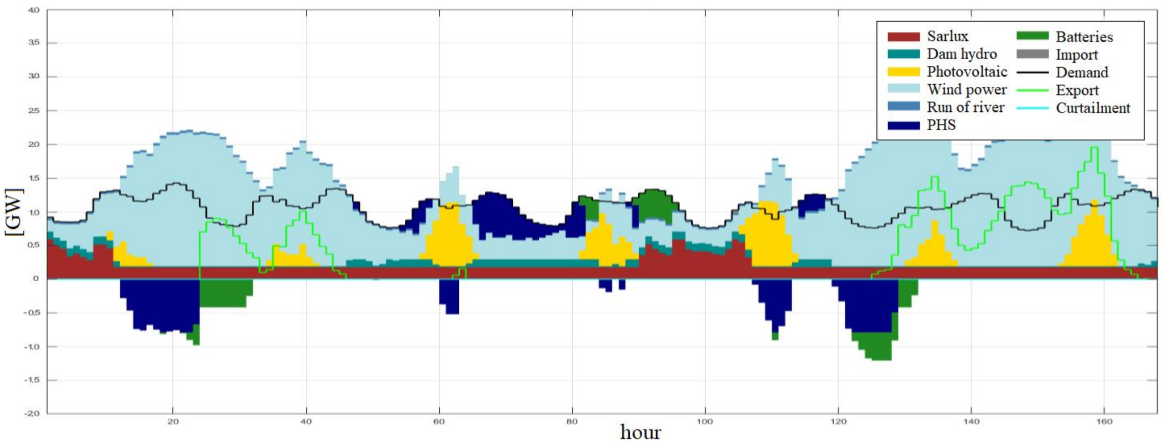


Figure 3.6: EnergyPLAN simulation: energy balance for one week in January.

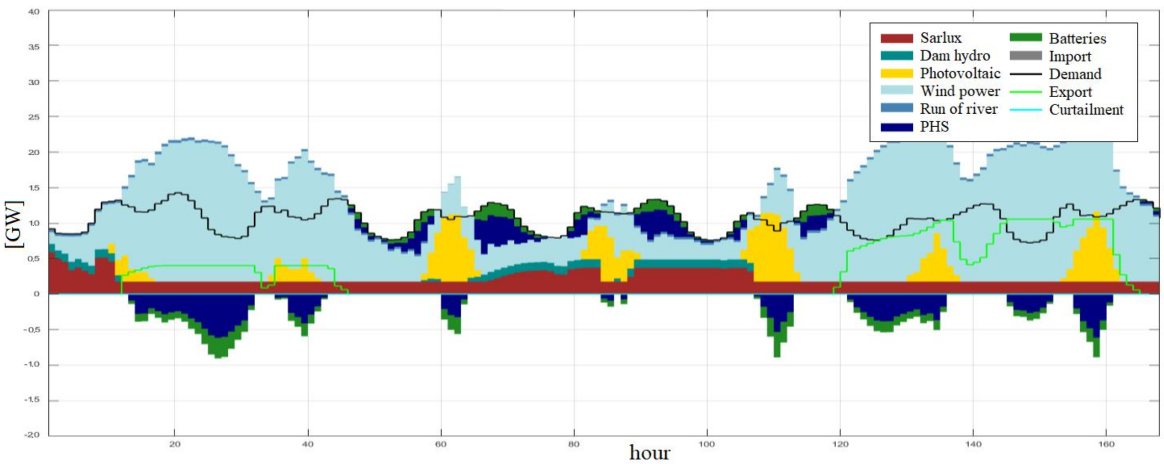


Figure 3.7: COMESE simulation: energy balance for one week in January.

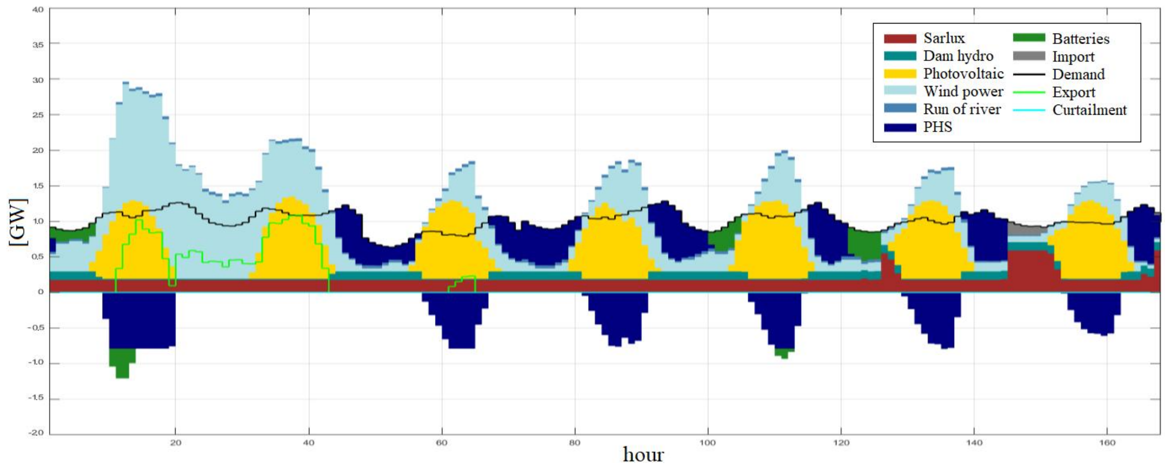


Figure 3.8: EnergyPLAN simulation: energy balance for one week in July.

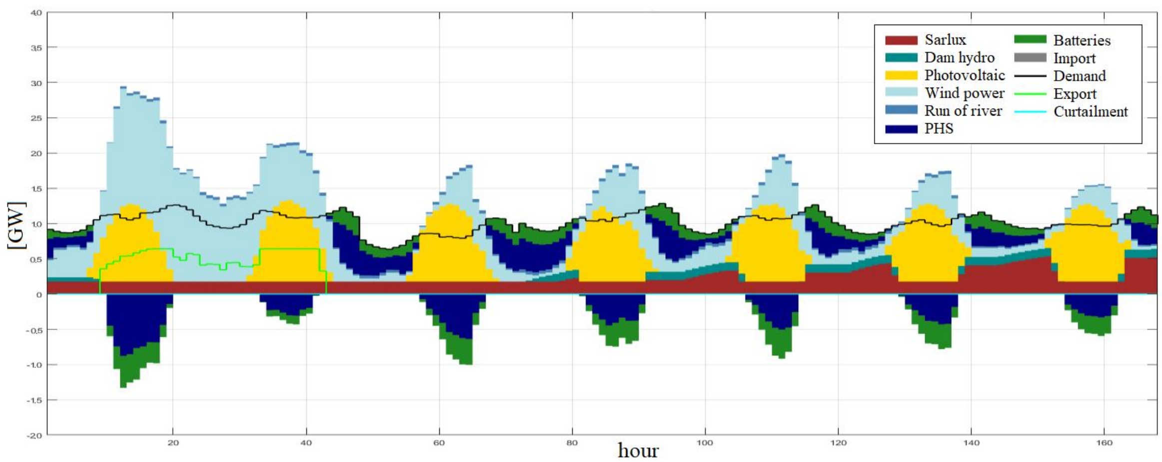


Figure 3.9: COMESE simulation: energy balance for one week in July.

activation of IGCC and dam hydro generators can be observed, from h =70. That is the effect of the "Joint Action" of flexible dispatchable generators and storage systems, described in section 3.3. By postponing the exploitation of stored energy, the system results more versatile in meeting the demand.

3.6.1.4 Conclusions

The comparison carried out in this section highlighted two important elements: the first one is that there is a good match in the overall operation of COMESE with a well validated tool as EnergyPLAN, that has the same purpose and adopts a very similar approach as an energy model. The second, and most important one, is that on the other hand the original features of COMESE, i.e. the short term forecast exploitation (section 3.3.1.1) and the joint action of dispatchable generators and storage systems (section 3.3.3) actually have a non negligible impact on the results of a simulation. This implies both the chance of designing optimized scenarios with a higher performance level, but also the chance to study and quantify the effectiveness of such operational strategies.

Chapter 4

Nuclear fusion impact on system assets requirements

In the following chapter long term Italian scenarios for the power system are presented. COMESE is used to compare two alternatives: power systems relying only on renewable energy, and power systems relying both on renewable energy and fusion power. Several scenarios are produced, exploiting the model with different degrees of detail and under different assumptions. Indeed the aim of these analyses is not only to assess what kind of energy mix and system design is the best, but also to understand what are the elements that makes it so, and what are the modelling tools necessary to simulate correctly their impact and their operation. The results described in this chapter are also discussed in the paper "Nuclear Fusion impact on the requirements of power infrastructure assets in a decarbonized electricity system" recently published in Fusion Engineering and Design [51].

For both cases, the analyses rely on the DE algorithm (section 3.5.3.1) in order to define an optimized system designs. The figure of merit of a scenario, and objective function of the DE algorithm, is the LCOTE (section 3.4.1), which means that the goal is the definition of a lest cost design for a power system. Specifically, the analyses focus on the impact that three elements have on the system configuration and the deriving costs: the first one is the energy storage systems, the second one is the flexible generation capacity, and the third one is the transmission grid capacity with respect to the renewable generators and storage systems siting throughout the system zones. DE optimization routine is used with different settings for the different stages of the analyses, that will be specified each time. However a common approach throughout all the scenarios is to exclude fusion from the decision variables: fusion is set to different fixed levels, following a sensibility approach. This is done in order to highlight the impact of Fusion under different availability assumptions, rather than obtaining a single optimal configuration with a unique capacity for this technology.

4.1 Analysis rationale

As each power system is almost unique, the choice of the Italian case clearly influence the results obtained, that cannot be completely generalized for any other power system: Italy is a fully developed industrialized country with a high energy consumption. Italy's primary energy supply per capita amounts to 2,31 ktoe per capita in 2020 (with a peak value of 3.21 ktoe in 2005). This makes of Italy the third economy, as well as the third country in terms of energy consumption inside the European Union. Electricity demand has a peculiar distribution throughout the country, influenced by a northern region inhabited by the major share of the country population (currently 46%), as well as the majority of industries and productive activities (currently 56% of the overall country GDP), and the presence of two major islands: Sicily and Sardinia, lacking bridge connection with the mainland. Table 4.1 summarize the current distributuon of population, GPD and electricity demand per zone in 2015, with respect to the zonal distribution defined by TERNA and adopted in the analyses described in this chapter.

Zone	Population [%]	GDP [%]	Electricity load [%]
N	46.4	55.7	55.5
CN	10.2	10.3	10.6
CS	21.4	19.4	16.1
S	11.2	7.3	8.6
Si	8.1	5.2	6.2
Sa	2.7	2.0	3.0

Table 4.1: Population, Gross Domestic Product and electricity Load distributions in Italy (2015) according to the zones defined by Italian TSO TERNA. Source: Istat (Population and GDP) and TERNA.

Zone	Full load hours [/]	Capacity Factor [%]	Relative value [%]
N	1352	15.4	100
CN	1385	15.8	102
CS	1442	16.5	107
S	1454	16.6	108
Si	1545	17.6	114
Sa	1496	17.1	111

Table 4.2: Generation potential for fixed photovoltaic generators per each Italian zone. Data from simulations based on reanalysis climate datasets for year 2015 [52].

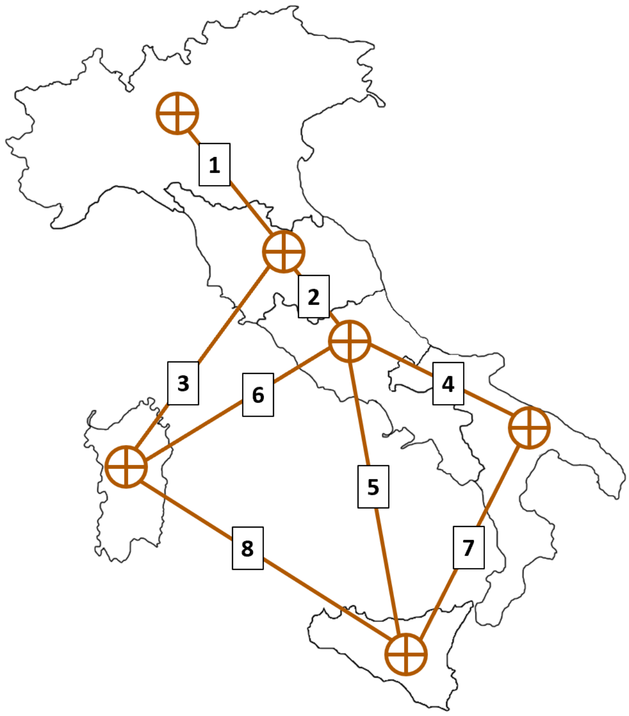


Figure 4.1: Transmission grid topology uses in the analyses.

Line	Link	Type	Capacity [GW]		
			Current	PdS21	DDS22
1	N-CN	OH	3.9	4.3	9.3
2	CN-CS	OH	2.5	2.9	8.4
3	CN-Sa	HVDC	0.3	1.1	1.1
4	CS-S	OH	4.6	5.6	8.8
5	CS-Si	HVDC	-	0.7	1
6	CS-Sa	HVDC	0.9	0.9	1.9
7	S-Si	OH	1.2	1.8	4
8	Si-Sa	HVDC	-	0.8	1

Table 4.3: Transmission grid capacities used in the analyses. Line numbering referring to Figure 4.1.

Photovoltaic capacity potential is basically function of the zones extension and orography, while generation potential increases gradually moving from northern regions towards southern ones, as a function of latitude. However, even if a non-negligible difference can be seen in terms of full load hours (Table 4.2), this doesn't prevent photovoltaic generators to be installed in northern regions: actually, as of today, the majority of the current Italian photovoltaic generation (22.6 GW) is installed in northern regions. On the other hand, wind power capacity and generation potential are quite limited in Italy, especially if we consider on-shore wind farms: suitable sites are mainly located in the South region and in the two islands. Both capacity and generation potential are much lower if compared with northern European countries, whose energy policies envisage a major deployment of wind power.

