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Consulting Services

Navigating the Energy Transition:

PATHWAYS TO NET ZERO IN ITALY

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EXECUTIVE SUMMARY

"Italy's efficient transition to a reliable and resilient net zero electricity system by 2050 is achievable with additional flexibility resources and infrastructure reinforcements and upgrades."

The European Green Deal followed by the "Fit for 55" package, sets binding Greenhouse Gas (GHG) emissions reduction targets for each Member State of the European Union (EU) to achieve climate neutrality by 2050. This is further reinforced by the European Climate Law which sets a legally binding target of net zero emissions by 2050. Consequently, Italy defined its recent National Energy and Climate Plan (NECP) that includes a set of planned measures to reduce CO_2 emissions in the power sector by 58-66%, aligning with the EU's 62% reduction target for 2030. This is expected to be accomplished by setting a target of at least 53% of renewable electricity consumption by 2030. Beyond 2030, the proposed 90% GHG reduction target for 2040 sets another interim goal.

In the presence of these ambitious emission reduction and renewables penetration goals alongside a projected 60% growth in demand by 2050, there is a need to explore credible pathways to achieve net zero in Italy. These pathways should investigate the role of various no or low carbon electricity generation technologies as well as the role of the electricity grid to efficiently enable this complex transition of the Italian power sector.

This paper explores alternative decarbonization pathways for Italy's power sector, considering the economic implications of different electricity generation technologies, capacity expansion strategies, and network infrastructure requirements to reach net zero in 2050. The paper provides insights into the challenges and opportunities to inform policymakers, industry stakeholders, and investors to support informed decision-making and effective planning for a sustainable and resilient future power system in Italy.

ITALY'S DECARBONIZATION GOALS

58%-66%
REDUCTION
in CO_2 emissions in power sector by 2030

53%
Target renewable electricity consumption by 2030

90%
REDUCTION
In CO_2 emissions by 2040

NET ZERO
By 2050

CHALLENGES

AN INCREASE OF
60%
Demand by 2050

MORE THAN
200 GW
Of new capacity will be required by 2050

~5X
The currently installed wind and solar in Italy

The salient features of the Italian power sector captured in this paper include CO_2 emissions reduction trajectory, growth in demand and its variability, renewables resource potential, cross border interconnection as well as inter-zonal transmission constraints:

- **Renewable Ambition** - assuming renewable additions aligned with Italy's NECP targets, and
- **Business As Usual** - assuming a more gradual renewables increase in line with recent trends.

In both scenarios, the least-cost expansion approach is applied to determine the optimal portfolio of generating technologies to deliver net zero by 2050 as shown in Figure 1. However, only the Renewable Ambition scenario will achieve 2030 Renewable Energy Directive (RED) based targets for renewable capacity as outlined in the NECP. In the Business As Usual scenario, the 2030 RED targets for wind and solar additions in Italy are assumed to be missed, while an earlier introduction and a higher utilisation of Carbon Capture and Storage (CCS) technology can keep Italy on the 2050 net zero trajectory.

Our analysis demonstrates that Italy can achieve its net zero goals through a successful transition to renewable energy by significantly accelerating renewables deployment – with total solar and wind capacity reaching 90 GW by 2030 (i.e. more than a two-fold growth from the 2024 level), investing in flexible thermal resource (e.g. CCS), and through timely reinforcements to the transmission grid. Key insights from our analysis are:

- **Flexible resources are imperative:** In order to maintain system reliability at current levels with a significantly larger penetration of renewables (solar and wind), a significant volume of flexible resources will be required in the system. We quantified that by 2050, at least 40 GW of battery energy storage system (BESS) capacity will be needed alongside existing 29 GW hydropower capacity, 13-17 GW of Combined Cycle Gas Turbines (CCGTs) with CCS and 8 GW of nuclear (potentially Small Modular Reactors or "SMRs").

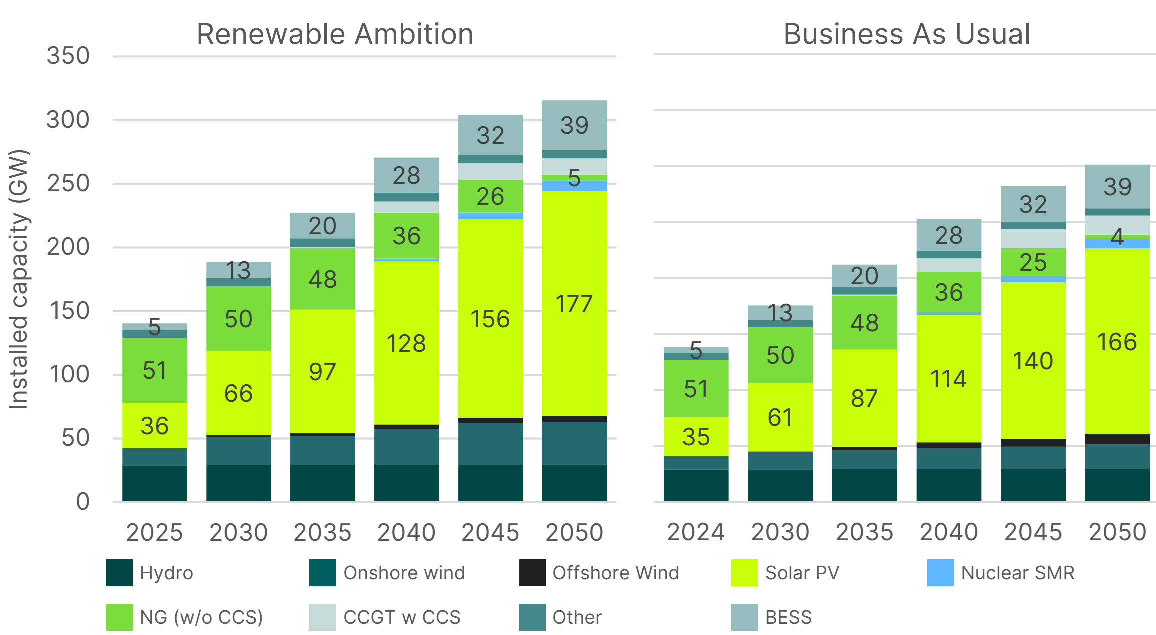

Figure 1 - Projected installed capacity (GW) by technology type.

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- **Accelerate transmission upgrades and further reinforcements in the south of Italy:** We concluded that transmission upgrades are essential and a cost-efficient way of integrating the required quantum of renewable energy. We estimate that energy curtailment could reach 58 TWh (circ. 12% of electricity demand) by 2050, even while considering the planned investments in the Hypergrid projects. Timely completion of these upgrades are estimated to save over €11 billion in system and re-dispatch costs by 2050.[1] The curtailment zones with high renewable capacity, lower demand, and limited flexible generation, such as in the south of Italy, will be more vulnerable to curtailment. Without additional transmission upgrades these zones will face significant curtailment, resulting in a loss of renewable energy and financial inefficiencies.

- **Mitigate risk around solar additions:** On an economics and resource potential basis, solar (PV) capacity is the largest single source of capacity additions. However, significant challenges will need to be overcome for both solar and wind integration that include standardisation and streamlining of the authorisation of connection procedures, adequate grid infrastructure to evacuate power from lower demand zones hence managing price risks, alignment of incentives for power producers and consumers (consumers pay a single national electricity price while generators receive zonal price), and reconsidering the ban on Contracts for Difference (CfD) for ground-mounted solar-PV in agricultural areas. With a significant part of solar PV poised to be curtailed by 2050, programmes incentivising smaller PV+BESS hybrid projects should be rolled out as soon as possible, in addition to the utility-scale energy storage support mechanism (MACSE).

- **Implications of 2030 renewables targets:** In case of missing the NECP 2030 Renewables targets (i.e. the Business As Usual scenario), emissions to 2030 will be relatively high due to increased use of thermal generation. However, Italy can still achieve its 2050 target with significantly more dependence on CCS technology (which is yet to commercialise and is associated with cost uncertainties), and electricity imports from its neighbouring countries.

- **Cost implications:** The total system costs (excluding imports) between the high renewables (Renewable Ambition) and relatively low renewables (Business As Usual scenario) are comparable. In the Renewable Ambition scenario, the capital expenditure will be greater, while the Business As Usual scenario is more reliant on natural gas and Hydrogen resulting in higher fuel (operational) costs. Additionally, in the Business As Usual scenario, Italy will rely more on imported power, increasing the cost to consumers in Italy.

In conclusion, Italy's efficient transition to a reliable and resilient net zero electricity system by 2030 is achievable, but it will be significantly dependent on ensuring adequate flexible resources in the system and timely augmentation of the electricity network infrastructure. Terna's Hypergrid projects represent a vital investment for delivering net zero, however these will be realised between the 2030-2040 period and therefore will not address energy curtailment in earlier years besides being inadequate for efficiently integrating the required volume of new generation by 2050.

[1] While zonal prices lead to relatively low compensation payment for curtailed energy, Hypergrid benefits can be estimated at over €70bn if curtailed energy is values at National Single Price (PUN).

INTRODUCTION

Context and objectives

The European Commission (EC) introduced the European Green Deal in 2020. It is a set of policy initiatives to reach climate neutrality in the European Union (EU) by 2050. The first step in achieving this goal is the “Fit for 55” package of policies to reduce overall emissions in 2030 by 55% compared to the 1990 level. The EU’s Regulation (EU) 2023/857[2], part of the “Fit for 55” package, sets binding Greenhouse Gas (GHG) reduction targets for each member state. Italy’s National Energy and Climate Plan (NECP)[3] includes a set of planned measures to reduce CO_2 emissions in the power sector by 58-66%, aligning with the EU’s 62% reduction target for 2030. The phase-out of coal is the main contributor and ensures a clear path to achieve the 2030 emission reduction target in Italy.