With regard to nuclear energy, Italy does not have operating fission power plants: actually the exploitation of the technology is currently forbidden by law since a popular referendum in 1987, later confirmed in 2011. On the other hand, the country hosts important fusion research facilities and is involved in international programmes on nuclear fusion. This contributes to outline a neat comparison between scenarios with and without fusion, since no technology switch from fission to fusion is conceivable extrapolating current conditions.

The Italian power transmission grid is managed by the transmission system operator TERNA, and can be roughly divided in a continental part, that connects the mainland zones from north to south with an overall comparable transmission capacity, and three submarine connections with the islands (two with Sardinia and one with Sicily). Figure 4.1 recalls the topology already described in section (3.2.3) of chapter 3. Table 4.3 indicates the connection capacities and type -Over Head (OH) lines and High Voltage Direct Current (HVDC) connections- for the current grid configuration and for two configurations used in this study, PdS21 and DDS22, described below.

It's clear that the concurrence of these features defines a pretty specific scenario, that can hardly entirely apply elsewhere. Nevertheless, beyond the quantitative results regarding the Italian system itself, the results can give qualitative insights on the subject valid also for the design of different power systems.

4.2 Common assumptions

By 2050 the Italian electricity demand is supposed to increase and double with respect to today, passing from the current 330 TWh to 650 TWh as a result of electrification of final uses envisaged by national decarbonization policies [53]. The total electricity demand is calculated as the Italian gross electricity demand in 2019 (330 TWh) increased by: 80 TWh for space heating [54]; 100 TWh for private transport; 140 TWh for hydrogen and e-fuels production for hard-to-abate industrial processes [53]. The current hourly profile of electricity demand coming from TSO database [55] is properly modified to include additional loads from residential, service, transport and industrial sectors. The electricity demand profile of heat pumps for space heating and hot water production is derived from the current hourly natural gas demand for the same final uses [54]. The electricity demand profile of EVs is taken from [56]. Finally, demand profile for hydrogen and e-fuels production is assumed constant over the year.

Due to the high penetration of heat pumps, electricity demand in cold seasons is 30% higher than in the rest of the year. This reverse the current trend for which peak demand takes place during summer, as it can be seen in Figure 4.2: in it, the 2019 Italian profile of daily electricity demand is scaled up to 650 TWh, for comparison with to the one used in these analyses, also shown. In addition also the current daily French electricity demand profile is shown (scaled to the same overall demand), for comparison with a case of demand in a country with higher electricity penetration: demand is 35% higher while population is only 15% higher with respect to Italy.

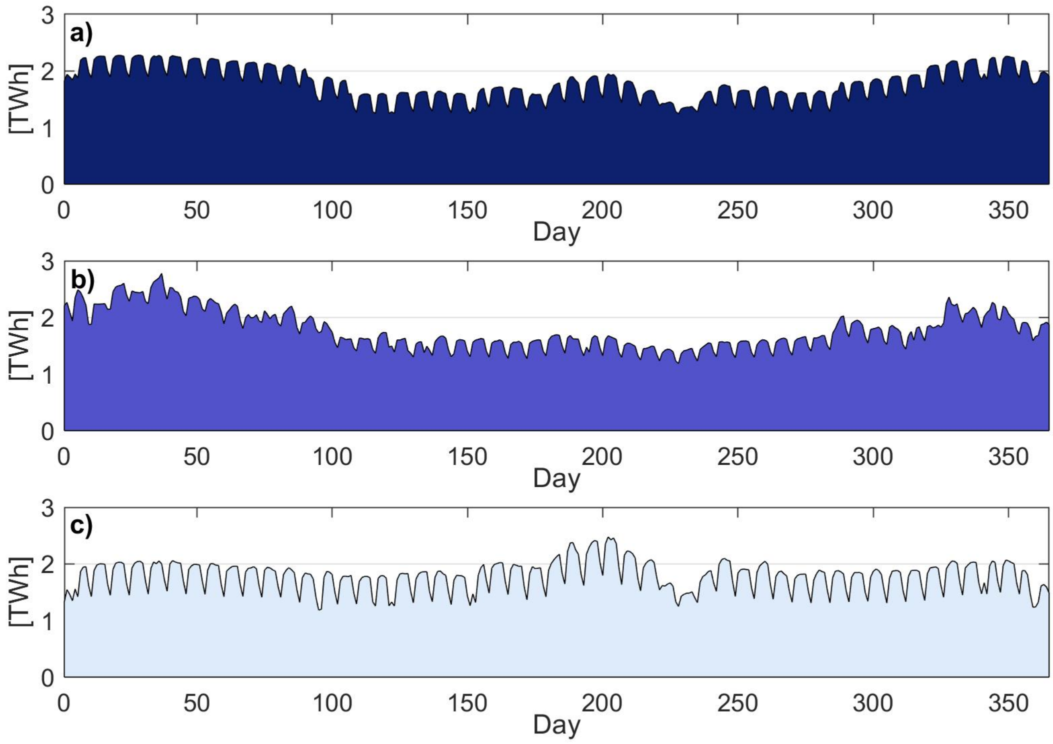


Figure 4.2: Daily electricity profiles comparison: a) 2050 Italian profile built for the analyses, b) 2019 Italian profile, c) 2019 French profile. Profiles b) and c) are scaled up to 650 TWh, in order to match the overall demand of profile a).

The techno-economic assumptions of the power system components are shown in Table (4.5). Cost ranges for stochastic analyses are also specified, although this study uses a deterministic approach based on the reference values. As in [47] most of the data are taken from [57] with the exception of costs of solar photovoltaic (PV), wind and storage that have been updated to the latest and more optimistic estimations as in [1] and [58, 59]. In all scenarios only domestic generation and storage systems are considered to satisfy power demand, i.e. no energy import is allowed, differently from today, as currently Italy imports slightly more than 10% of its electricity demand, mainly due to abundance of nuclear generation from France. The system is forced to be completely self sufficient, which is a conservative approach, since it cannot benefit neither from foreign generation capacity to prevent loss of load by supplying energy during undergeneration events, nor from foreign markets to sell any unnecessary surplus generation.

In all the scenarios discussed here, geothermal, run-of-river hydro and municipal waste power plants provide base-load generation. Installed capacity is the same or slightly higher than today, as their maximum potential is already almost fully exploited [55]. Nuclear fusion power plants provide firm baseload generation for 7000 h/year (80% CF). In order to better match demand and generation profiles, it was assumed that yearly maintenances activities of each power plant are planned so to allow 90% of the total installed capacity to be in operation from October to March, while only 70% in the rest of the year (2Seasons operation). in Figure 4.3 the monthly electricity demand is compared to the generation from 50 GW of fusion power in the case of constant baseload and in the case of 2Seasons operation. Due to the fact that different climatic zones are subjected to different kind of restrictions on the use of heating systems, the heat demand through the year are not perfectly overlapping in the six system zones. As a consequence, also the operation of fusion plants with the two described levels is not perfectly matching, and the overall fusion power output during April and October results 83% and 77% of the nominal power, as it can be noticed in Figure a). Figure b), on the other hand, shows the montly residual demand left to cover with the two operation strategies. Figure c) shows the duration curve of the resdual hourly demand, in the two cases. As for the installed generation capacity, as ancicipated, this study explores the effect of three choices: 0, 25 and 50 GW. 50 GW has been chosen since little beyond this value oversupply events from baseload generation start to happen during nighttime. While in principle there's no reason why storage system's couldn't handle this kind of events, it was chosen to design a system that has to deal with them only due to variable renewable power output fluctuation. Also, the energy output of 50 GW operating with an average 80% CF is roughly half -54%- of the yearly electricity demand, which was considered a meaningful case to be assessed. The value for the second scenario with Fusion, 25 GW, was chosen consequently as an intermediate case. Fusion power plant costs are computed with the FRESCO code [60] and are in line with the EUROfusion figures [61].

Utility scale PV power stations are equipped with mono-axial tracking systems to maximize the CF. The total capacity of these power station is an decision variable. The maximum ground mounted solar PV potential is set to 800 GW, that corresponds to 20000 km^2, which is half the difference between the total available agricultural land and the portion presently used for farming activities [62] in Italy. Beyond utility scale PV, it was assumed that 46 GW of fixed PV panels would be installed on residential and commercial rooftops, roughly evenly divided between these two categories. This value is about two times the current photovoltaic capacity installed in Italy and it's quite conservative with respect to potential

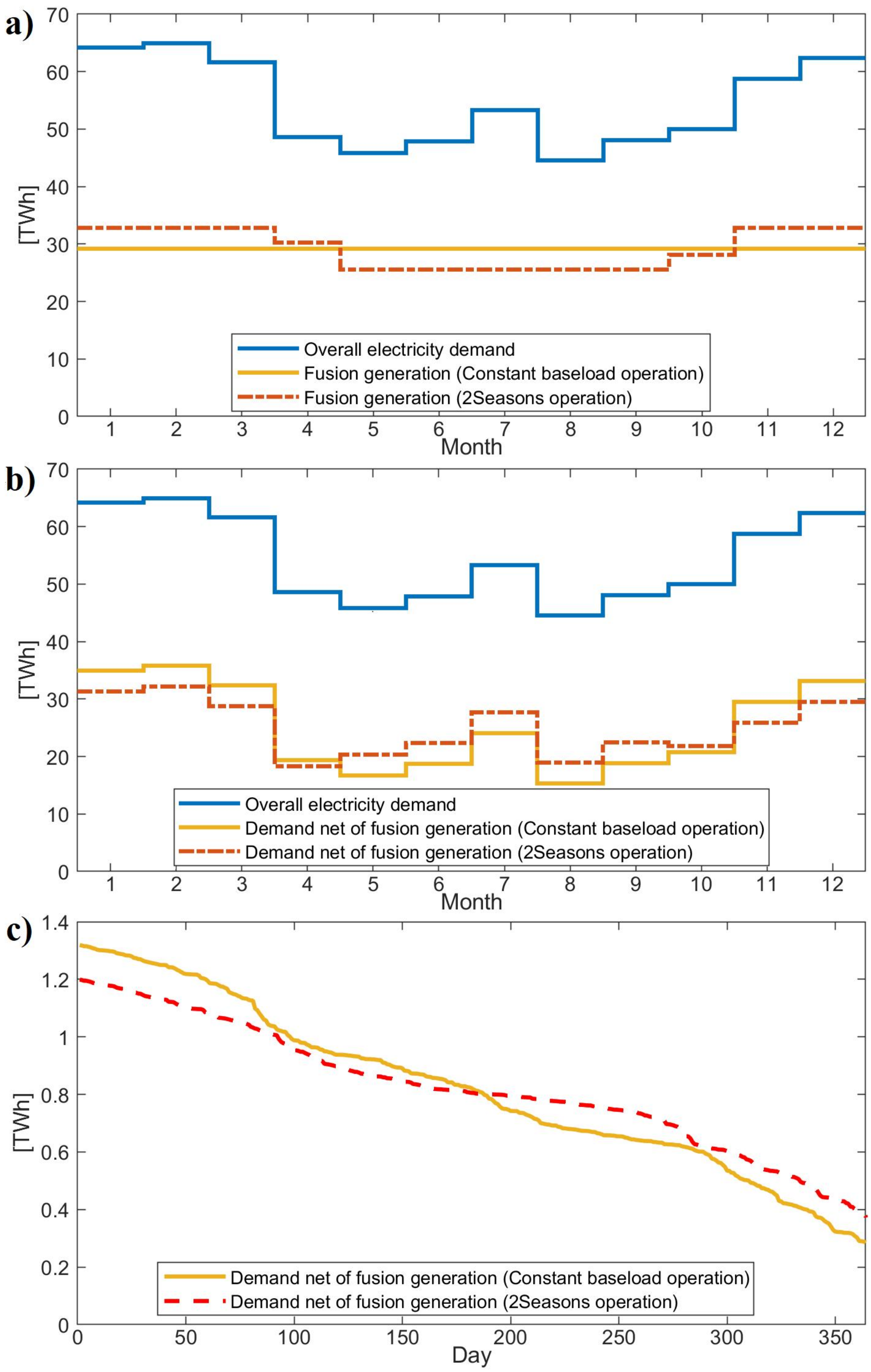


Figure 4.3: Constant generation vs "2Season" generation for Fusion power plants. a) Monthly generation. b) Monthly demand net of Fusion generation. c) Daily demand net of Fusion generation (duration curve).

Table 4.4: Installed power and electricity generation per technology

		Installed power [GW]	Electricity generation* [TWh]
Baseload generation technologies			
Geothermal		1.2	9.3
Hydro Run of River		5.3	25
Municipal Waste (η = 30%)		0.1	0.8
Nuclear Fusion		0 / 25 / 50	0 / 175 / 350
Intermittent generation technologies			
Photovoltaic	Residential rooftop	23	27
	Ind/comm rooftop	23	30
	Utility scale (w/ tracking)	DV	**
Wind	Onshore	35	70
	Floating offshore	10	30
Flexible generation technologies			
Biomethane fired OCGT (η = 42%)		DV	**
Dam Hydro		10.5	23
Energy storage technologies			
Electrochemical storage (η = 85%) – 8h storage		DV	**
Pumped Hydro storage (η = 80%)		9	0.1

* Energy capacity for storage technologies.
** Model output.
DV Decision Variable.

assessment such as [63]. The installed power of fixed panels on residential and commercial buildings are set as a user defined fixed value for multiple reasons: the first one is that in the eye of the model they would appear as a technology with comparable costs, lower CF and a generation profile harder to manage than utility scale ones. They would then be automatically discarted, unless the 800 GW potential for utility scale plants is reached. The second one is that optimization run are computationally demanding, and to include multiple kind of PV generation technologies would lower the model performances without adding an appreciable degree of detail to the analysis. Finally, these kind of plants have an exploitable potential strongly linked to the distribution of buildings across the zones. One of the aims of this study is to assess the impact of different zonal distribution of renewable generation, and therefore it was chosen to set their installed potential to a fixed and conservative value, allowing a utility scale plants capacity to be subjected to more relevant variations.