Furthermore, the Renewable Energy Directive (RED) mandates an EU-wide target for renewable energy share of 42.5%.[4] Italy has reflected this by setting a target of at least 53% of renewable electricity consumption by 2030 (NECP Reference scenario), with an ambition to reach 63% by 2030 (NECP Policy Scenario). This will require significant renewable capacity additions in the next few years. While RED targets will primarily drive renewable additions in Italy up to 2030, the European Climate Law sets a legally binding target of net zero by 2050 and therefore creates a binding requirement to fully decarbonize the economy between 2030 to 2050.[5]

In early July 2025, the European Commission (EC) proposed an amendment to the EU Climate Law, setting a new EU climate target of a 90% reduction in net greenhouse gas emissions by 2040, compared to 1990 levels[6]. Although not power sector-specific, this interim goal is expected to translate into an equally ambitious target for the power sector as shown in Figure 2.

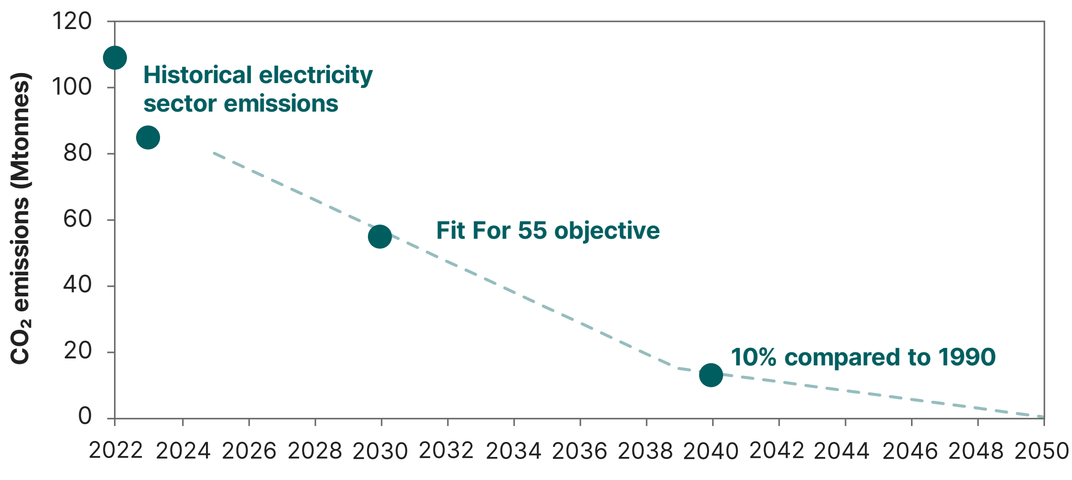

Figure 2 - Modeled CO_2 emissions limit for the power sector in Italy.

[2] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2023.111.01.0001.01.ENG
[3] https://commission.europa.eu/publications/italy-final-updated-necp-2021-2030-submitted-2024_en
[4] https://energy.ec.europa.eu/topics/renewable-energy/renewable-energy-directive-targets-and-rules/renewable-energy-directive_en
[5] https://climate.ec.europa.eu/eu-action/european-climate-law_en#:~:text=The%20European%20Climate%20Law%20sets,greenhouse%20gas%20emissions%20by%202050
[6] https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2040-climate-target_en

With the binding EU emission targets and the decreasing cap for emission allowances, decarbonisation of the economy in Italy becomes a financial commitment as much as environmental. The power sector plays a pivotal role in this transition. Therefore, a clear decarbonisation pathway for the Italian power sector is required.

This study explores how the decarbonisation goals across the electricity, transport and heating sectors can be achieved in Italy through an efficient transformation of the power sector. The paper is intended to inform policymakers, industry stakeholders, and investors by providing a comprehensive analysis of the economic, technical, and spatial aspects of different energy technologies and strategies for transitioning to a sustainable and resilient power system in Italy.

In the rest of this section, we describe two scenarios designed to meet net zero objective in Italy, in line with the strategic goal for the EU to be climate neutral by 2050, along with the key inputs that include demand growth, technology characteristics, transmission constraints and the availability of renewable resources.

Scenarios Overview

A significant expansion of renewable capacity is essential to decarbonize the electricity sector in Italy. Therefore, our core scenarios are designed to capture the ambition as well as the uncertainty in future growth of renewables in the country as outlined below.

- **Renewable Ambition:** A scenario that assumes renewable additions can proceed at the pace required to meet the RED 2030 targets in Italy as outlined in the final NECP, and
- **Business As Usual:** A scenario that assumes renewable additions are proceeding at the same pace as 2023/2024 – record years for renewable additions.

In both scenarios we:

– Keep the electricity demand growth identical, capturing the growth in demand driven by electrification of the heating and transport sectors, and reaching a peak of 94 GW and overall electricity consumption of around 500 TWh in 2050.

– Let the model choose the best expansion pathway post-2030 and constrain CO_2 emissions from electricity generation down to 10% by 2040 and to zero by 2050.

– Impose an overall limit of 10 GW for the offshore wind additions with a rate of 0.4 GW/yr, aligned with ANEV estimate for the offshore wind potential in Italy.[7]

– Assume an upper bound for Battery Energy Storage System (BESS) additions in line with recent additions close to 15 GW and 40 GW by 2030 and 2050, respectively. This is supported by Terna plans and the new MACSE scheme.[8] However, we allow the model to decide the actual capacity required and choose between 4-hour and 8-hour duration batteries based on the economics and system needs.

The key difference between the scenarios is the rate at which wind and solar additions can proceed in Italy.[9] In the Renewables Ambition scenario, solar additions are capped at 7 GW/yr and onshore wind at 2 GW/yr in line with NECP projections. However, in the Business As Usual scenario solar and onshore wind additions are capped at 5 GW/yr and 0.5 GW/yr, respectively. Additionally, we have performed the following sensitivity analysis on the Renewables Ambition scenario:

- Hydro sensitivity, as available annual hydro energy can have a material impact on the CO_2 reduction trajectory in Italy. Hydro inflows are fundamentally uncertain and will fluctuate year on year. As part of the analysis, we have quantified the impact of lower hydro output on generation and CO_2 emissions in Italy.
- Transmission upgrades, where all planned transmission upgrades are assumed cancelled in order to quantify the impact on renewable curtailment and to estimate the cost-benefit of the planned transmission upgrades.

[7] https://www.anev.org/2024/03/22/commissione-via-esito-positivo-del-primo-eolico-offshore-floating/
[8] https://www.rse-web.it/wp-content/uploads/2024/05/08_MACSE-inglese.pdf
[9] Additions exclude off-grid capacity that may be reserved for Hydrogen production.

Geographic Scope of the Analysis

Although the focus of this analysis is the Italian electricity system, it is important to model a wider region around Italy to capture the impact and interactions of other (mainly European) grids with Italy through cross border interconnector flows with other countries. A schematic representation of the geographic scope covered by the analysis is presented in Figure 3. We have included countries that have interconnectors with Italy and/or have a significant influence on its electricity system because of indirect electricity exports or imports.

We have divided Italy into electricity transmission zones (power zones) based on Terna's transmission network to assess the impact of transmission constraints on the integration of renewables. Figure 4 shows the current transfer capacities as well as expected values in 2040. Future transmission reinforcement assumptions are based on Terna's 2025 Development Plan[10], and specifically the Hypergrid projects.[11] Substantial new renewable capacities will necessitate investment in the Italian transmission network to minimise curtailment.

Figure 3 - Countries included in the model.

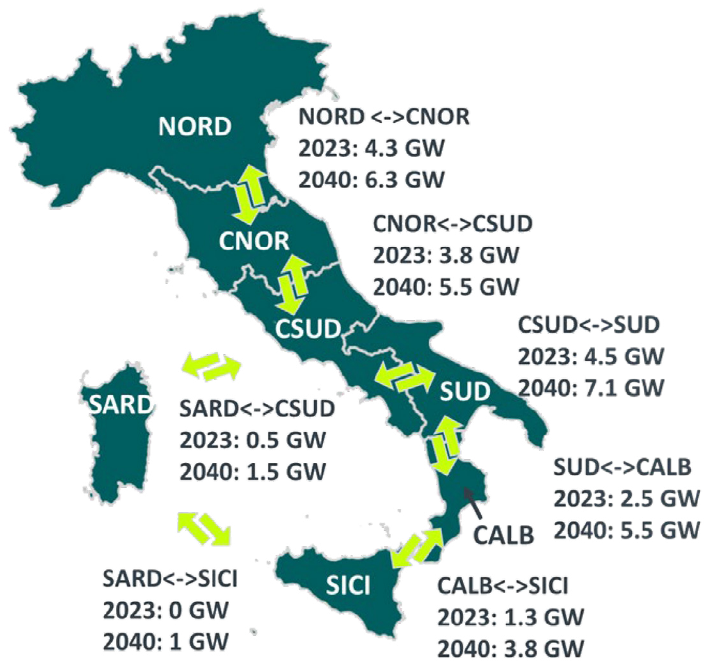

Figure 4 - Transmission limits across electricity transmission zones in Italy.

[10] https://www.terna.it/en/media/press-releases/detail/2025-development-plan

[11] https://www.terna.it/en/electric-system/efficient-territorial-planning/national-electricity-transmission-grid-development-plan

Levelized Cost of Electricity (LCOE)

The list of candidate technologies included in our analysis, and the key inputs for economic optimisation of build decisions, are listed in Table 1. CCS systems on retrofitted units will consume additional energy for capture, compression, and transport of CO_2 impacting the plant efficiency and increasing the running costs. An 8% efficiency penalty and a 100% increase in variable operation and maintenance costs were assumed. Additional infrastructure for CO_2 transport will be necessary and can be substantial, though their assessment is beyond the current study's scope.

Type	Size (MW)	Build Cost (€2023/KW)[12] 2030	2035	Economic Life Years	Full Load Efficiency
CCGT with CCS	800	2050	1900	20	59%
CCS retrofits	400-800	1300	1000	20	52-57%
H_2-capable CCGT	800	900	900	20	62%
H_2-capable OCGT	300	690	690	20	38%
SMR	300	6400	6100	60	36%
Solar PV	10	760	620	20	N/A
Onshore wind	10	1700	1560	20	N/A
Offshore wind	10	2550	2260	30	N/A

Table 1 - New capacity thermal candidates.

We have used the inputs from Table 1 along with 8.5% hurdle rate to compare the LCOE[13] for different type of candidate power plans, including renewables, in 2035 – this is shown in Figure 5. Capacity factors for renewables are based on the reanalysis data, aligned with historical values, and are differentiated by power zone in the least-cost expansion. Thermal unit capacity factors are the output of the least-cost expansion. Capacity factors used for the LCOE calculations are illustrative.

Solar PVs have the lowest LCOE due to relatively high solar irradiation in Italy, low CAPEX and near-zero variable costs. However, the economics of the renewables will be impacted by the reduced load carrying capacity that is considered in the least-cost expansion as their share increases.

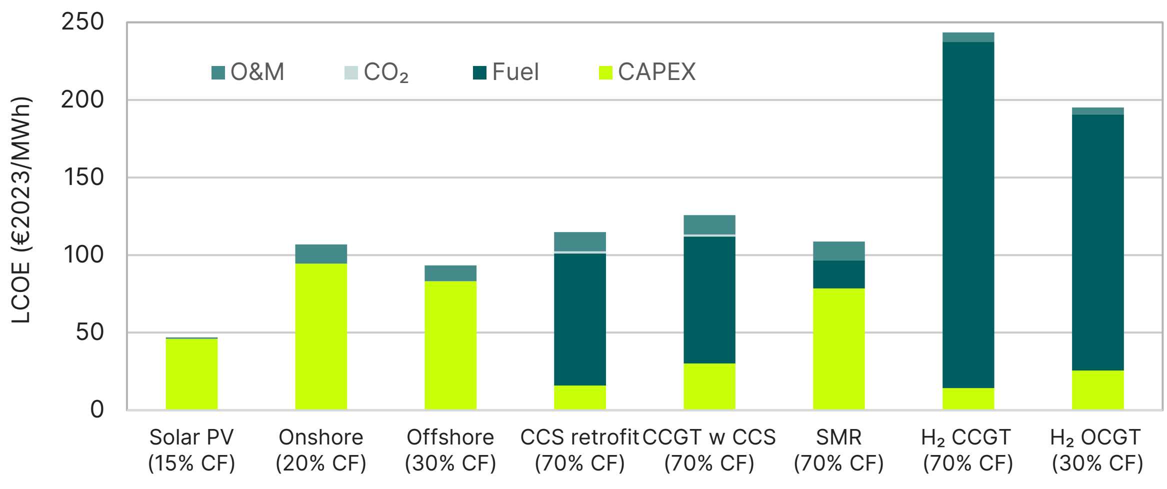

Figure 5 - LCOE comparison for different technologies in 2035.

[12] https://www.gov.uk/government/publications/beis-electricity-generation-costs-2020

[13] The Levelized Cost of Energy (LCOE) is used to evaluate the average cost of generating one unit of electricity over the lifetime of a generating asset.

The LCOE for onshore and offshore wind in Figure 5 is comparable. Although the build cost of the offshore wind is higher, it has a higher capacity and a longer economic life typically applied to offshore projects, resulting in slightly lower LCOE.

The LCOE for retrofitting CCS to an existing CCGT power plant is comparable with a new unit. Lower build cost for a retrofit is partly offset by the higher fuel cost due to efficiency. The LCOE for a CCGT with CCS is also closer to the LCOE of a nuclear Small Modular Reactor (SMR). While SMRs will have a significantly higher build cost, it will be amortised over a longer period. SMR fuel cost will also be significantly lower, reducing its LCOE. Finally, a high cost of Hydrogen makes the units running on this fuel economically least attractive, particularly for a CCGT unit that would be expected to operate at higher capacity factor than an OCGT. Unless there is a substantial Hydrogen cost reduction, its use is likely to be limited to peaking operation and cases where other technological solutions are not available (e.g. due to CO_2 injection capacity limits or extended SMR build timelines).

ANALYSIS RESULTS

Outcomes of our analysis are listed below, beginning with the outlook on the system installed base.

Capacity Expansion Pathways to Meet Net Zero

The modelling objective was to find least-cost capacity expansion pathways to meet the target of fully decarbonising the Italian electricity system by 2050.

We have modelled two scenarios as pathways for Italy to reach its net zero goals. A Renewable Ambition scenario takes the cumulative wind and solar capacity to around 90 GW by 2030, or over 2 times their capacity at the start of 2024. On the other hand, Business As Usual scenario results in circ. 80 GW of wind and solar by 2030. In both scenarios, we let the model choose the mix of new generation beyond 2030 to meet the goal of fully decarbonising electricity. Added wind and solar capacity is assumed to be repowered if it reaches the end of technical life before 2050.

Figure 6 summarises the required additions by technology in each scenario. Over 200 GW of new capacity will be required by 2050 in both scenarios – almost twice the entire 2024 generating capacity and over 5 times currently installed wind and solar in Italy. This will include around 40 GW of new BESS and just under 20 GW of natural gas units equipped with the CCS, which will be key for providing system flexibility. Additions are highest during 2025-2039 as this period will correspond to the highest rate in demand growth from electrification of heating and transport in Italy. Tailing off in capacity additions after 2045 corresponds to the period with lower demand growth.

This power system transformation will result in a fundamental change to the installed base as shown in Figure 7. Wind and solar capacity constitute well below 50% of the installed base in 2025 but their share will increase to almost 70% in 2050. This also means that the relative installed share of hydro and thermal units, which traditionally have provided the flexibility to the system, will be dramatically reduced.

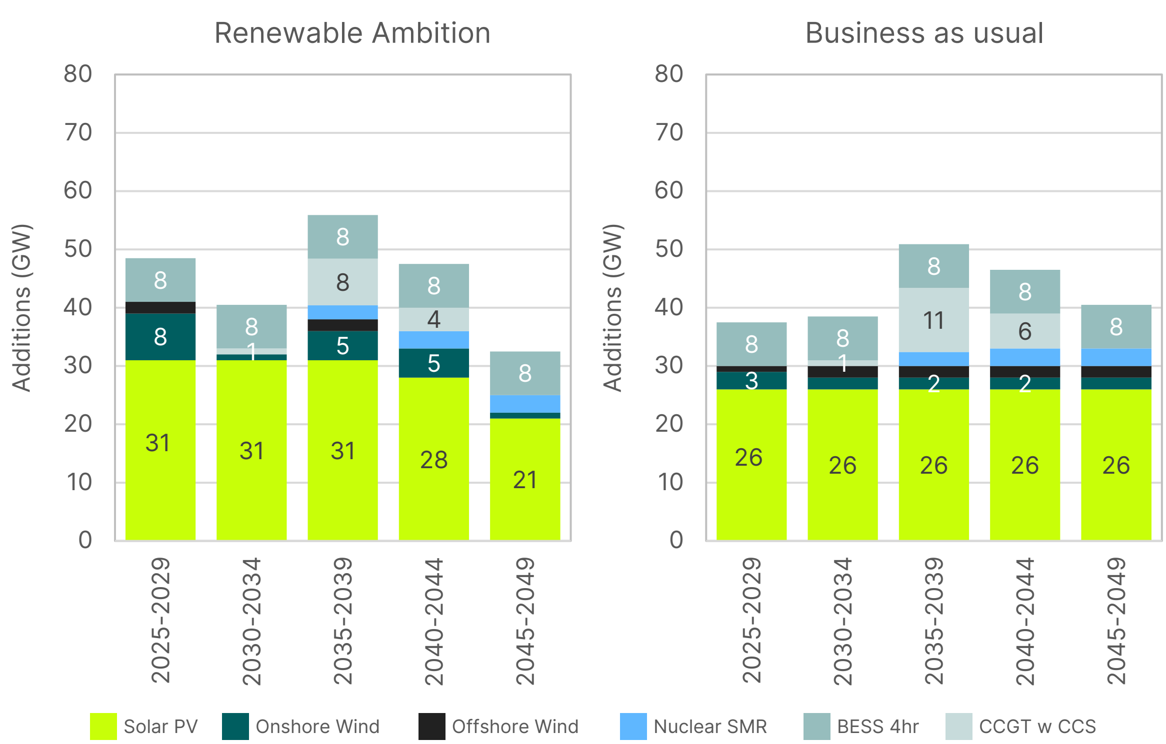

Figure 6 - Summary of capacity additions in Italy between 2025 and 2050.