Table 4.5: Cost and lifetime options for the technologies composing the electricity generation mix

		CAPEX [€/kW]	OPEX [€/kWy]	lifetime [y]	Full load hours[1] [h]	LCOE [c€/kWh]
Baseload generation technologies						
Geothermal[2]		3500	80	30	7800	4.1
Hydro Run of River[2]		3000	75	60	3100 - 5200	8.9
Municipal Waste (η = 30%)[2,3]		4500	130	25	7800	0.5
Fusion[4]		6000	110	60	7000	6.4
Intermittent generation technologies						
Photovoltaic	Residential rooftop	450	12	25	1100 - 1350	3.4
	Industrial/commercial rooftop	350	10	25	1300 - 1500	2.7
	Utility scale (tracking)	350	12	25	1650 - 1950	1.8
Wind	Onshore[5]	1300	30	25	1250 - 2400	5.9
	Floating offshore	2200	70	25	3000	9.2
Flexible generation technologies						
Dam Hydro[2]		3400	50	60	2300	12.0
Biomethane fired OCGT (η = 42%)[6]		550	20	30	*	*
Storage technologies						
Pumped Hydro (η = 80%)[2]		1500	30	60	-	-
Batteries (8h storage - η = 85%)		960	20	10	-	-
Transmission grid[7]						
Overhead lines	Lines	425	30	25	1250 - 2400	5.9
	Substations/converters	3000	70	30	3000	9.2
HVDC submarine	Lines	1300	30	25	1250 - 2400	5.9
	Substations/converters	3000	70	30	3000	9.2

* Model output

[1] The ranges indicate minimum and maximum nominal full load hours considering different geographical locations with their generation potential.

[2] Average values as reported in by the EU SET plan SETIS database [57].

[3] Fuel cost is assumed to be negative, -80 €/ton.

[4] CAPEX, OPEX and LCOE of a future fusion power plant are derived from the literature for a DEMO-like commercial power plant [61].

[5] Value from IEA Net Zero scenario for the EU [64], with unitary currency conversion rate.

[6] The cost of biomethane (0.92 €/m^3) derives from the assumptions of digesters (CAPEX: 1,800 €/kW - OPEX: 3%) operating with 90% capacity factor and biomass cost of 5 €/GJ [65]. The result is in line with the estimation reported in [66].

[7] Cost are expressed in [€ MW^{-1} km^{-1}] for lines and in [€ MW^{-1} km^{-1}] for substations, and are taken from [67] and [68]

Due to the country morphology and limited wind potential, wind capacity is not a decision variable. Wind farms are assumed mostly on-shore (35 GW), with an additional (10 GW) offshore floating capacity, globally generating 100 TWh, in line with the assumption of Fit for 55 PRIMES European scenario [69]. Dam hydro power plants operate as flexible generators with an installed capacity of 10.5 GW and electricity generation up to 23 TWh. Both capacity and generation are assumed as high as today because the country potential is already almost fully exploited. Flexible generation can be also provided by biomethane fired Open Cycle Gas Turbines (OCGT). The maximum allowed electricity production (45 TWh) is derived from the bio-methane national potential (107 TWh [70]) assuming 42% conversion efficiency, while the installed generation capacity is one of the decision variables.

Pumped-hydro installed power is assumed to be slightly higher than today (9 GW), in line with the national potential [55]. The corresponding energy storage capacity is 100 GWh. Further storage needs are assumed to be satisfied by electrochemical devices (8-hour Li-Ion batteries), whose capacity is also a decision variable. Seasonal storage technologies based on power to hydrogen were also simulated, with the aim of avoiding curtailment. However, when it was included, it resulted only in a minor LCOTE reduction. Moreover, the operation of H2 storage was actually very similar to short term storage systems: it didn't involve a major curtailment reduction or long time shifts of relevant amounts of energy. Taking into account these evidences, it was chosen to exclude hydrogen storage from these analyses, in order to lower the decision variables and consequently the computational burder of the simulations. The potential role of long term hydrogen storage has been assessed in dedicated analyses described in Chapter 5.

Table 4.3 shows the two different transmission grids that are used in this study. They share the same topology (Figure 4.1) with but different capacities. The configuration named PdS21 (*Piano di Sviluppo 2021*) refers to the development plan up to 2030 by the Italian TSO TERNA [42] . The second configuration, named DDS22 (*Documento di Descrizione Scenari 2022*) reflects the upgrades the transmission grid would need to cope with a major increase of RES by 2030 according to the TSO evaluations [71]. It must be noted that the transmission capacity enhancement encompasses the development of new transmission grid infrastructures as well as a revision of the power grid operation rules so to increase the effective transmission capacity while both preventing the need of building additional lines and ensuring the security of supply.

As for the optimization process, the objective function is the system LCOTE: the aim is the design of a least cost power system. The three decision variables, as already mentioned, are the utility scale PV generators capacity, biomethane OCGT generator capacity and battery storage capacity. A system design is fit for the analysis if it complies with two kind of constraints: the first one is a maximum of 1 hour Loss of Load during all the year. A Loss of Load hour is defined as an hour when less than 99% of the electricity demand was met, and is set as a constraint in order to compare power systems with the same adequacy. The second constraint is the exploitation of a maximum of 45 TWh generation from biomethane, in order to comply with the national production potential and the assumption of system self-sufficiecy.

4.3 Results and discussion

4.3.1 *Copper Plate* scenarios

Scenarios described in this section have been optimized under the CP assumption. The overall installed power of utility scale phovotoltaic generators and battery storage systems was optimized while keeping an a priori fixed distribution for both technologies across the six system zones. Specifically, photovoltaic generators and batteries were allocated proportionally to each zone extension.

Electricity generation in 100%RES is completely covered by renewable sources. Baseload generation (3% of total production) is provided by geothermal, run of the river and municipal waste power plants, while 91.5% by intermittent renewables. The rest is covered by dispatchable generation. As already said, in FUS25 and FUS50 ~25% and ~50% of the total electricity demand is covered by 25 and 50 GW of fusion capacity, which is 18% and 44% of the total production, respectively. Intermittent generation, on the other hand, is responsible for 74% and 47% of the demand, respectively.

	100%RES	FUS25	FUS50
Installed capacity of decision variables [GW]			
Photovoltaics	527	376	170
Batteries	94	50	19
Biomethane fired OCGT	39	27	16
Energy balance [TWh]			
Baseload	35	210	385
Intermittent	1000	740	378
Flexible	57	44	33
Total generation	*1092*	*994*	*796*
Excess Energy	660	473	200
Curtailed Energy	410	320	135
Roundtrip efficiency losses	39	24	11
Figure of merit [c€/kWh]			
LCOTE	8.1	7.7	7.3

Table 4.6: Copper Plate scenarios: installed capacity of decision variables, energy balance and figure of merit.

None of the scenarios has unserved energy. Therefore, the corresponding power system configurations are to be considered equally feasible options at this stage of the analysis. In line with [47], as much as the fusion capacity increases, the electricity demand is covered at lower costs (-10% in FUS50 compared to 100%RES), despite fusion electricity being more expensive than solar; almost twice for residential roof photovoltaic, up to almost four times for utility scale photovoltaic (table 4.5). This is due to the overall lower photovoltaic, storage and dispatchable capacities required to cover the demand, as resulting from the optimization (see Table 4.6). Also, the amount of excess energy to be curtailed progressively decreases with the increasing share of fusion power. In FUS50 scenario 135 TWh are curtailed, as compared to 320 TWh in FUS25 and 410 TWh in 100%RES, which means 17%, 32% and 38% of the total generation, respectively.

4.3.2 *Transmission Grid* scenarios

In these scenarios, the system design described in the previous section for cases 100%RES and FUS50 (see Table 4.6), obtained as a result of the optimization process under the CP assumption, where kept unchanged both with respect to the overall installed capacities and to the zonal distribution. These system configurations were simulated with a higher detail, i.e. taking into account the power grid model and the transmission constraint to the energy exchange between zones. The transmission capacity between zones was at first attempt set at very high values (ten times the DDS22 capacities) in order to replicate "CP-like" constraints, and then progressively reduced (two and one times DDS22) down to the PdS21 capacities, indicated in Table 4.3.

As shown in table 4.7 (a) and (b), the stricter the bounds on the maximum allowed power flows, the higher the curtailed and unserved energy. Curtailed energy increases because a greater portion of excess energy cannot be neither directly used nor stored, being impossible to move it between different zones due to transmission lines congestions. As a consequence, the number of events of unserved demand increases. Both in 100%RES and FUS50, in order to cover the demand a strong enhancement of the transmission capacity is necessary, namely ten times DDS22 that corresponds to 20 times the capacity expansion of PdS21. Specifically, the capacity of the mainland connections (lines 1, 2, 4 and 7) should be seven times as large as in DDS22, while the capacity of submarine connections (lines 3, 5, 6 and 8) ten times larger.

In all cases, the FUS50 scenario results as the least cost one. However both scenarios can no longer be considered optimized, as they were defined under a different assumption (Copper Plate) for the grid capacity, therefore the comparison is less relevant. Still it can be pointed out that, for all the grid configuration tested in this section, the unserved energy is lower when fusion is included. Thus, we can expect that scenarios with fusion power should require minor adjustments to cope with the constraints imposed by any choice on the grid configuration. This will be assessed in the following sections, where optimized scenarios are proposed taking into account the actual constraints of the transmission grid for three grid capacity alternatives: PdS21, DDS22 and two times DDS22.

(a)	Transmission grid configuration			
	PdS21	DDS22	2·DDS22	10·DDS22
Energy [TWh]				
Curtailed	460	440	422	414
Unserved	37	17	0.7	0
Figure of merit [c€/kWh]				
LCOTE	9.7	9.2	8.7	9.9
Generation	7.5	6.8	6.3	6.1
Storage	2.1	2.1	2.1	2.1
Transmission grid	0.1	0.2	0.3	1.7

(b)	Transmission grid configuration			
	PdS21	DDS22	2·DDS22	10·DDS22
Energy [TWh]				
Curtailed	190	162	140	136
Unserved	19	5	0.3	0
Figure of merit [c€/kWh]				
LCOTE	8.8	8.1	7.6	8.9
Generation	8.1	7.4	6.8	6.7
Storage	0.6	0.5	0.5	0.5
Transmission grid	0.1	0.2	0.3	1.7

Table 4.7: Transmission Grid scenarios: installed capacity of decision variables, energy balance and figure of merit in scenario 100%RES (a) and FUS50 (b).

4.3.3 *Least Cost Power Plants Siting* scenarios

In this case the three scenarios (100%RES, FUS25 and FUS50) are studied under the assumption of PdS21 transmission grid configuration in order to define the least-cost capacity siting of utility scale photovoltaic generators and battery storage systems. This means that, for these two technologies, the installed capacity in each zone is treated as a single decision variable: consequently not only the overall installed capacity can vary, but also its distribution across the six system zones. Nuclear fusion and OCGT power are instead set proportional to the zonal electricity demand (Table 4.8) being the optimal layout as resulting from dedicated analyses. In all the cases, the resulting least-cost photovoltaic and battery siting, shown in Table 4.8, is markedly different from the one adopted in the CP analyses of section 4.3.1. Specifically, a major share of capacity is moved from southern zones (especially S, Si and Sa) to northern zones (especially N), even though the latter features lower capacity factors for solar generators.

The resulting capacity distribution is more similar to the zonal electricity demand distribution, but a clear proportionality cannot be highlighted, possibly due to the presence of other kind of generation and storage technologies (Table 4.4) with distributions fixed a priori.

Compared to scenarios with CP configuration, we can observe a minor increase in the overall photovoltaic generators installed capacity: 2.61%, 1.9% and 1.8%, respectively for 100%RES, FUS25 and FUS50 scenarios. On the other hand, given the higher share installed in northern regions, the total generation results almost unchanged. Instead, batteries and OCGT generators capacities are higher, up to +30% and +40%, respectively (Table 4.9). This means that the grid transmission capacity is a major constraint as it affects in a relevant way energy exchange among zones, both when dealing with surplus energy to be redistributed or stored, and when flexible generation is required. Figure 4.8 shows the energy mix in 100%RES and FUS scenarios, as compared to the current situation (2021), along with the relevant amount of curtailed energy (~40% of electricity from solar power). The lowest LCOTE is again achieved in FUS50. The cost gap between 100%RES and FUS50 is wider if compared to the scenarios obtained under the CP assumption in section 4.3.1: 17% vs 10%. This further stress the economic burden of storage and flexible generation, whose contribution increases inversely to fusion power. The optimal siting of PV and batteries reduces the LCOTE up to 13% as compared to scenarios with PdS21 configuration and capacity siting proportional to the zone areas.

Finally, the effects of a more enhanced transmission grid combined with the least-cost photovoltaic generators and batteries siting are explored in 100%RES and FUS50 cases. The LCOTE in 100%RES is 9.2, 8.9, 8.8 cEur/kWh with PdS21, DDS22 and 2xDDS22 configurations, respectively. The LCOTE in FUS50 is 7.7 cEur/kWh whatever the scenario. Therefore, transmission grid enhancements are beneficial for 100%RES as the LCOTE decreases by 5%, whereas they do not affect the LCOTE in FUS50 scenarios. Indeed, in both cases, a reduction of the generation and of the storage costs (Figure 4.9) is observed, and it's the outcome of two factors: a reduction of the overall installed capacity of photovoltaic, storage systems and OCGT generators (-3%, -13% and -25% in scenario 100%RES and -9%, -25% and -13% in scenario FUS50) and a shift of photovoltaic generation and storage capacity from northern to southern regions, thus exploiting higher capacity factors for solar generators.

Figures 4.4, 4.5, 4.6 and 4.7 show, both for the 100%RES scenario and the FUS50 scenario, how photovoltaic generation and battery storage siting changes. The distribution obtained with the PdS21 grid configuration is compared to the one obtained with the 2xDDS22 configuration: red dots stand for the optimal solution, while breaks stand for other suboptimal solutions generated by the optimization routine with comparable costs (up to +0.5%). The shift of the installed capacity takes place in a similar fashion in both scenarios: the higher capacity increase takes place in the zones with the higher photovoltaic generation potential (South, Sicily and Sardinia), to the detriment of the installed capacity in the zone with the lower generation potential (North). Zones Center-South and Center-North are interested by

		Zone					
Technology	**Scenario**	**N**	**CN**	**CS**	**S**	**Si**	**Sa**
Photovoltaic	100%RES	60	11	15	8	4	2
	FUS25	59	12	13	10	4	1
	FUS50	58	14	12	11	4	1
Batteries	100%RES	55	12	16	11	5	1
	FUS25	55	15	14	12	3	1
	FUS50	55	19	12	12.5	1	0.5
Zone extension distribution		39	14	14	16	9	8
Electricity demand distribution		55	10	18	8	6	3

Table 4.8: Zonal capacity distribution [%] as resulting from the optimization compared to the distribution proportional to zone areas and zonal electricity demand.