Therefore, the location, operating strategies and characteristics of flexible generation need to be carefully considered to achieve secure and reliable power system.

In the following subsections we discuss modelled capacity additions in each category in more detail.

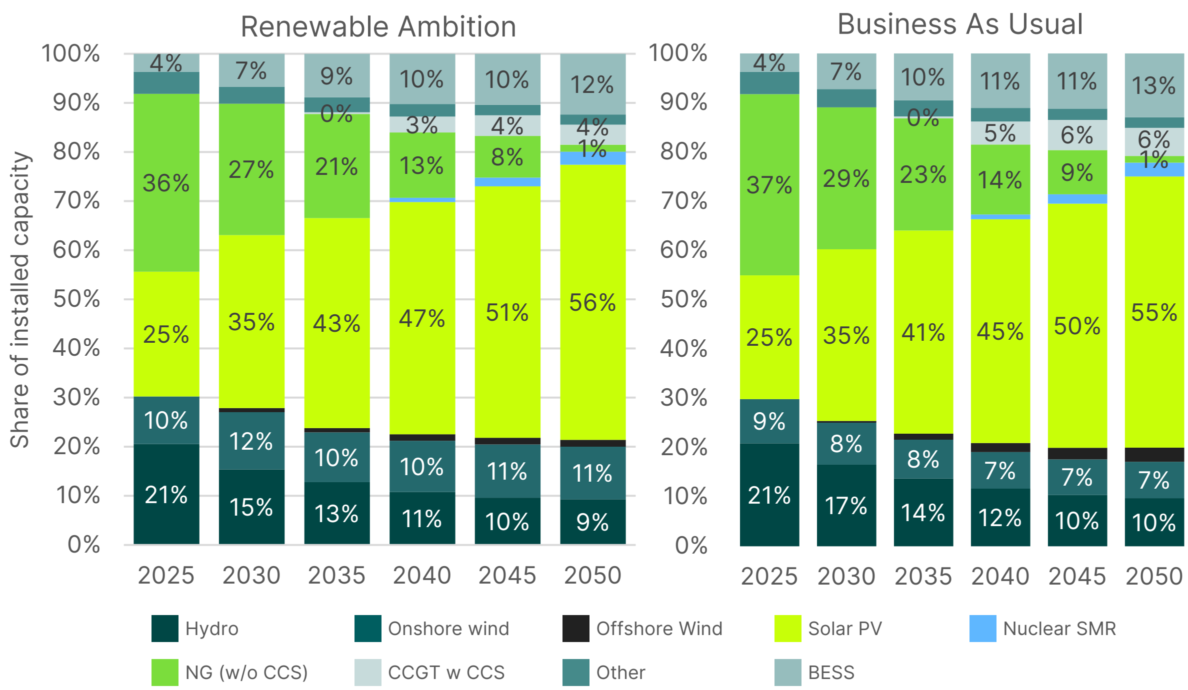

Figure 7 - Installed capacity by technology type.

Solar PV

Capacity additions of solar PVs are expected to be the highest among all technologies, in line with the recent trend and their estimated LCOE. The modelling suggests that additions should continue at 5-6 GW/year until 2040, and then at a somewhat reduced rate to reach the total additions of 130-140 GW, depending on the scenario, as shown in figure 6. This will result in 165-180 GW of installed solar PV capacity in 2050, still somewhat below the 245 GW estimate included in the final NECP as an indicative cost-effective potential.

The historical trend of solar PV installations was 0.8 GW per year during 2014-2020. The rate of additions increased recently to 3 GW in 2022, 5.2 GW in 2023, and 6.8 GW in 2024. The main drivers were the Superbonus 110 scheme, the increase in power prices, as well as the new connection standard at 36 kV simplifying connection process at this voltage level. With the end of Superbonus scheme and lower power prices, there is a risk of reduced interest in solar PV investments making the capacity additions above recent historical levels challenging.

On the other hand, Terna had already received requests for connection of 124 GW of solar PV. Realising all of these projects would have been more than sufficient to reach 2030 targets and to be on track for the net zero power system in 2050. However, a number of issues hinder the progression of these projects to development, including:

- Limited progress on the standardisation and streamlining of the authorisation procedures for solar PV connection, particularly at higher voltage levels.
- Lack of infrastructure and system flexibility, leading to inability to evacuate power from zones with lower demand and higher renewable penetrations. This resulting in low or zero power prices these zones, increasing financial risk for PV developers.
- Misalignment of incentives for power producers and consumers. Power consumers are not interested in local power production, since they pay a single national price for electricity, while generators receive zonal prices.
- Ban on Contracts for Difference (CfD) for solar PV with ground-mounted modules in agricultural areas that are suitable for solar PV. This limits available locations for PV development.

Considering the above, the challenge of achieving the required growth in solar PV capacity is significant and could pose a risk to delivering net zero by 2050 unless these key barriers are removed.

Onshore and Offshore Wind

The ambition for onshore wind additions included in the NECP is significantly above the historical level of additions. While the development of the offshore wind will be supported by FER2 decree for the period up to 2028, the support for onshore wind is not included.[13] In both of our scenarios, onshore wind additions are not achieving the maximum allowed capacity by 2050. The total additions during 2025-2050 for offshore and onshore wind are expected to be:

- 20 GW of onshore and 4 GW of offshore wind in the Renewable Ambition, and
- 10 GW of onshore and 9 GW of offshore wind in the Business As Usual.

This is a moderate growth from the currently installed base of 13 GW of onshore wind and no offshore wind. A combination of factors leads to the moderate build-out of wind in Italy. Capacity factor for wind is lower in Italy compared with the regions with higher wind speeds, such as along the coast of the North Sea, reducing the return on investment for wind. Equally, the regions with highest wind potential in Italy are in the south, while electricity demand distribution is weighted more towards industry-heavy north of the country.

Thermal Capacity

Retrofitting CCS onto existing units emerges as an economically viable solution in the medium term (i.e. 2030-2040) when a high demand growth from transport and heat electrification is expected. In the longer term (post-2040), the rationale prevails for new CCGT units with high efficiency located in the power zones where additional capacity is required (e.g. electricity demand in the NORD power zone accounts for over 50%). NORD power zone is also projected to have limited new wind capacity. The model suggests that over 7 GW of higher-efficiency units located in the NORD and CNOR power zones can be cost-effectively converted to units around 2035, coinciding with acceleration in transport and heat electrification rates. While the assumed technology costs include new infrastructure for CO_2 transport and storage, specific sites will need a detailed assessment to confirm the suitability for a CCS project. It would be cost-effective to add 6-10 GW of new CCS units around 2040.

The modelling suggests that it is economical to install around 8 GW of nuclear SMR in both scenarios as this technology becomes available (assumed post-2035). This is in line with the national ambition outlined in the NECP. However, should the nuclear moratorium be extended, we would expect this capacity to be covered by CCGT units with CCS or running on Hydrogen, depending on the availability of Hydrogen supply and/or CO_2 storage.

[13] https://www.mase.gov.it/notizie/energia-mase-pubblicato-il-decreto-fer2

Hydro Sensitivity

With around 15% of total generation currently coming from hydropower in Italy, it is an important component of the generation portfolio. Hydro inflows vary year by year and can impact generation from other sources, primarily from gas, depending on water availability.

For the Renewable Ambition scenario, we have assumed an average hydro inflow observed in the last 10 years. However, we have also tested how different hydrology scenarios can affect least cost build-out. The difference in hydro output between the dry and the average weather year is about 15 TWh, equivalent to a 2 GW thermal unit generating at 85% capacity factor. As a result, we have identified the need for additional 2 GW of CCGT+CCS under the low (dry) hydro sensitivity assumption. However, it is unlikely that there will be several consecutive dry years requiring this additional capacity to run at high-capacity factors. Instead, a reliance on additional imports, higher utilisation of existing thermal units, peaking gas unit running on Hydrogen, avoidance of solar & wind curtailment, and more optimal use of BESS and other energy storage resource would be economic for covering potential shortages of water during dry years.

Geographical Distribution of Capacity Additions

Geographical distribution of capacity additions in the Renewable Ambition scenario is shown in Figure 8. Thermal additional are concentrated in the North, where largest demands centres are located. Wind distribution is weighted towards southern power zones, where capacity factors will be highest, while the solar PV additions are spread relatively evenly.

It is worth noting that geographical distribution of BESS was unconstrained in the model to get the most efficient distribution based on the locations chosen for renewable capacity. As a result, preferred sites for BESS are primarily in the zones where most of the solar PVs will be located, except for the NORD power zone where large hydro and thermal installed base can provide the required flexibility to the system.