	100%RES	FUS25	FUS50
Installed capacity of decision variables [GW]			
Photovoltaics	541	383	173
Batteries	115	63	25
Biomethane fired OCGT	56	37	21
Energy balance [TWh]			
Baseload	35	210	385
Intermittent	1006	734	376
Flexible	68	51	40
Total generation	*1109*	*995*	*801*
Excess Energy	681	494	230
Curtailed Energy	420	321	139
Roundtrip efficiency losses	38	24	11
Figure of merit [c€/kWh]			
LCOTE	9.2	8.3	7.7

Table 4.9: Least Cost Power Plants Siting scenarios: installed capacity of decision variables, energy balance and figure of merit.

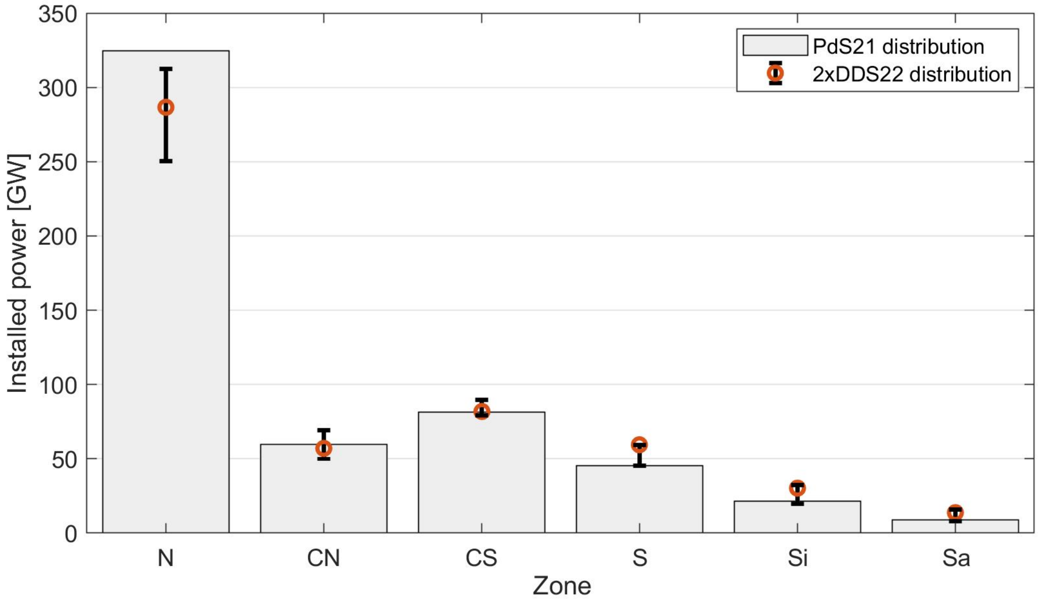


Figure 4.4: Photovoltaic capacity zonal distribution in the 100%RES scenario. Comparing the distribution obtained using the PdS21 and the 2xDDS22 grid capacities.

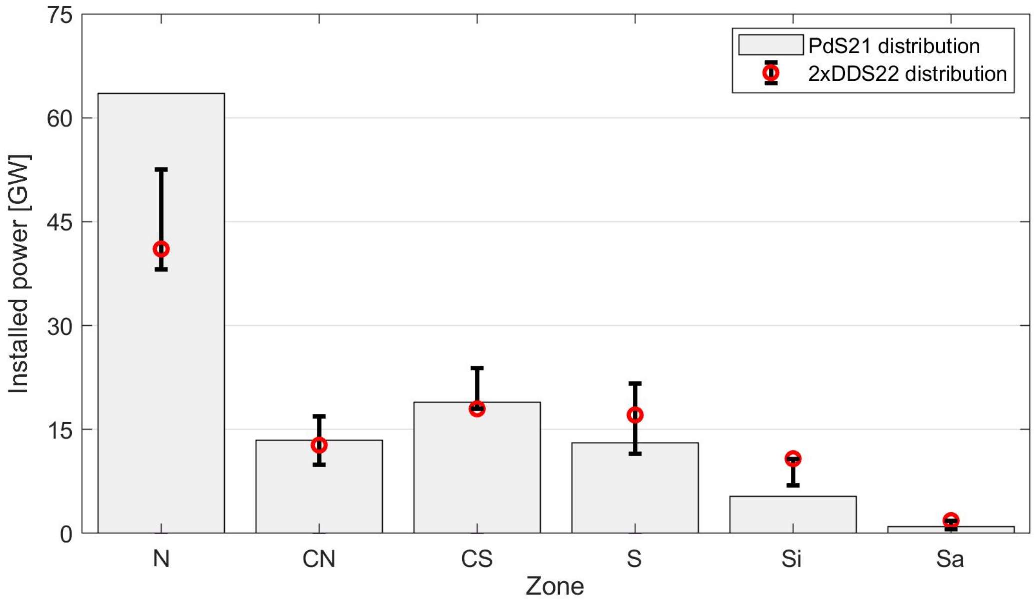


Figure 4.5: Battery storage capacity zonal distribution in the 100%RES scenario. Comparing the distribution obtained using the PdS21 and the 2xDDS22 grid capacities.

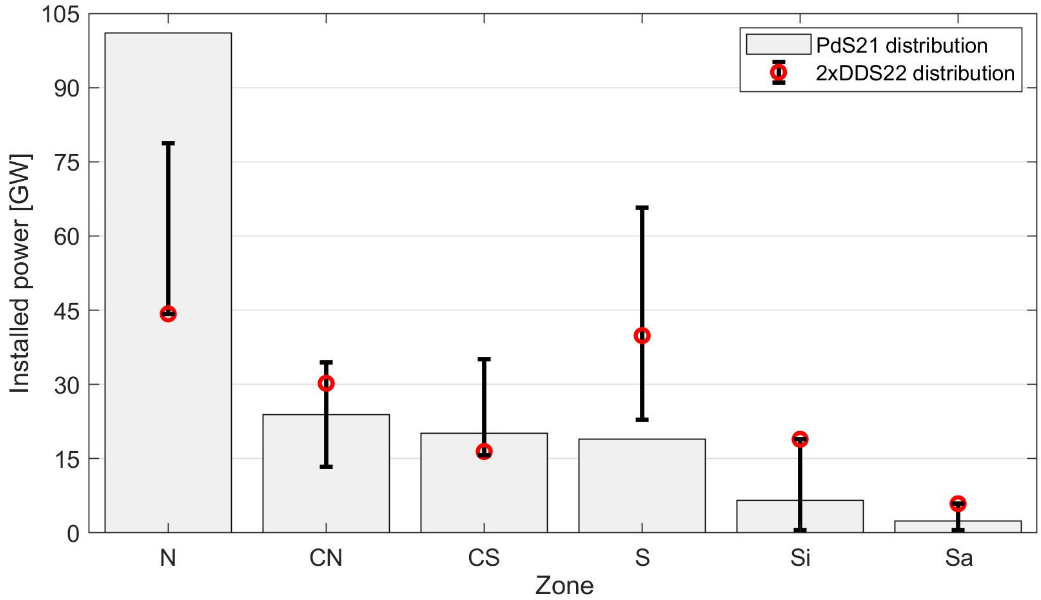


Figure 4.6: Photovoltaic capacity zonal distribution in the FUS50 scenario. Comparing the distribution obtained using the PdS21 and the 2xDDS22 grid capacities.

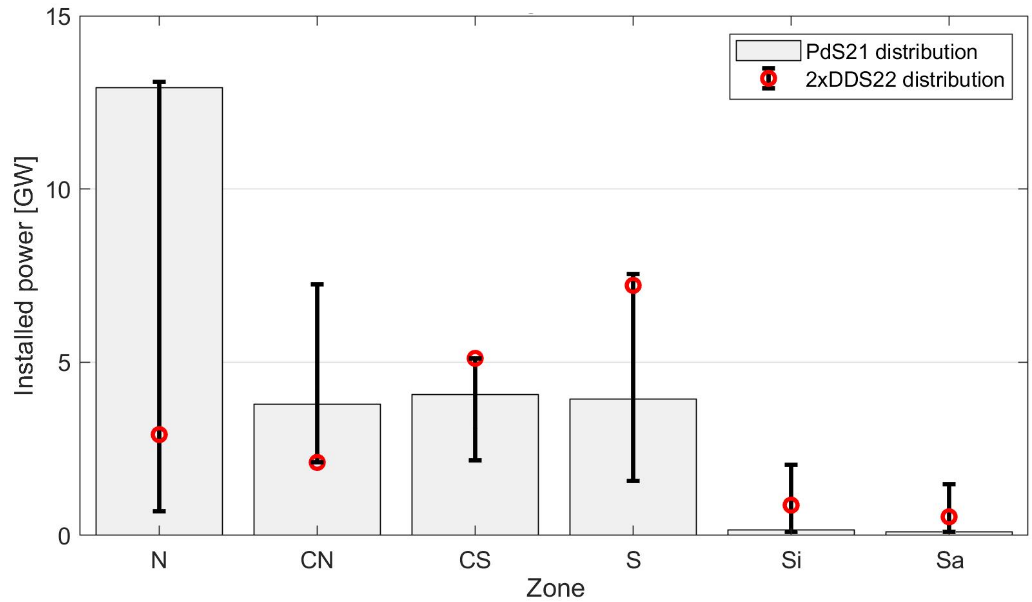


Figure 4.7: Battery storage capacity zonal distribution in the FUS50 scenario. Comparing the distribution obtained using the PdS21 and the 2xDDS22 grid capacities.

the same phenomena, respectively, but with a smaller magnitude. The best plants siting is the one that exploits as much as possible the grid to meet the loads in the North region with energy generated in the southern ones. Only any additional capacity between zones Center-North and Center-South, not exploitable in this way, can induce a shift in the installed capacity between these two zones.

It's interesting to note that while the relative change in the distribution is quite different in the two scenarios, absolute values are actually quite similar: as an example we can notice that the photovoltaic capacity decrease in zone North is around 50 GW in both cases. Indeed the amount of generation capacity that can be shifted is a function of the absolute value of the transmission capacity increase, that is the same in both cases, which makes this a reasonable behaviour. Nevertheless, as Figure 4.9 shows, the cost reduction gained from these changes overcome the cost of a stronger grid only in the 100%RES case, while it only equals them in the FUS50 case, with no relevant impact on the final LCOTE value.

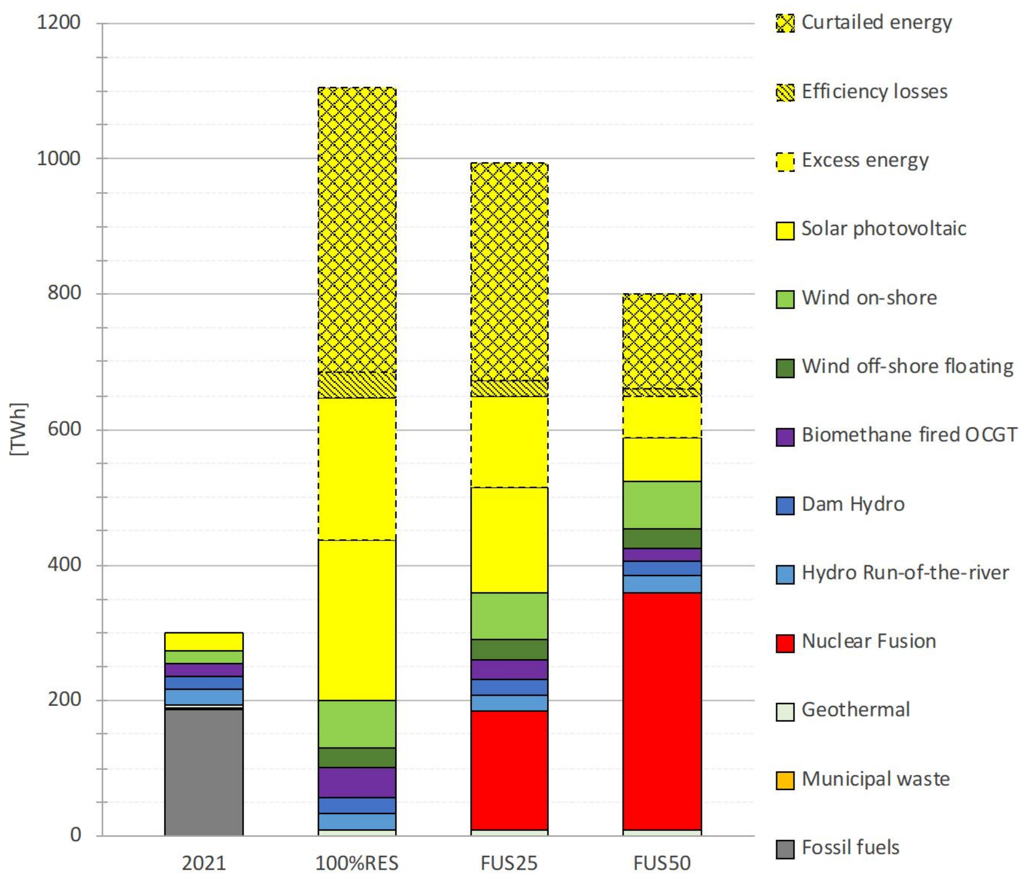


Figure 4.8: Electricity generation by technology with details on the excess energy (curtailed energy and energy losses due to storage efficiency). Generation siting optimized with PdS21 grid configuration.

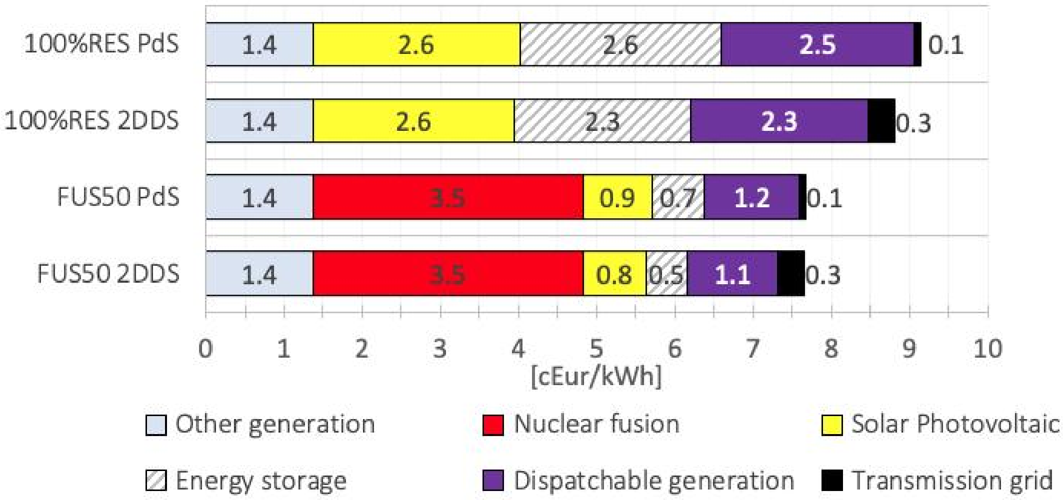


Figure 4.9: LCOTE cost components in scenarios 100%RES and FUS50 with least-cost power plant siting and increasing transmission grid capacity.

4.4 Conclusions

This study analysed different Italian decarbonized power generation systems with the aim to explore how and to what extent they can take technical and economic advantages from a bold baseload low-carbon generation, like the one from future nuclear fusion power plants. In line with previous works, the average levelized system cost of electricity (LCOTE) decreases as much as the fusion power capacity increases, as far as fusion costs are in line with the current estimations. When the constraints given by the transmission grid to power flows among zones are simulated, the LCOTE increases (+20%) because higher flexible generation and storage capacity are needed to cover the zonal electricity demand, in face of the mismatch between demand and variable generation. If constraints on the location of generation capacity are relaxed, the least cost arrangement corresponds to generation capacity zonal distribution proportional to zonal loads. Nevertheless, the equilibrium changes if the transmission line capacities are increased. Indeed, a portion of both photovoltaic generators and batteries capacities are shifted to areas with higher solar potential and lower electricity demand. The two factors are beneficial in 100%RES scenarios as the economic burden due to the transmission grid enhancement is lower than the benefits of reducing the installed storage and flexible capacity, thus leading to a net 4% LCOTE reduction. Instead, if a bold firm base load generation is available and it is distributed proportionally to demand, whatever the transmission grid configuration, the LCOTE does not change as the economic burden of a larger transmission grid equals the benefits of lower flexible and storage capacities.

These analyses confirm that, when dealing with systems relying on a relevant share of variable renewable generation, it's crucial to take into account the requirements of the power system in terms of transmission capacity, storage systems and flexible generation. Actually, if we look at the costs breakdown in Figure 4.9, we can notice that when fusion generation is introduced in the energy mix, the cost of energy generation actually grows, but the LCOTE lowers due to the lower requirements (and related costs) in terms of the three aforementioned system assets. This is the reason why, even assuming very optimistic cost reduction for renewable generation technologies (in particular photovoltaic generation), the optimal system configuration is the one including a major generation share from fusion energy. As it happens, even if we unrealistically assume that we could entirely eliminate the costs of photovoltaic generation, the LCOTE of 100%RES and FUS50 scenarios presented in this study would settle down nearly to the same value, as it can be easily seen from figure 4.9

Finally, besides providing economic benefits, a bold firm baseload low-carbon generation can also limit the environmental impact of the decarbonization process. Indeed, further transmission grid enhancements wouldn't be required and land occupation by solar and storage plants would be much limited as compared to a fully-renewable generation (-70% and -20% installed capacity, respectively).

Chapter 5

The seasonal storage role and the "Fusion to Hydrogen" option

In the following chapter long term scenarios for the Italian power system are presented. In scenarios with relevant shares of intermittent renewable power generation, the hourly mismatch between demand and generation has to be managed by a combination of short-term energy storage systems and flexible dispatchable generation, to be possibly operated along with long term (seasonal) storage systems (e.g. power-to-gas). Being hydrogen currently considered a promising asset in the energy transition [72, 73], the scenarios discussed in this chapter aim at investigating how and to what extent a base-load generation technology like fusion and a seasonal storage infrastructure based on power to hydrogen to power (P2H2P) might improve the system reliability and mitigate its costs, in comparison to a solar-based system (typical of a southern EU Country like Italy). Moreover, alternative ways for hydrogen production are investigated, namely, by electrolysis powered by either dedicated fusion power plants or excess electricity during surplus events. The results described in this chapter are also discussed in the paper "The Fusion to Hydrogen option in a carbon free energy system" currently submitted for publication in IEEE Access [74].

5.1 Analysis rationale

The energy scenarios reported in this study analyse the impact of two power system assets on the costs of a fully decarbonized Italian electricity system, namely: firm base-load carbon-free electricity generation from nuclear fusion power plants and long-term energy storage based on the Power-to-Hydrogen-to-Power (P2H2P) strategy. Being Italy a country with a high solar potential and a relatively limited wind potential compared to northern European countries, the exploitation of long-term energy storage options is particularly relevant. Indeed, photovoltaic generation features lower capacity factors (i.e. higher power fluctuations for a given amount of generated energy) and higher fluctuation of the monthly generated energy, as it was shown in Figures 1.7 to 1.12. These features suggest that the availability of both long and short term storage systems, rather than just the second ones, could be a key element in the integration of high shares of photovoltaic generation in an energy mix.

In fact, previous studies carried out with COMESE [47], including the scenarios descried in Chapter 4, show that the availability of a firm base-load technology is beneficial in terms of overall system costs, when compared to alternative power system configurations relying only on variable renewables and short term storage technologies. They also show that, although a relevant share of curtailed energy is present in both cases, in the latter it is much larger. Curtailed energy is mainly related to the seasonal mismatch between renewable generation and electricity demand: long-term storage systems might make that energy available for loads even after a long time, enhancing the value of otherwise curtailed energy, and reducing the need for both additional generation capacity and alternative (and more expensive) sources of energy. In this context long term energy storage could contribute to lower the cost in both system configurations, but also equalize the economic performance of the two, or even make the one entirely relying on renewables the chaepest one.

Indeed, P2H2P could also operate as a short term storage technology to be used either together with batteries and pumped hydro, or in place of them. Moreover, hydrogen reserves can be used as CO2-free fuel to feed flexible generators (e.g. fuel cells or hydrogen turbines), enlarging the otherwise limited availability of this kind of generators (biomethane OCGT and hydroelectric dam plants) of which fully decarbonized electricity systems are likely to lack [67].

In a future fully decarbonized energy system hydrogen is very likely to be used as an energy vector in some hard to abate energy sectors (e.g heavy industries, such as steel, e-fuels, fertilizers production, and long distance transport) [72, 73]. In fact, as it will be described more in detail in section 5.2, out of the electricity demand considered for the analyses reported in this paper, a base-load addendum supplies electrolysis plants, working at 80% capacity factor, to produce hydrogen to be used in hard to abate sectors. However, the simulation of the hydrogen infrastructure operation (production, storage and use) is limited to hydrogen as an energy vector in a P2H2P storage infrastructure, in a future CO2-free power system with or without a contribution from a firm low-carbon technology such as fusion. Electricity demand related to hydrogen production for other uses is simulated in the same way as the demand from any other sector or type of user, and does not interact with P2H2P operation.

In the power system simulations hydrogen storage and P2H2P infrastructure are modeled, taking into account four different cases: a) In No Hydrogen (NH) scenarios, electrolyzers, fuel cells and hydrogen storage are not available (and consequently their investment costs are not taken into account). b) In Surplus to Hydrogen (S2H) scenarios electrolyzers, fuel cells and hydrogen tanks can be installed.

Electricity generation, whenever exceeding both demand and charging capacity of short term storage systems (batteries or pumped hydro plants), can be used to feel electrolyzers and generate hydrogen. Hydrogen will be stored in hydrogen tanks to be used at a later stage to generate electricity through fuel cells. c) In Surplus to Hydrogen with No Curtailment (S2HNC) scenarios, the same approach is used, but the system is constrained to work without curtailed electricity all over the year. That means that hydrogen infrastructure is forced to use any surplus electricity that may be generated at any hour. d) In Fusion to Hydrogen (F2H) scenarios, three different shares of the base-load fleet of fusion power plants (15, 30 or 45 GW, out of the 50 GW available) are devoted exclusively to hydrogen production through dedicated electrolysis plants working at 80% capacity factor. The F2H case is considered in order to investigate whether increasing amounts of hydrogen, used to fuel flexible generators, might allow a better integration of variable renewables, regardless of surplus electricity exploitation, with a consequent system cost reduction.

In addition, in order to assess the impact of different assumptions on the possible future costs of selected technologies, two cost options were considered, as indicated in section 5.2: a "Net Zero" cost option, where significant cost reductions are assumed and the "Conservative" cost option with more moderate cost reductions from current values.

5.2 Common assumptions

Several assumption described in the following section are the same described in Chapter 4, still, for the sake of clarity, they are recalled together with the ones that have been changed.

5.2.1 Scenario assumptions

As shown in 4, if the constraints due to the power grid operation are taken into account by means of an hourly power flows analysis, power systems fully relying on variable renewable generation (mainly solar photovoltaic) are penalized more than power systems relying on a bold baseload generation fleet. Also, in the specific case of the Italian system, unless strong upgrades of the transmission grid are assumed, a siting same as the zonal load distribution would be recommended both for photovoltaic generation and short term storage systems, in order to lower the overall power system cost. Taking into account these results, the analyses described on this chapter were carried out by means of simulations of the power system under the Copper Plate assumption. This choice was deemed valid since it would penalize scenarios including fusion generation, thus ensuring a conservative approach in the assessment of its beneficial impact.

Removing the power flows analysis lowered the computational burden of the simulations of COMESE, allowing to include more decision variables in the study: this was necessary as in order to simulate effectively P2H2P infrastructure the charging installed power (electrolyzers), the storage system itself (hydrogen tanks) and the power output devices (fuel cells) has to be managed as three independent variables, differently from short term storage systems (batteries) where input power, capacity and output power are dependent variables. By neglecting the power grid constraints, the analyses carried out become also much more generalizable: this is the reason why in these scenarios also floating offshore power has been included in the DVs. Even if with an exploitable potential much lower than solar photovoltaic, offshore wind power can reach significant values of installed power. This has allowed also to have a hint on how this renewable source could integrate under different assumptions on the availability of fusion and P2H2P infrastructure.

Domestic generation is assumed to satisfy the entire electricity demand - neither electricity import nor export are allowed - in order to explore the most demanding circumstances for the country, which must be fully self-sufficient in electricity generation. Modeling international trades would require a Europe-wide analysis that is out of the scope of this study. However, the possibility of exporting excess generation to neighbouring countries is considered in an ex-post analysis discussed in section 5.3.

In the following scenarios, the power system operation is modelled in a generic year of the second half of the century when nuclear fusion power plants are likely to be commercially available. The yearly electricity demand is assumed to be 650 TWh, which is about two times higher than today, that in turn is consistent with the estimations of the Italian long term strategy for greenhouse gas emissions reduction [75]. The demand increase is due to a strong electrification of all major end-use sectors (from the current 21,5% to around 55%), which is expected to be a key measure to achieve the goal of carbon neutrality, in addition to a bold reduction in energy intensity. Specifically, the Italian 2019 gross electricity demand (330 TWh) is increased by 80 TWh for the complete electrification of the domestic and tertiary sector for space heating, hot water production and cooking, 100 TWh for the complete electrification of private transport and 140 TWh for the production of hydrogen to be used in hard to abate end-use sectors, either directly or as e-fuels [75].

The reference hourly demand profile has been derived from the national TSO database [76] to which specific profiles of the foreseeable future additional loads have been added. Concerning the domestic and tertiary sector, the hourly natural gas demand has been converted into electricity demand to power electrical devices (heaters, cookers, heat pumps, etc.) according to the profiles reported in [77] and [78]. As for electric vehicles, the hourly demand profile reported in Fig. 5.1 is adopted, adapted from the "*Tarda sera*" (late evening) profile in [79] by smoothing the night demand profile. Finally, the electricity demand profile for hydrogen production is taken as constant over the year. Due to the high penetration of heat pumps, the daily average/peak electricity demand in cold seasons is almost 30% higher than in the rest of the year. See Figure 4.2 in Chapter 4 for the daily demand profile used in this study and its comparison to two other meaningful demand profiles: the current (2019) French and Italian demand profiles.

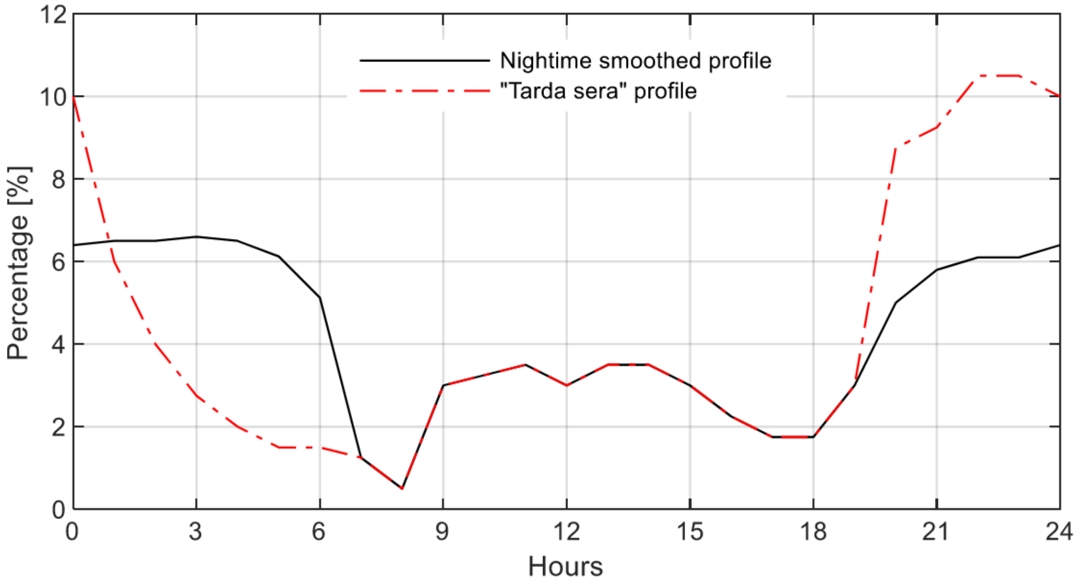


Figure 5.1: Electric vehicles charging profiles.