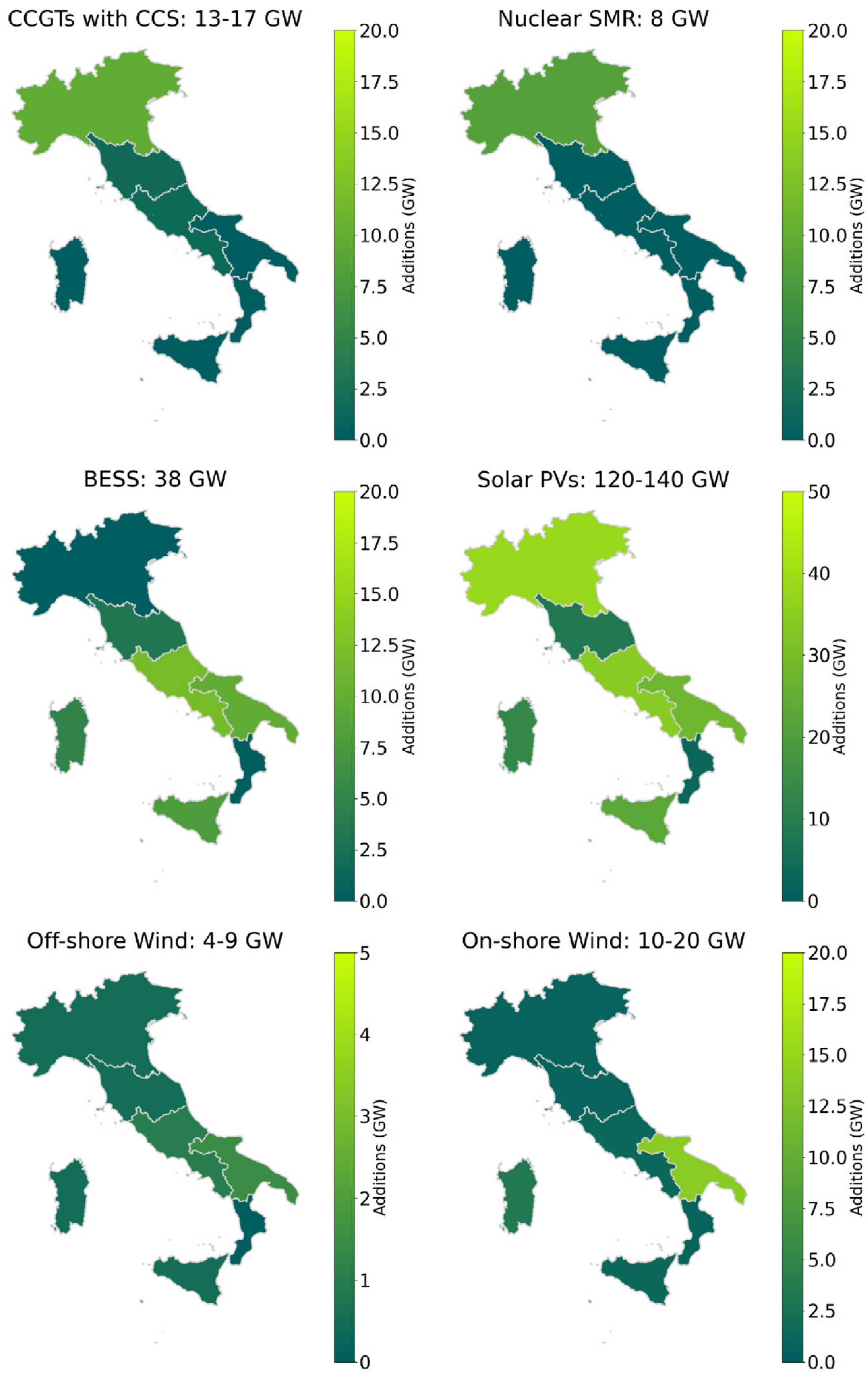

Figure 8 - Cumulative capacity additions by technology by zone in Italy, 2025 – 2049. Ranges represent variation between the Business As Usual and Renewable Ambition cases

Electricity Generation

The overall projected generation in Italy by technology type is shown in Figure 9 and Figure 10 for both scenarios. Vertical axis in Figure 9 shows annual generation in TWh, while the axis in Figure 10 is in percentages, showing the share of generation in each category relative to the total demand, excluding charging and discharging of BESS. There are important differences between the scenarios in generation for several categories. First, we will discuss how generation in each key category evolves in the Renewable Ambition scenario, and then will highlight the differences observed in the Business As Usual scenario.

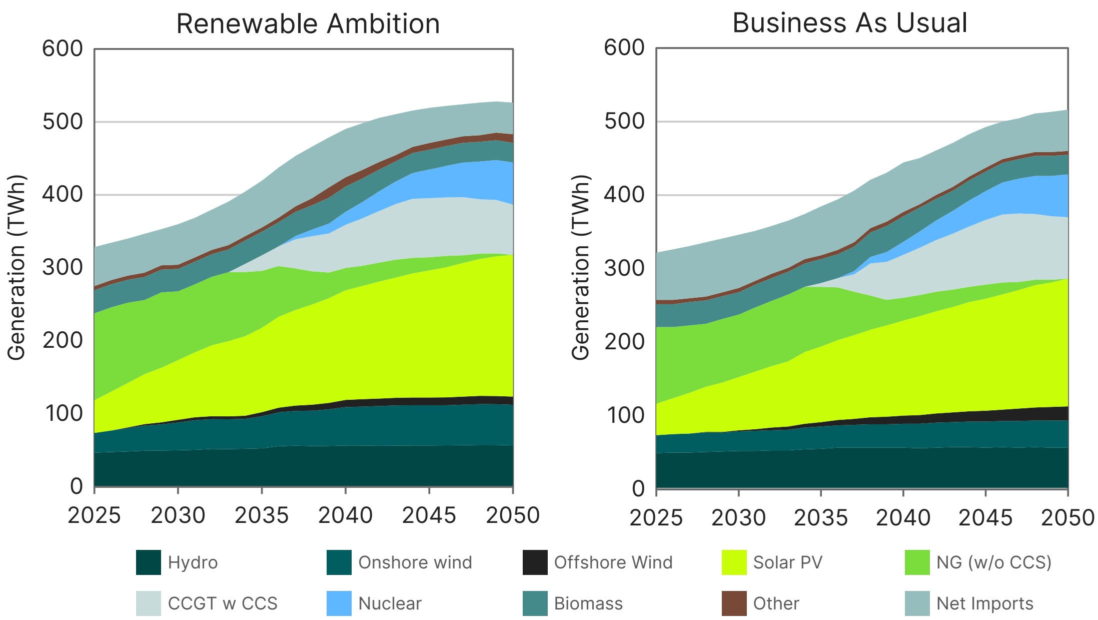

Figure 9 - Total projected generation in Italy.

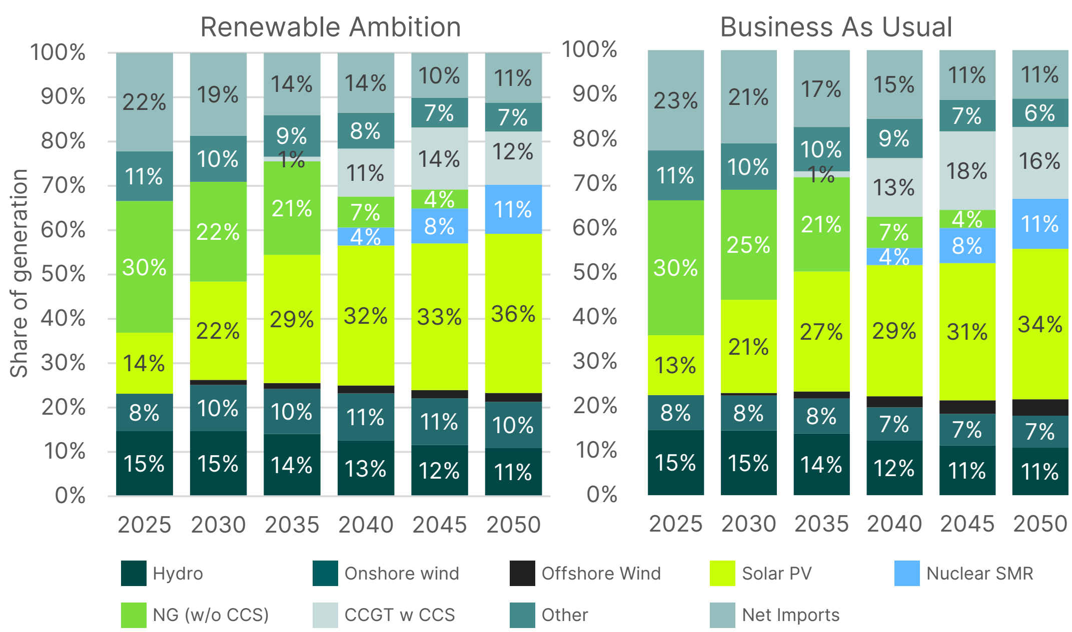

Figure 10 - Electricity generation mix by technology type.

Renewable Ambition Scenario – Generation Mix

In 2025, natural gas based CCGT generation meets around 30% of country's total demand, followed by 15% from Hydro and 14% from solar PVs. The total share of renewable generation in 2025 is projected to be 47%, increasing to 57% by 2030 – somewhat below the NECP Policy Scenario target of 63%.

The generation mix under the Renewable Ambition scenario evolves as follows:

- In 2030, the largest share in domestic generation will be from solar PV, increasing from meeting 14% of demand in 2025 to 22%. Post-2030, solar PV additions continue to dominate as the largest generation source (36% of demand in 2050) contributing to meeting the additional demand besides partially displacing the older thermal generation before the CCS units become available.
- Gas based generation share gradually decreases from meeting 30% of the demand in 2025 to 22% of demand in 2030. The utilisation of individual thermal units will vary significantly depending on their location and merit order positioning, as well as services they provide to the grid. We project the switch away from the unabated natural gas generation around 2040. The share of natural gas generation with CCS increases to 14% around 2045, but then reduces to 12% as new nuclear SMRs come online. Since the demand in 2050 is significantly larger, the smaller share of natural gas generation in the overall mix corresponds to about 50% reduction relative to the current generation.
- Italy continues to import power close to the historical level up to around 2035. In the longer term, higher demand growth from electrification leads to increase in imports. These however stabilise and start to reduce closer to 2045, as Italy increases its baseload and mid-merit capacity through nuclear SMRs and CCGTs with CCS respectively.