Installed capacity and production of electricity generation technologies whose potential is already almost completely exploited today, are user-defined and the same values apply in all scenarios. On the contrary, installed capacity of technologies whose potential is still to be exploited are DVs of the optimisation problem. Both are summarized in Table 5.1. In order to set the hourly generation profile of both baseload (geothermal, municipal waste and run-of-river) plants and variable (photovoltaic and wind power plants) generation, the national TSO database for year 2015 [76] is taken as a reference, being 2015 representative of average generation and climate conditions of the last decade. On the basis of the historical data, the generation profiles for each technology are built as described in the following.

As shown in Table 5.1, both installed capacity and annual electricity generation of run-of-river hydro, dam hydro, pumped hydro, geothermal and municipal waste power plants are assumed to not increase by 2050. Corresponding values are taken from the national TSO databases [76]. The hourly profiles of run-of-river hydro power plants generation are derived from the national TSO dataset [76]. Those of geothermal and municipal waste power plants are assumed to be baseload. Dam hydro and pumped hydro storage plants hourly generation is an outcome of the simulation.

50 GW of residential rooftop-mounted PV is assumed to be in operation by 2050, along with 50 GW installed on commercial/industrial rooftops, so as to exploit a major share (75%) of the whole available potential reported in [63], assuming 170 W/m^2 potential per unit area. Differently from what was done in 4, since the distribution of solar generators is not the subject of the study, the installed power of rooftop-

Table 5.1: Installed power and electricity generation per technology

		Installed power [GW]	Electricity generation* [TWh]
Mature technologies			
Hydro Run of River		5.3	25
Dam Hydro		10.5	25
Pumped Hydro storage (η = 80%)		9	0.1
Geothermal		1.2	9.3
Municipal Waste (η = 30%)		0.1	0.8
Technologies under development for which cost reductions are expected			
Photovoltaic	Residential rooftop	50	59
	Ind/comm rooftop	50	66
	Utility scale (w/ tracking)	DV	**
Wind	Onshore	35	70
	Floating offshore	DV	**
Fusion		0 / 50	0 / 350
Biomethane fired OCGT (η = 42%)		DV	**
Electrochemical storage (η = 85%) – 8h storage		DV	-
Electrolysers (η = 70%)		DV	-
Fuel Cells (η = 60%)		DV	-
Hydrogen Tanks and equipment		-	DV*

* Energy capacity for storage technologies.
** Model output.

mounted photovoltaic generators has been set to a less conservative amount. The installed capacity is allocated in the market zones proportionally to the electricity demand. Their hourly generation profiles are derived from 2015 registered generation profiles [76] and simulations based on reanalysis climate datasets for year 2015 [52]. Specifically, the same profile is used for both generators, but in the case of residential rooftops it is scaled so as to match the full load hours currently registered in Italy [76], while for commercial and industrial rooftops it is scaled so as to match the full load hours obtained by the simulations from [52]. This is done in line with the assumption that residential panels are more likely to be installed in a sub-optimal configuration, while commercial and industrial panels can be assumed to reach the maximum available full load hours. Consequently, the zone average value of nominal load hours varies between 1100 and 1350 hours/year for the residential panels, and between 1300 and 1500 hours/year for the commercial and industrial ones, as indicated in Table 5.2.

Due to the country morphology and limited wind speed, the Italian onshore wind capacity is set to 35 GW, still 25% higher than the assumption in the "Fit for 55" PRIMES European scenario [80]. The capacity is assigned to each market zone proportionally to the current geographical distribution, which is a consequence of local average wind speed. As a consequence, 96% are in the Centre-South, South, Sardinia and Sicily zones. The nominal load hours varies as indicated in Table 5.2 with an average value of 2000 hours/year, which is the same as in [80]. Fusion power plant installed capacity, when available, is set to 50 GW, generating 350 TWh/y (80% capacity factor), which is 54% of the total electricity demand. To better match demand and generation profiles, we assume that annual maintenance activities are planned so as to allow 90% of the installed capacity to be in operation from October to March, 70% otherwise. Figure 4.3 in Chapter 4 shows a detailed comparison between daily demand and daily generation between this generation strategy and a constant power output alternative. As indicated in Table 5.1, the installed capacities of the remaining generation technologies (namely, ground mounted utility scale photovoltaic, offshore floating wind generators and OCGT generators fuelled by biomethane) are the DVs of the optimization problem.

We assume a theoretical land area availability as wide as 20000 km^2 for utility scale ground mounted PV systems, which is half the difference between the total available agricultural land and the portion presently used for farming activities [62]. In addition, we assume that the in utility scale PV plants generators are equipped with mono-axial tracking. Consequently, the upper boundary set for the installed capacity of photovoltaic generators, which is a DV, is set at 800 GW. As explained in the introduction of this chapter, whatever the total installed capacity, such PV plants are distributed among the market zones with a fixed distribution, which is proportional to the electricity demand, coherently with the results discussed in Chapter 4. Their hourly generation profiles are derived from simulations based on reanalysis climate datasets for year 2015 [52]. Consequently, the zone average value of nominal load hours varies between 1650 and 1950 hours/year.

Due to seafloor depth of Italian offshore windiest sites, floating offshore wind is a necessary, though more complex and expensive, technological choice. In the simulations we assume that the floating offshore wind capacity, which is a DV, reaches a maximum value of 50 GW (13 times higher than in [80]). Whatever the total installed capacity, plants are evenly distributed throughout the three windiest zones (one third in the South market zone, one third in Sicily and one third in Sardinia). The hourly generation profiles are taken from a wind database [81] and adjusted so that the average value of the nominal load hours is optimistically set at 3000 hours/year (which is 15% higher than in [80]).

OCGT plants fuelled by biomethane are available to generate dispatchable electricity with a high degree of flexibility. The installed capacity is a DV, while the generated electricity cannot exceed 45 TWh. This value derives from the national bio-methane potential (107 TWh, as in [82]) with turbine efficiency of 42%.

Storage technologies include batteries with 8 hours storage as well as the infrastructure needed to produce, store and finally convert hydrogen into electricity, i.e. electrolyzers, hydrogen thank and fuel cells, respectively. As shown in Table 5.1, batteries, electrolyzers and fuel cells installed capacities as well as hydrogen tanks size are DVs, on which no upper bounds are imposed.

Due to the uncertainties on the future cost evolution of the electricity generation and storage technologies, two cost options are considered, namely "Conservative" and "Net Zero", corresponding to moderate and relevant cost reductions by 2050, respectively (Table 5.2). The aim is to investigate the impact of key technologies still under development, which are likely to experience cost reduction due to further technological learning. Generation technologies are photovoltaic (both rooftop and utility scale) and offshore floating wind power, while storage technologies are batteries and P2H2P infrastructure, excluding the hydrogen tanks.

Regarding photovoltaic, in [83] cost breakdown is reported for existing plants together with cost ratio between ground mounted utility scale plants, industrial rooftop plants and residential rooftop plants. In the “Conservative” cost option, assuming a capital cost (CAPEX) reduction from 300 €/kW to 50 €/kW by 2050 for the modules, the final capital cost for a utility scale plant results 550 €/kW. Then, by keeping the same ratio among residential, industrial and utility scale plants as in [83], the resulting capital cost is 1200 €/kW for residential rooftop installations and 950 €/kW for industrial/commercial rooftop installations. On the other hand, in the “Net Zero” cost option, the capital cost of utility scale plants is the same as the "Net Zero" cost in [64], i.e. 340 €/kW. Keeping the same ratio among different type of plants, the capital cost for residential installations becomes 750 €/kW and that of industrial/commercial installations 600 €/kW.

As for offshore floating wind plants, for the “Net Zero” cost option, capital cost is taken from [84, 85]. In the “Conservative” cost option, the capital cost is set at 3000 €/kW, i.e. 50% higher than that reported in [84].

Highly diverging opinions on future cost reductions of batteries are reported in [86]. For the "Net Zero" cost option, the capital cost reported in [64] is used, i.e. 1080 €/kW (corresponding to 135 €/kWh). Under the “Conservative" cost options, the capital cost of storage plants is assumed to be 50% higher as that reported in [64], i.e. 1600 €/kW (corresponding to 200 €/kWh).

As for hydrogen infrastructure, in the “Conservative” case, capital cost of electrolyzers is expected to be as high as in the “Stated policies” scenario in [64] and in [86], i.e. 445 €/kW, while the capital cost of fuel cells reaches the same value as in [86], i.e. 800 €/kW. In the "Net Zero" case, electrolyzer capital cost is assumed as large as in "Net Zero" scenario in [64], i.e. 230 €/kW, while fuel cell capital cost is half that in the "Conservative" case. Hydrogen Tanks, on the other hand, are a conventional technology for which a much lower uncertainty in cost projection can be assumed. Their cost is assumed to be 95 €/kg H_2, as reported in [72], in all cases.

In Table 5.2, both capital and operation and maintenance costs, together with lifetimes and capacity factors adopted in the LCOE and LCOTE calculation are listed per each technology, for both the "Net Zero" and the "Conservative" case.

Table 5.2: Cost and lifetime options for mature and under development technologies composing the electricity generation mix (values in brackets refer to the "Net Zero" cost option).

		CAPEX [€/kW]		OPEX [€/kWy]	lifetime [y]	Full load hours[1] [h]	LCOE [c€/kWh]	
Mature technologies								
Hydro Run of River[2]		5600		75	60	3100 - 5200	8.9	
Dam Hydro[2]		3400		70	60	2300	-	
Pumped Hydro (η = 80%)[2]		1500		30	60	-	-	
Geothermal[2]		3600		80	30	7900	4.1	
Municipal Waste (η = 30%)[2,3]		4500		140	25	7000	0.5	
Technologies under development for which cost reductions are expected								
Photovoltaic	Residential rooftop	1200	(750)	12	25	1100 - 1350	8.0	(5.3)
	Ind/comm rooftop	950	(600)	10	25	1300 - 1500	5.9	(4.0)
	Utility scale (tracking)	550	(340)	12	25	1650 - 1950	2.6	(1.7)
Wind	Onshore[4]	1300		30	25	1250 - 2400	5.9	
	Floating offshore	3000	(2000)	70	30	3000	9.2	(7.0)
Fusion[5]		6000		110	60	7000	6.4	
Biomethane fired OCGT (η = 42%)[6]		550		20	30	-	-	
Batteries (h= 85%) – 8h storage		1600	(1080)	20	10	-	-	
Electrolysers (η = 70%)		445	(230)	10	20	-	-	
Fuel Cells (η = 60%)		800	(400)	10	20	-	-	
Hydrogen Tanks and equipment (€/kg H_2)[7]		95		-	20	-	-	

[1] The ranges indicate minimum and maximum nominal load hours considering different geographical locations with different generation potential.
[2] Average values as reported in by the EU SET plan SETIS database [57].
[3] Fuel cost is assumed to be negative, -80 €/ton.
[4] Value from IEA Net Zero scenario for the EU [64], with unitary currency conversion rate.
[5] CAPEX, OPEX and LCOE of a future fusion power plant are derived from the literature for a DEMO-like commercial power plant [61].
[6] The cost of biomethane (0.92 €/m^3) derives from the assumptions of digesters (CAPEX: 1,800 €/kW - OPEX: 3%) operating with 90% capacity factor and biomass cost of 5 €/GJ [65]. The result is in line with the estimation reported in [66].
[7] Costs of large tanks and related auxiliaries for hydrogen storage are reported in [72].

5.2.2 Hydrogen strategies

As introduced in section 5.1, four different cases are considered concerning the possible use of hydrogen infrastructure. All scenarios are optimized exploiting the DE algorithm in order to find the combination of the chosen decision variables that outlines the least cost system design. For the first 3 cases, both a fully renewable power system (hereafter referred as "100%RES" scenario) and a system including 50 GW baseload fusion generation ("FUS50" scenario) are considered. In the fourth case, a 50 GW fusion power plant fleet is always available, and the chance to devote different shares of its power output eclusively to the production of hydrogen is investigated with three scenarios:

NH In No Hydrogen scenarios, no installation of electrolyzers, fuel cells and H_2 storage is foreseen, thus the DVs are the capacity of ground mounted utility scale photovoltaic, floating offshore wind, biomethane fueled dispatchable generators and electrochemical battery storage. Since flexible generation is limited by domestic biomass production potential and no seasonal storage is available, in this case a rather high renewable capacity is expected to be necessary, along with a large amount of curtailed energy, as suggested by the scenarios discussed in Chapter 4.

S2H In Surplus to Hydrogen scenarios, the hydrogen infrastructure, namely electrolyzers, fuel cells and H2 storage tanks, are included in the electricity system, and their capacities are added as DVs to the ones previously mentioned. The optimization routine of the COMESE code searches then for the optimal amount of excess electricity, which would be otherwise curtailed, to be converted into Hydrogen and used to generate electricity at a later stage.

S2HNC In Surplus to Hydrogen with No Curtailment scenarios a further constraint is imposed: no energy curtailment is allowed, i.e. all the excess electricity must be used either to charge batteries or to supply electrolyzers. This implies a rather high storage capacity and a smaller renewable capacity than in the previous cases. Specifically, since it was already proven that system relying on short term storage include a large share of curtailed energy, this constraint is implemented by forcing the P2h2P infrastructure, which could actually modify this trend, to absorb any surplus generation. DVs are the same as in the previous case.

F2H In Fusion to Hydrogen scenario part of the fusion power plants supply in-situ electrolysers, operaing at 80% capacity factor. As already said in section III, three scenarios are considered with 15 GW, 30 GW and 45 GW, out of the 50 GW fusion plants fleet, dedicated to hydrogen production. This scenarios aim at investigating whether the high capacity factor of the hydrogen infrastructure can positively affect the system cost, exploiting fusion generation to make available a significantly larger amount of flexible energy with respect to previous scenarios. These scenarios will be referred to as "F15", "F30" and "F45".