Business As Usual Scenario – Generation Mix

With a relatively slow buildout of solar PV and wind (limited to historical growth rates), part of the demand needs to be met by other generation source in the Business As Usual scenario compared to the Renewable Ambition scenario. By 2030, this is largely achieved by additional gas generation and increased imports, while the share of renewable generation remains at 53% in 2030 - in line with the NECP Reference scenario target and significantly below the 63% NECP Policy scenario target.

Post-2030, unabated natural gas will start to be phased out to keep the emissions on track for net zero in 2050, while net imports will be constrained by the interconnection capacities and the available generation in neighbouring countries (that will also undergo system transformation). However, imports will remain high, primarily from France and Switzerland. In this scenario, Italy will rely more on CCS technology which will have to meet close to 20% of demand in 2045, and which will be partly displaced by nuclear SMR closer to 2050.

Electricity Generation Emissions

In recent years, a significant reduction in the CO_2 emissions for electricity sector in Italy was achieved through phasing out coal generation. Figure 11 demonstrates that emission trajectory to 2030 is met both in the Renewable Ambition and Business As Usual scenarios relying primarily on the coal phase-out. However, CO_2 emissions from thermal units will need to decrease significantly to reach the interim 2040 target leading to net zero in 2050. The reduction in coal generation will need to be met by addition of renewables. On the other hand, thermal generation will also be required to balance renewable generation and to ensure adequacy during *dunkelflaute*.[15] Therefore, adoption and rollout of low/no carbon technologies (i.e. CCS and nuclear) will be important to remain on the emission reduction trajectory as a substantial amount of emissions would need to be captured after 2030 as shown in Figure 11.

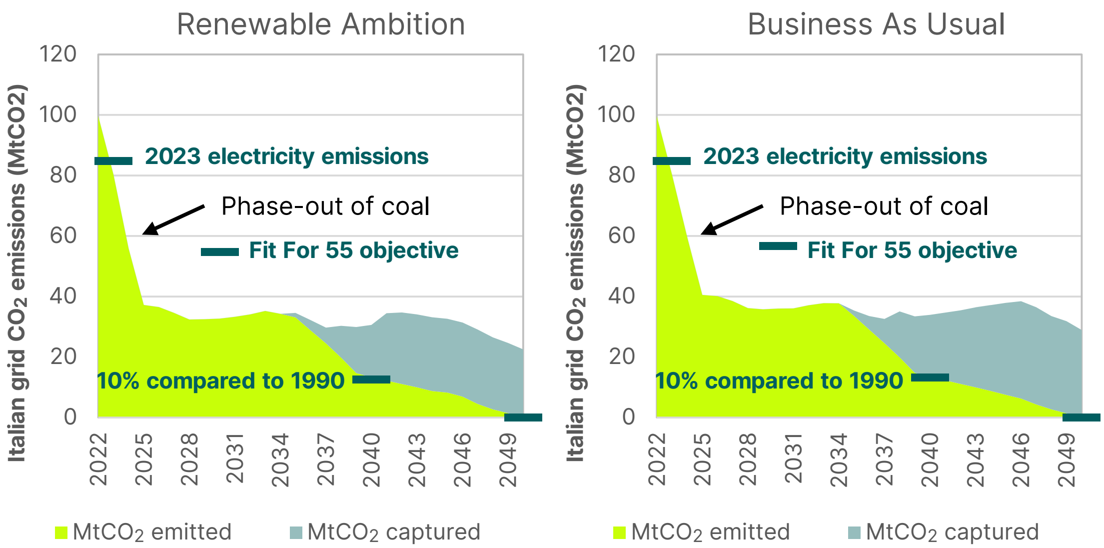

Figure 11 - Projected CO_2 emissions from electricity generation in Italy.[16]

Lower Renewable Growth Impact

As previously discussed, the Business As Usual scenario will have a more conservative wind and solar buildout and therefore more reliant on gas generation post-2030. It will also need a more rapid deployment of CCS to avoid CO_2 emission increase as shown in Figure 11. Post 2030, the CO_2 to be captured will peak around 2045 and will decline in later years as nuclear SMR capacity increases. In absolute terms, more CO_2 would need to be captured in the Business As Usual scenario by almost 8 $MTCO_2$ per year on average post 2045, consistent with higher generation by CCGT units with CCS (due to lower penetration of renewables).

Post 2045, the ability to capture and store sizeable volumes of CO_2 will remain a key requirement in both scenarios, i.e. up to 25 $MTCO_2$ per year in the Renewable Ambition scenario and 30 $MTCO_2$ per year in the Business As Usual scenario.

Lower Hydro Generation Impact

With a significant year on year inflow variability in Italy, hydro generation can have a material impact on CO_2 emissions in years with lower hydro inflows. By 2030, in a year with lower hydro inflows, thermal generation will increase, resulting in circ. 5 MT CO_2 per year additional emissions compared to an average hydro year if unabated natural gas plants compensate for lower hydro output.

Post-2030, any reduction of hydro generation below the average historical levels would require an increased output from CCGT with CCS to ensure that the emissions remain on the trajectory to net zero. This needs to be considered when planning for the required CO_2 annual storage injection capacity. If the CO_2 injection capacity remains limited, utilising Hydrogen-capable units can be an option to address hydro uncertainty.

[15] A period of multiple consecutive days (and nights) when low wind and no or little sun result in minimal energy generated by solar and wind.

[16] It is assumed in this study that CCGTs with CCS will not emit any CO_2. Currently, CCS technology can remove up to 98% of CO_2. The remaining CO_2 will need to be offset elsewhere, e.g. through negative emissions achieved by Direct Air Carbon Capture and Storage (DACCS) or Bioenergy with Carbon Capture and Storage (BECCS).

Significance of the Transmission Network

By 2030, solar and wind meet around 29%-34% of entire electricity demand depending on the scenario. Their share rises further to 45%-48% by 2050. However, because of the zonal limits on renewables additions (based on the current Terna plans) as well as resource availability in different zones, these sources are not always located close to the demand centres. For example, over 50% of electricity demand in Italy is the NORD power zone, while only around 20% of new renewable capacity is expected in this power zone. As a result, adequacy of power transmission becomes key for integrating new renewable capacity while minimising curtailment.

Impact of Transmission on Energy Curtailment

The total energy curtailment is quantified to be around 16 TWh (circ. 5% of annual demand) in 2030 in the Renewable Ambition scenario. This is higher than Terna's estimate for wind and solar energy curtailment (5-6 TWh)[17] which were quantified before the final NECP and has different assumptions regarding demand and renewables growth. In the subsequent years, curtailment is expected to rise more, reaching 35 TWh (8% of demand) by 2040 and 58 TWh (12% of demand) by 2050 in the Renewable Ambition scenario, which takes into account Hypergrid upgrades. Figure 12 highlights the Italian zones where wind and solar will be curtailed, and how the curtailment distribution will change between 2030 and 2050.

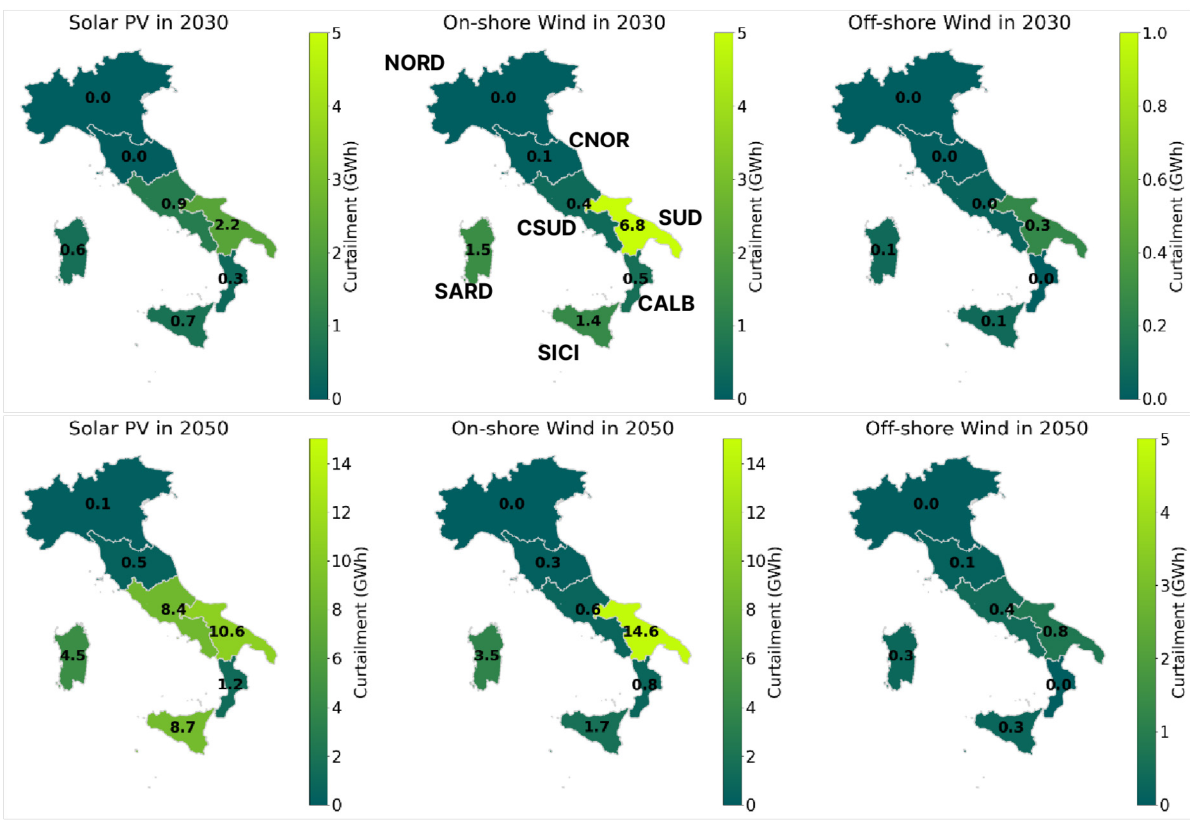

Figure 12 - Distribution of energy curtailment across different power zone in Italy in 2030 and 2050.