5.3 Results and discussion

As shown in Figure 5.2, the first clear result is that both with and without an H2 infrastructure to operate as storage system, the availability of a baseload generation technology, such as nuclear fusion, allows to lower the LCOTE. Indeed, under both cost options, the FUS50 scenario has always lower LCOTE: under the "Conservative" cost option it ranges from 8.6 to 9.3 c€/kWh, as compared to the 100%RES scenarios where LCOTE is 30%, 28% and 31% higher in NH, S2H and S2HNC cases, respectively. On the other hand, as expected, under the "Net Zero" cost option the gap narrows: for 100%RES scenarios LCOTE is 14%, 12% and 17% higher than for FUS50 scenarios, in NH, S2H and S2HNC cases, respectively.

The LCOTE breakdown, summarized in Table 5.3, shows that the presence of fusion reduces the cost components due to storage systems (both short term and H2 infrastructure) and flexible generation much more than it increases the component due to both baseload and variable generation. As shown in Table 5.2, in this study fusion capex is assumed as large as 6000 €/kW; however, sensitivity analises have been carried out to asses up to what value the LCOTE of FUS50 scenarios remains cheaper than that of 100%RES scenarios, as described more in detail in the following. Another clear result also evident in Figure 5.2 is that in case F2H, whatever the share of fusion fleet dedicated to hydrogen production, the LCOTE is always higher than that of any FUS50 scenarios under the same cost options.

Instead, the availability of H2 infrastructure doesn't have a unique impact on LCOTE. In fact, as shown in Figure 5.2, scenarios in the S2H case are slightly cheaper than in NH case, but those in the S2HNC case are more expensive. Namely, the LCOTE of 100%RES is 4% lower in the S2H case than in NH case, under both the "Conservative" and the "Net Zero" cost options. In fact, as shown in Table 5.3, generation cost component remains almost unchanged, while the LCOTE reduction is mainly due to the reduction of short term storage systems capacity that are to a large extent more effectively replaced by H2 infrastructure. Also FUS50 scenarios show a similar behavior, with a lower (2.3%) LCOTE reduction, under both the "Conservative" and the "Net Zero" cost options, due to the fact that in these scenarios the storage cost component is less relevant. On the contrary, as shown in Table 5.3, in the S2HNC case, LCOTE component due to generation shows a rather negligible change, while the components due to H2 infrastructure grow significantly. In fact, short term storage systems are almost entirely removed, and so their cost contribution, but the higher installed capacity of all the H2 infrastructure components makes the LCOTE higher than in NH case. Figure 5.2 shows that, under the "Conservative" cost option, the LCOTE of 100%RES scenarios is 6% higher in the S2HNC case than in NH case, while, under the "Net Zero" cost option, the LCOTE is 9% higher. A 6% incease is found for FUS50 scenarios, under both cost options.

The results show that the hydrogen infrastructure has a negligible impact on the total wasted energy. Indeed, it is worth noticing that in the the S2H case, 100%RES scenario, the total electricity generation

Figure 5.2: Optimization results in terms of a) installed power b) generated energy c) overgeneration, energy curtailment and losses. The total demand, equal to 650 TWh, is reported in dashed line.

is almost the same as in the NH case (only slightly smaller than in the NH case, under the "Conservative" cost option and slightly larger than in the NH case, under the "Net Zero" cost option). This means that, as shown in Figure 5.2, the amount of wasted energy (curtailment added to efficiency losses) is almost the same. However in the S2H case, curtailed energy decreases and efficiency losses increase in comparison with the NH case, due to the operation of H2 storage systems, which replace a relevant amount of short term storage and operate with a lower round-trip efficiency than short term storage. Also in FUS50 scenarios, the H2 infrastructure does not reduce significantly the amount of overgeneration. However, in this case it is slightly higher than in the S2H case, under the "Conservative" cost option, and a little lower under the "Net Zero" cost option.

Indeed, in both 100%RES and FUS50 scenarios, the amount of energy finally delivered to the loads by the storage systems is very similar in the NH and S2H cases (for the 100%RES scenarios 172 vs 160 TWh; for the FUS50 scenarios 55 vs 57 TWh, respectively); however, as in the S2H case P2H2P is available, the installed power of short term storage systems, i.e. batteries and pumped hydro, is much smaller than in the NH case (see Table 5.4). This means that in the S2H case, the H2 infrastructure in not acting as a seasonal storage system. As a consequence, the LCOTE reduction achieved in the S2H case is not linked to a reduction of wasted energy, as previously pointed out. This can be better understood looking at the performance of the H2 storage infrastructure. For instance, in 100%RES scenario, under the "Conservative" cost option, it features 69 full load hours in charge and 90 full load hours in discharge and make use of a 103 kton (4 TWh) H2 thank. This is even more evident in the FUS50 scenario of the S2H case, where the full load hours of the H2 infrastructure reduce to 24 (charge) and 23 (discharge) and a 13 kton (0.5 TWh) H2 thank is installed. As can be clearly seen from Figure 5.3, the capacity of the hydrogen tanks is not compatible with the postponement of a sufficient amount of surplus energy to a period with significant undergeneration from renewables and baseload generation. Indeed also the full load hours of the P2H2P infrastructure confirms it, since a postponement of months and not just days would be necessary. It is then clear that in the S2H case the P2H2P infrastructure is behaving as a short to medium term storage system rather than a seasonal one.

Looking at the S2HNC case, it must be pointed out that forcing the system to operate without energy curtailment implies the search for a suboptimal solution, since the S2H case shows that, in the minimum LCOTE solution, curtailment is present and the H2 infrastructure is not operating as long term energy storage. Nonetheless, the S2HNC case is considered in order to investigate what kind of system would be achievable under this constraint. A different system configuration and operation logic such as one that minimize wasted energy could lower the need for important factors, crucial to policy makers, such as construction materials and land occupation, and highlight the magnitude of the resulting system overcosts. The configuration designed is then the least cost one that exploits entirely the surplus energy.

Unlike in the S2H case, in both scenarios of the S2HNC case we observe a strong reduction of

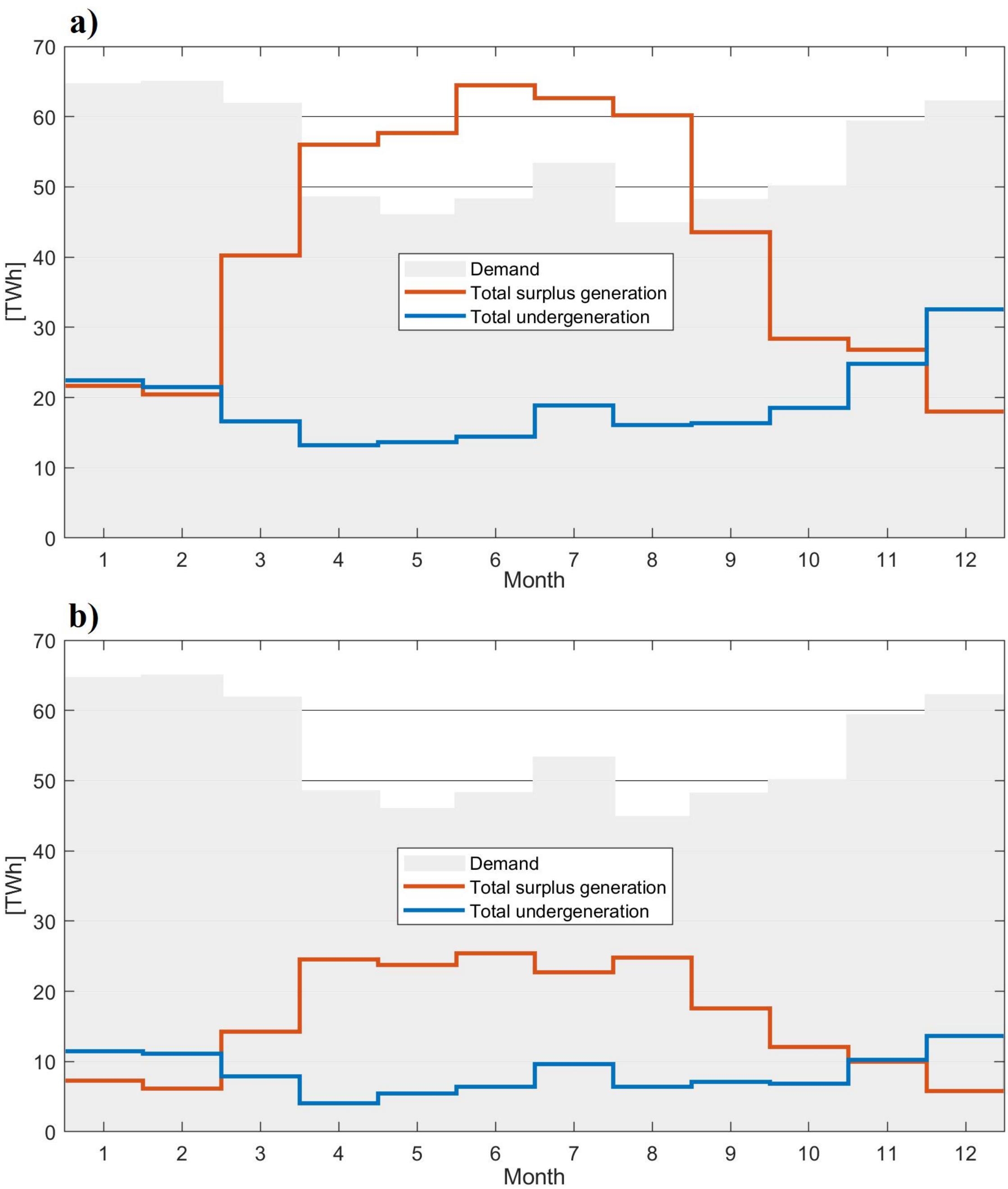


Figure 5.3: Monthly distribution of generation from photovoltaic, wind power and fusion generators, compared to the monthly distribution of the electricity demand.

Table 5.3: Optimization results in terms of LCOTE [c€/kWh] for a) Conservative cost option and b) Net zero cost option.

	LCOTE	*Baseload + variable generation*	*Flexible generation*	*Short term storage systems*	*P2H2P infrastructure*		
					Electrolysers	*Fuel cells*	*Hydrogen Tanks*
a)			Conservative cost option				
NH							
100%	11.5	*6.2*	*2.4*	*2.8*	*0.0*	*0.0*	*0.0*
FUS50	8.8	*6.3*	*1.7*	*0.8*	*0.0*	*0.0*	*0.0*
S2H							
100%	11.0	*6.3*	*2.5*	*1.3*	*0.5*	*0.3*	*0.1*
FUS50	8.6	*6.5*	*1.5*	*0.2*	*0.2*	*0.2*	*0.02*
S2HNC							
100%	12.2	*6.0*	*2.6*	*0.3*	*1.4*	*0.6*	*1.2*
FUS50	9.3	*6.2*	*1.6*	*0.2*	*0.7*	*0.2*	*0.5*
F2H							
F15	9.9	*7.2*	*1.5*	*0.6*	*0.1*	*0.2*	*0.3*
F30	11.0	*8.0*	*1.7*	*0.5*	*0.2*	*0.3*	*0.4*
F45	12.1	*8.4*	*2.2*	*0.4*	*0.3*	*0.4*	*0.5*
b)			Net Zero cost option				
NH							
100%	9.0	*4.6*	*2.3*	*2.0*	*0.0*	*0.0*	*0.0*
FUS50	7.9	*5.9*	*1.2*	*0.7*	*0.0*	*0.0*	*0.0*
S2H							
100%	8.6	*4.7*	*2.2*	*1.0*	*0.4*	*0.2*	*0.1*
FUS50	7.7	*5.9*	*1.2*	*0.3*	*0.1*	*0.1*	*0.01*
S2HNC							
100%	9.8	*4.6*	*2.5*	*0.2*	*0.9*	*0.4*	*1.2*
FUS50	8.4	*5.6*	*1.5*	*0.2*	*0.4*	*0.1*	*0.5*
F2H							
F15	8.8	*6.5*	*1.4*	*0.4*	*0.1*	*0.1*	*0.2*
F30	9.6	*6.8*	*1.4*	*0.5*	*0.1*	*0.2*	*0.5*
F45	10.5	*7.2*	*1.8*	*0.4*	*0.2*	*0.3*	*0.5*

short term storage systems installed capacity, excluding pumped hydro systems, whose capacity is not a DV. As shown in Table 5.4, under the "Conservative" cost option, the 100%RES scenario includes only 5 GW of electrochemical storage (79 GW in the NH case and 33 GW in the S2H one), while in the FUS50 scenario almost no electrochemical storage capacity is necessary. Under the "Net Zero" cost options, almost no electrochemical storage capacity is present. Moreover, in the 100%RES scenario, the total photovoltaic installed capacity is about 30% lower (almost 150 GW less) than in both the NH and S2H cases, under both cost options, while floating offshore wind capacity reaches its maximum allowed value, i.e. 50 GW, under both cost options.

In fact, overgeneration is mainly due to the seasonal unbalance in the photovoltaic plant output. Therefore, meeting the zero curtailment constraint calls for minimizing their capacity and installing as much as possible both floating offshore wind, which is much closer to a baseload operation than photovoltaic (and therefore less demanding for the H2 infrastructure) and biogas power plants (see Table 5.4). In the FUS50 scenario, the total photovoltaic capacity is 24% and 14% smaller than in the S2H and NH cases, respectively, under the "Conservative" cost option, and 30% and 33% smaller than in the S2H and NH cases, under the "Net Zero" cost option, while floating offshore wind capacity is still almost zero, like in the S2H and NH cases, for both cost options. The neat difference for the wind power capacity between 100%RES and FUS50 scenarios can be explained considering that the less fluctuating seasonal generation distribution of wind power is probably less beneficial for the second ones, being FUS50 scenarios already relying on a major baseload generation fleet. Figure 5.4 recalls the difference between the monthly generation profile of photovoltaic, wind power and fusion, and compares it to the monthly load.