[17] Figure 11, Terna 2023 Development Plan - Overview

Onshore wind will experience particularly high curtailment in the SUD power zone as demand is low in this zone and power will need to be transmitted to load centres in the north, causing congestion in the transmission network and leading to curtailment. The transmission corridors from the SUD power zone should be a priority for reducing curtailment and evacuating power to the load centres. Specifically, this supports Terna's plans to advance the HVDC Foggia-Forli project timeline that will involve the modernisation of existing AC/DC lines and a new undersea HVDC cable with the scheduled commissioning date moved from 2036 to 2034.[18]

Sardinia (SARD) is expected to become a significant renewable hub with more than 15 GW of solar PV and 5 GW of the wind capacity installed on the island by 2050,which is still below the connection requests as of 2022. That means Sardinia will have around 10% of total installed wind and solar in Italy and will have to curtail a significant portion of renewable generation if it can't be transmitted to the load centres on the mainland. Our results support Terna's decision to advance the HVDC Fiumesanto-Montalto interconnection with mainland Italy by 1 GW from 2040 to 2035, however higher capacity, as well as even earlier commissioning should be considered for SARD-CNOR transmission link to avoid excessive curtailment.

Figure 13 shows how relative curtailment of wind and solar in Italy will change with time in the Renewable Ambition scenario. There is a noticeable reduction in curtailment in 2034 as the HVDC Foggia-Forli project is expected to be commissioned, having been accelerated by 2 years from the original planned completion in 2036. It will link the Puglia region (Foggia, SUD) to Emilia-Romagna (Forli, NORD), traversing CSUD and CNOR power zones. The project is to be implemented in two phases: first converting the existing overhead line between Foggia (SUD) and Villanova (CSUD), second converting the overhead line between Fano (CNOR) and Forli (NORD) to HVDC. A significant part of the curtailment can be avoided if further transmission upgrades are carried out to alleviate congestion on the SUD to NORD and SARD to CNOR transmission corridors.

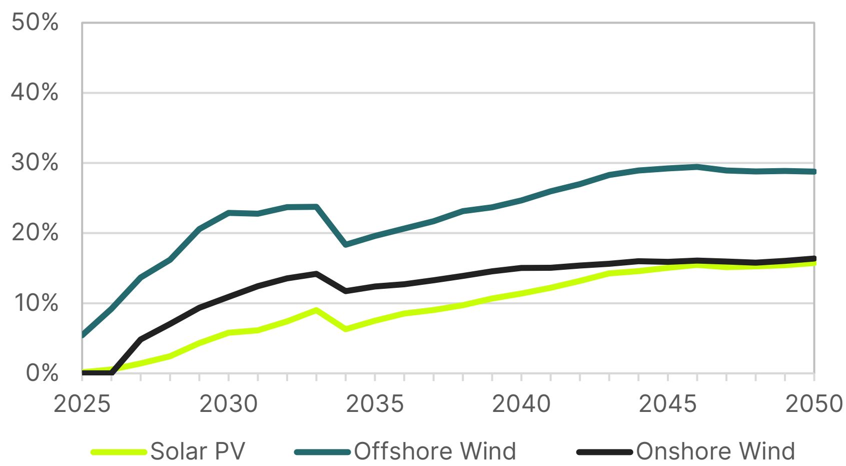

Figure 13 - Energy curtailment as a percentage of total available generation of respective renewable source.

[18] https://www.terna.it/en/electric-system/efficient-territorial-planning/national-electricity-transmission-grid-development-plan

Importance of Hypergrid Transmission Upgrades

Delaying or cancelling planned transmission upgrades is a significant risk for integrating renewable generation in Italy. To quantify the importance of planned Hypergrid transmission upgrades we have analysed a scenario without these upgrades as a counterfactual to the Renewable Ambition scenario.

Figure 14(A) demonstrates the increase in energy curtailment if planned Hypergrid upgrades do not go ahead. The overall curtailment in 2050 will increase by around 14 TWh (around 3% of demand in 2050, with the total curtailment reaching 70 TWh or 15% of demand) leading to higher dispatch cost. When transmission capacity is not sufficient to deliver power from the generation centres to the load centres, dispatchable capacity at the load zone will need to be utilised. This incurs additional costs, primarily because of additional fuel use, emissions and other variable operating costs of thermal units. We estimate that in the absence of Hypergrid, there will be ca. €10bn additional cost to the system by 2050 as shown in Figure 14(B).

Additionally, renewable energy producers will have to be compensated for the curtailed energy and this will result in additional circa €1.5bn by 2050 if compensated at zonal market prices. During renewable curtailment periods, zonal price where energy is being curtailed is typically low leading to a relatively low compensation requirement. However, the potential value of this curtailed energy can also be estimated by taking the National Single Price (PUN) resulting in this curtailed energy cost to be over €60bn by 2050 as shown in Figure 14(B).

It is projected in the analysis that the Hypergrid projects will provide significant net benefit to the system soon after their commissioning during 2030-2040, considering that Terna estimated total project cost at €11bn.[19] From the modelling, it is also evident that should the project be delayed, the cost of this will grow as more renewable come online and the cost of redispatch becomes higher.

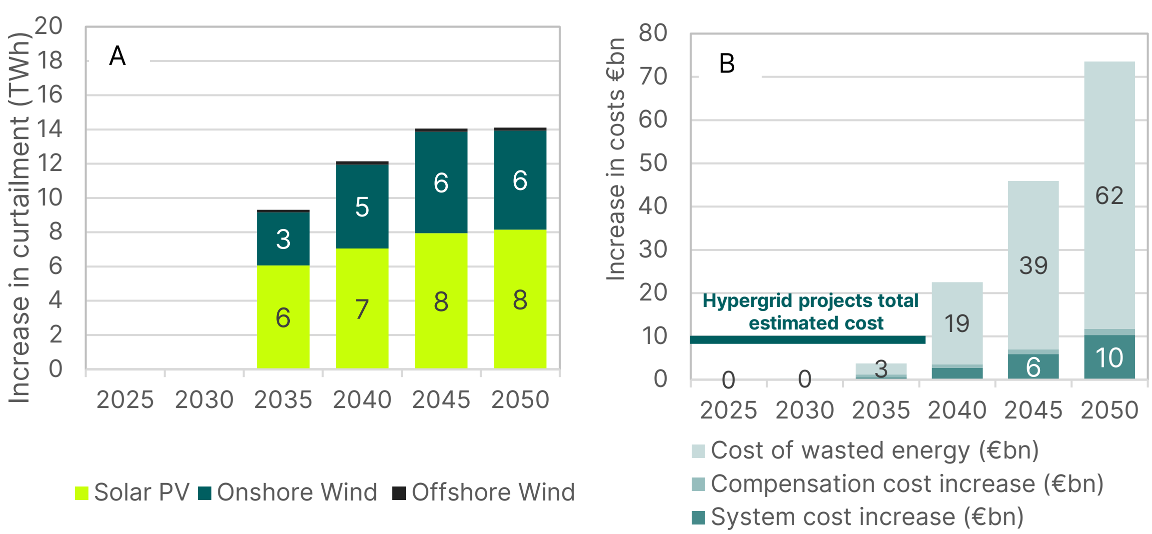

Figure 14 - (A) Increase in curtailment of renewable energy in the counterfactual scenario if Hypergrid projects does not go ahead in Italy, and (B) the respective increase in overall costs

[19] https://download.terna.it/terna/2023_Hypergrid_project_and_development_requirements_8db79602cedc732.pdf

CONCLUSIONS AND RECOMMENDATIONS

The Italian electricity system is expected to undergo a complex transition in order to achieve net zero by 2050 with nearly 60% increase in demand and substantial penetration of renewables generation to decarbonize the system. We draw the following insights from our detailed analysis of this transition.

Ensuring Required Deployment of Renewable Energy

To achieve the National Energy and Climate Plan (NECP) renewable capacity targets for 2030, Italy will need to accelerate the deployment of solar PV and wind power to achieve around 90 GW of total wind and solar capacity by 2030, or over 2 times the 2024 wind and solar capacity.

Solar PV, with a relatively low Levelized Cost of Electricity (LCOE), will see an accelerated growth and Offshore wind will benefit from the FER2 decree, under which it will be eligible for 25-year Contracts for Difference (CfD). However, offshore wind will remain a small portion of the overall generation mix due to a limited wind potential around the Italian coast (i.e. lower capacity factors compared to installations in the North Sea), impacting its economic case.

Growth in onshore wind capacity growth will be particularly challenging for Italy as the additions will need to ramp up to around 2 GW per year for the next 5 years, from only 0.4 GW per year on average in the last 5 years.