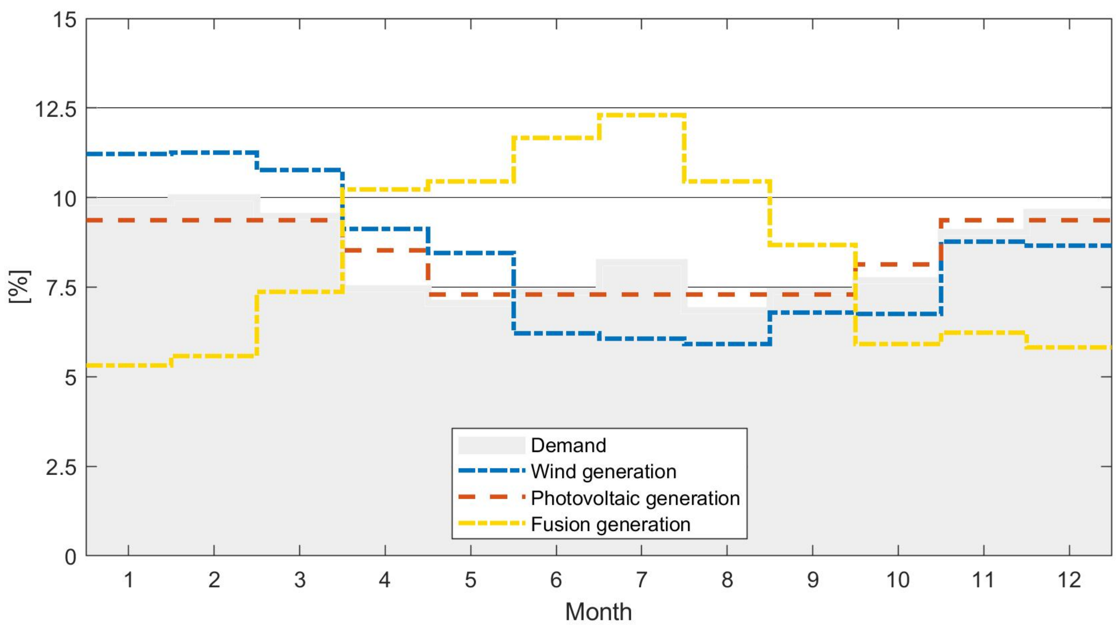


Figure 5.4: Monthly distribution of generation from photovoltaic, wind power and fusion generators, compared to the monthly distribution of the electricity demand.

As for the H2 infrastructure, Table 5.4 shows that in the 100%RES scenario the electrolyzer capacity

(a)	NH		S2H		S2HNC			F2H	
	100%RES	FUS50	100%RES	FUS50	100%RES	FUS50	FUS15	FUS30	FUS45
Generation									
Utility scale photovoltaic	359	70	336	93	219	47	114	120	128
Offshore wind power	32	0	39	1	50	0.5	14	31	40
Biomethane fired OCGT	40	24	49	37	61	35	40	45	52
Energy Storage									
Batteries (8h storage)	79	18	33	2	5	0.5	14	9	7
Electrolyzers	-	-	78	33	219	101	15	30	45
Fuel cells	-	-	25	15	50	18	13	23	33
Hydrogen Tanks [TWh]	-	-	4	0.5	32	13	7	11	13

(b)	NH		S2H		S2HNC			F2H	
	100%RES	FUS50	100%RES	FUS50	100%RES	FUS50	FUS15	FUS30	FUS45
Generation									
Utility scale photovoltaic	369	118	375	108	227	46	127	149	171
Offshore wind power	31	0	34	0	50	1	16	23	35
Biomethane fired OCGT	39	19	46	30	63	36	38	33	50
Energy Storage									
Batteries (8h storage)	78	24	35	7	0	0.2	13	14	10
Electrolyzers	-	-	100	34	224	100	15	30	45
Fuel cells	-	-	23	14	53	18	13	21	35
Hydrogen Tanks [TWh]	-	-	2	0.4	33	13	7	15	14

Table 5.4: Optimized system configuration in terms of installed capacity [GW] for each decision variable, under the a) "Conservative" and b) "Net Zero" cost options.

is much larger -more than double- than for the S2H case: 219 vs 78 GW, and 224 vs 100 GW, under the “Conservative” and “Net Zero” cost options, respectively. This was indeed expected, since the electrolysers installed power must be as large as the maximum power surplus event in order to meet the zero curtailment constraint. On the contrary, the fuel cell capacity growth is more modest than that of electrolyzers (50 GW in the S2HNC case against 25 GW in the S2H case and 53 against 23 GW, under the "Conservative" and "Net Zero" cost options, respectively). In fact, fuel cell capacity is driven by undergeneration events, whose magnitude is much smaller than that of surplus. Finally, the H2 tank size is the H2 infrastructure component with the highest growth: it is around 8 and 16 time larger than in the S2H case, under the "Conservative" and "Net Zero" cost options. In fact, the H2 tank size depends on the maximum level of energy that must be stored, and it’s function of the magnitude and frequency of both surplus (charge) and undergeneration (discharge) events. Given the sizes of the different components of the H2 infrastructure just mentioned for the 100%RES scenario, the full-load hours are 209 in charge and 384 in discharge, and 210 and 374, under the "Conservative" and "Net Zero" cost options, respectively. Since the system is forced to exploit seasonal storage, the full load hours of H2 infrastructure grows consequently.

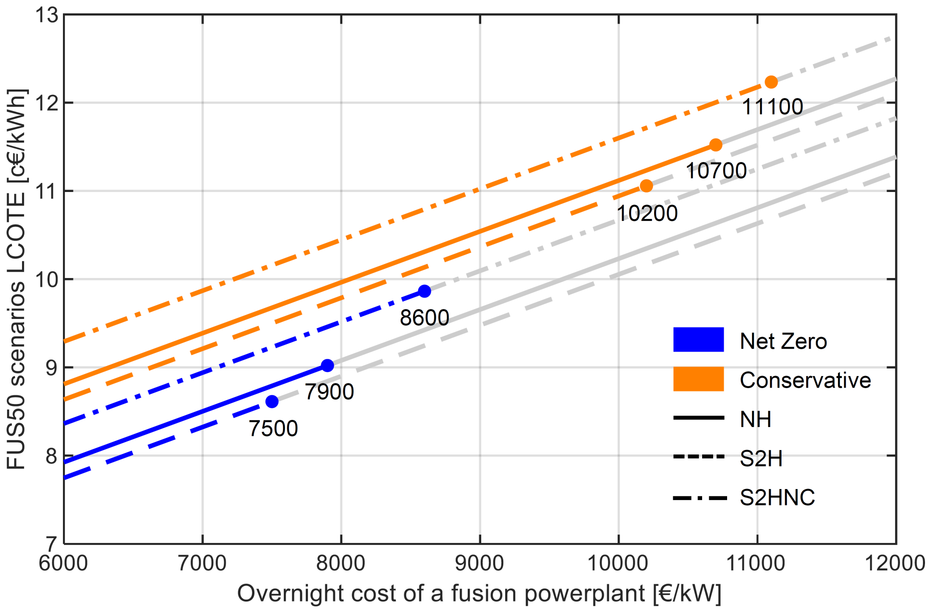


Figure 5.5: LCOTE sensitivity analysis.

As previously anticipated, all the FUS50 scenarios have undergone a sensitivity analysis, in order to find out up to what fusion capital cost the use of such technology remains beneficial in the described scenarios. These analyses answer the following question: up to what fusion capital cost, a system designed under the assumption of 6000 €/kW for fusion power, and expected to be cheaper than a 100% renewable based system, remains that way? Results show that the breakeven fusion capex depends mainly on the cost option considered, i.e. on the economic competitiveness of alternative storage and generation technologies, but also on the specific case considered (NH, S2H and S2HNC), and varies from 7500 to 8600 €/kWh for the "Net Zero" cost option and from 10200 to 11100 €/kWh for the "Conservative" cost option, as shown in Figure 5.5.

As explained in section 5.2, simulations are carried out under the conservative assumption that neither electricity import or export are viable options during the system operation. Nonetheless, since the results show that overgeneration and curtailed energy remain a relevant feature for all the cases but S2HNC, where a zero curtailment constraint is deliberately set, a check on the maximum yearly exportable energy is done. Considering the curtailed energy profiles and the current 11 GW Italian cross-border transmission capacity [87] the maximum energy export ranges for 24 TWh (in FUS50 scenarios) to 33 TWh (in 100%RES scenarios), under the optimistic assumption that all possible energy export is actually imported by neighbour countries. These figures represent 27% and 10% of the curtailed energy, respectively. Even assuming a strong upgrade of connection wtith foreign countries, resulting in a transmission cross-border capacity twice as large as the current one, the potential energy export would range between 34 a and 60 TWh, corresponding to 38% and 18% of the curtailed energy. This result confirms that the curtailment of major amounts of energy in all likelihood will be a feature of any future fully decarbonized power system, unless the system design is specially made to prevent it. While energy exchange with foreign countries can for sure bring benefits to the system operation and costs, it's unreasonable to think that it can be used to manage all surplus energy not needed by the national users.

5.4 Conclusions

The study confirms that in zero-emission solar-based energy systems, firm baseload electricity generation by fusion power plants does contribute to lower the system cost of electricity. Indeed, if the fusion fleet is as large to cover half of the demand, the renewable capacity necessary to meet the remainder is far more than halved as compared to a 100% renewable energy system, while the overall generation and storage capacity is almost halved. As a consequence, less flexible generation and storage assets are required, with clear benefits on costs, as well as on the amount of material requirement and land occupation.

If P2H2P is deployed as storage technology, it allows to slightly decrease the overall system cost, replacing part of the electrochemical storage capacity. However, although potentially capable of operating as a long term storage, P2H2P infrastructure is used for short term storage. If P2H2P is operated as long term energy storage, in order to achieve a zero curtailment system, then the overall system cost increases.

A bold base load generation also reduces the amount of both excess and curtailed energy. This study also shows that converting the whole excess energy into hydrogen to prevent curtailment is not the most effective strategy. Indeed, due to the higher costs of the hydrogen infrastructure, mainly of the tanks for H2 storage, the overall LCOTE increases.

Finally, due to the low overall efficiency of the P2H2P process, also operating fusion for H2 production for long term storage is not a cost effective strategy.

To conclude, as long as the capex of nuclear fusion power plant is lower than 10200 eur/kWh and 7500 eur/kWh, under "Conservative" and "Net Zero" cost options respectively, the cheapest option for carbon-free generation is a power system where fusion delivers half of the electricity demand, operates jointly with renewables, and excess energy is made available for meeting the load by a mix of electrochemical storage and P2H2P storage, without any seasonal storage strategy.

Conclusions

This thesis presents the main research activities that I carried out during my Ph.D. These activities can be divided in two distinct, though closely related, parts: the first is the development of the power system modelling tool COMESE. The model, whose operation criteria are accurately described in this document, has been deeply restructured and upgraded. The main features that were the object of this effort are the implementation of a short-term forecast operation strategy and of the so called "Joint Action" of flexible dispatchable generators and storage systems; the zonal representation of the power system and the introduction of a power flow analyses section based on a power transport model; the coupling of the model with a Differential Evolution algorithm for the design of optimized power systems. The short-term forecast and the joint action operation strategies are in particular, to the best of the author's knowledge, an original feature not shared by similar modelling tools, and have proven to be effective in assessing the power system reliability as well as designing optimized power systems. The second part of my research activities has been focused on the exploitation of the COMESE model to carry out long term scenario analyses on possible future designs of decarbonized Italian power system.

The two more comprehensive studies carried out with COMESE are presented in this document. They have been formulated with the two-fold objective of assessing the role of thermonuclear fusion generation in a future decarbonized power system, and to analyse relevant features that are likely to strongly influence the design and performance of these systems themselves.

The first study focused on the role that generator siting and transmission grid capacity will have on the feasibility and reliability of a power system. It showed clearly that when dealing with renewable generators, their siting cannot follow the criteria of the highest energy generation potential, if not supported by a transmission constraint compatibility analysis. It also showed that storage technologies required capacity and optimal siting as well is related to the one of renewable generation, and in turn to the transmission grid constraints. In this context the availability of Fusion resulted clearly beneficial with respect to the overall system costs. The analyses also highlighted what factors influence this cost gap: the different requirement of storage systems, flexible generators and transmission capacity, while it showed that the cost of energy generation itself and the amount of curtailed energy are less relevant factors.

The second study focused on the availability of a long term storage system such as hydrogen, by means of a power-to-hydrogen-to-power infrastructure. P2H2P has shown that it is very likely to enter an energy mix, and to reduce the overall system cost by doing that. It also showed that its availability doesn't cancel the need for short term storage systems, and that actually its best use is not as seasonal storage, but as what can be called a "mid-term" storage: a storage system with a storage duration only moderately longer than short term (daily) ones. The direct consequence of this finding is that high amounts of curtailed energy seems to be a feature of any optimized power system that relies on a relevant share of variable renewable generation. Fusion resulted beneficial in lowering the overall system costs also in presence of P2H2P infrastructure. Also, it was shown that this beneficial influence stands as long as fusion is exploited as a baseload generation technology. An alternative use of fusion for the production of large amounts of hydrogen to be later used for flexible generation did not result in a competitive system design alternative.

Future works

The work carried out prospects some interesting further developments. Scenario analyses with COMESE could reach a higher degree of detail by including a module that simulates an "imperfect" short term forecast. This would allow to address the problem of faulty renewable generation forecasts and to assess its impact on the system reliability, as well as what strategies can be adopted to mitigate it.

Multi-year analyses could be exploited to address the problem of yearly renewable generation variability: the definition of "standard" year, which guides the choice of the profile to be used in power system simulation, is usually done by means of mean yearly production criteria. Still, as well as hourly simulation proves that the yearly amount of energy produced is not a sufficient element to assess the reliability of an energy mix, also such criteria could not be the most suited to choose the input data for the hourly simulations. The definition itself of best-year, worst-year and mean-year, and their use in multi-year simulation is a promising topic.

Market simulation is another tool that could result useful to increase COMESE versatility, as the search for market rules suited for high-renewable power mixes is a issue of primary importance that should be addressed as soon as possible.

Finally, the exploitation of the zonal representation in COMESE to analyse European scenarios, with wider transmission grids and more heterogenous renewable sources availability than a single nation, is for sure another topic of primary importance.

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