An accelerated growth in onshore wind and solar PV will require streamlining administrative processes and incentivizing investment in these technologies. Specifically, authorisation procedures for higher voltage connections need to be simplified, and the rules around CfD for onshore wind and solar PVs may need to be revisited.

Flexible Technologies as a Key Enabler of Achieving Net Zero

The reliance on variable output from solar PV and onshore wind, which have relatively low capacity factors, coupled with the limited development opportunities for relatively higher capacity factor offshore wind, will need dependable and flexible generation to ensure system reliability. We project 8 GW of nuclear SMR and 13-17 GW of CCGT with CCS in 2050, meeting around 25% of projected demand. Therefore, deployment of these thermal technologies will be a key contributor to achieve the net zero target.

As a counterfactual to the Renewable Ambition scenario, we analysed a Business As Usual scenario where Italy continues renewable additions at the level of 2023 growth rate. While the scenario indicates that Italy can still achieve its net zero goals by 2050, this is contingent on (1) higher dependency on electricity imports, and (2) higher utilisation of abated CCGTs.

There also remains an uncertainty in the nuclear SMR development and deployment timeline in Italy. However, our analysis suggests that this would be a cost-effective option to meet net zero in both scenarios. However, if these nuclear additions are delayed or not pursued, much higher volumes of CCGTs with CCS would need to be deployed requiring the CO_2 storage injection capacity above and beyond potential estimates published by the Italian authorities so far.

Furthermore, around 40 GW (4-hour duration) of BESS will be needed for daily peak shaving, reduction of wind & solar curtailment, congestion management and ensuring system reliability. Even with this magnitude of BESS capacity, a significant curtailment occurs, and we recommend prioritising support schemes for smaller scale hybrid PV+BESS projects to address this. Similarly, leveraging demand-side flexibility programs can help manage peak loads as well as reduce energy curtailment. This can involve encouraging consumers to shift their energy consumption to off-peak hours or participate in demand response programs. By implementing these strategies, Italy can enhance its energy system's resilience and reduce the risk of curtailment and energy shortages while progressing towards its net zero goals.

Importance of Electricity Transmission Upgrades

Another key pillar for achieving net zero is the substantial development of the transmission infrastructure to support the growth of renewables and reduce energy curtailment which may reach 58 TWh (around 12% of demand) by 2050 even if all current transmission upgrade projects proceed as planned. Significant part of curtailment can be avoided if further transmission upgrades take place to alleviate the congestion on the SUD to NORD and SARD to CNOR transmission corridors.

The planned Hypergrid projects will help to avoid circa 14 TWh of curtailment and will save over €11bn in system and redispatch cost, i.e. equivalent to the estimated build cost, by 2050. However, the potential cost of wasted energy estimated at National Single Price (PUN) adds over €60bn in net benefits to the Hypergrid project. The Terna development plan 2025 has brought forward the planned commissioning dates for transmission links to Sardinia and the south of Italy. These projects represent a vital investment for delivering net zero, however most of them will be realised post 2035 and therefore will not address the energy curtailment issues in earlier years. Our analysis also revealed that some of these transmission upgrades are not fully aligned with the plans for additional renewable capacity in terms of locations. Specifically, we've identified the interconnection between Sardinia and mainland Italy as requiring further expansion beyond 1 GW included in the Hypergrid plan, as well as the strengthening of the interconnection of the SUD power zone.

KEY INPUTS

Electricity Demand

Electricity demand growth in Italy is aligned with the NECP. It is projected to grow significantly from current levels due to the electrification of transport and heating sectors consistent with the net zero target. Our methodology for analysing demand electrification relies on the logistic function (S-shaped curve). It is fitted to historical data, and targets where available, to estimate future growth of electric vehicles (EVs) and heat pumps as shown in Figure 15A. There is already a considerable number of heat pumps installed in Italy and we model future growth in line with the rate of recent additions. For electric vehicles, we aligned the growth with the target of 4.3 million fully electric vehicles by 2030 and expect an accelerated growth after 2030. We have also included the projections for additional electricity demand from data centres. The overalll electricity demand forecast in Italy is shown in Figure 15B.

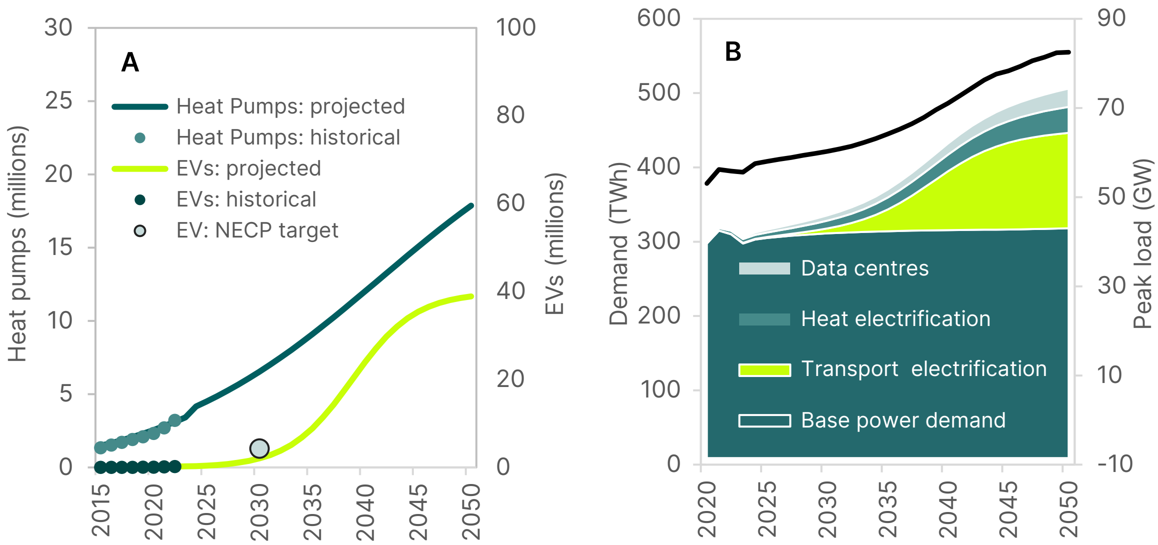

Figure 15 - (A) Uptake of heat pumps and electric vehicles and (B) resulting electricity demand in Italy.

Demand response and advanced control technologies, i.e. virtual power plants, are not explicitly modelled in this study. However, it is accounted for by optimising scheduling of the additional demand from Electric Vehicles (EVs) and heat pumps – i.e. it is modelled as a uniform daily load profile, while still representing the seasonal variation which is particularly relevant for heat pumps.

Wind and Solar Representation

Renewable generation will play a crucial role in decarbonizing Italy's power sector. Differences in potential output profiles between different power zones are captured by calculating hourly generation profiles for new wind and solar farms using the European Centre for Medium-Range Weather Forecasts' (ECMWF) Reanalysis v5 (ERA5) dataset. This dataset provides information on wind velocity and solar irradiation across Italy, which is used along with wind turbine and PV panel configurations to calculate power generation data for each power zone. Capacity factor maps for wind farms and solar PVs are shown in Figure 16.

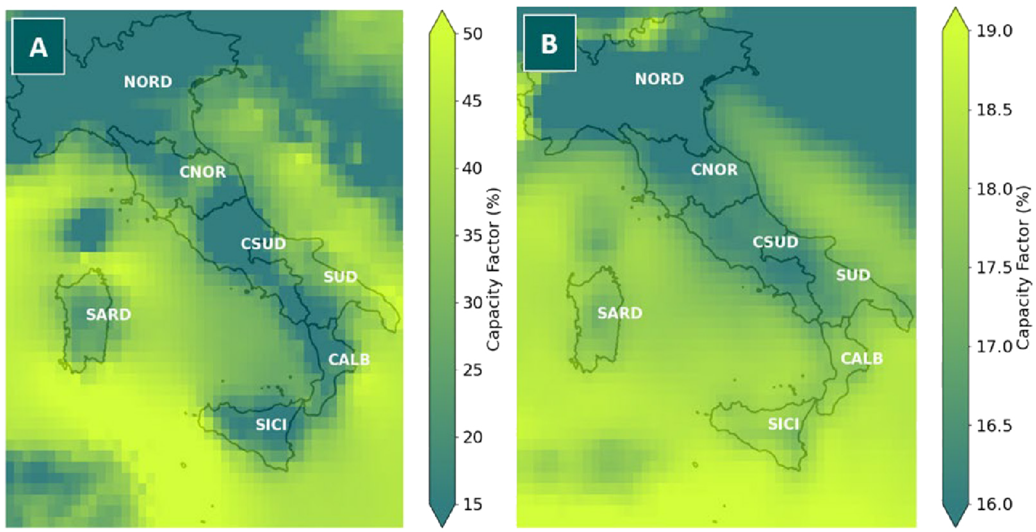

Figure 16 - Capacity factors for (A) wind and (B) solar PV generators in Italy.

An important part of this study was to examine the implications of the planned geographical distribution for new renewable capacity. The limits on future renewable additions by power zone were derived from Terna's development plan, which is based on connection requests. This is shown in Table 2 and has two important implications:

- connection requests may not lead new capacity co-located with load centres, and
- connection requests may not lead to an optimal capacity distribution according to the resource availability.

This study makes an assessment of the current transmission plans and quantifies the potential curtailment of renewable energy and the associated costs of redispatch due to transmission constraints.

Zone	Solar PV	Onshore Wind	Offshore Wind
CALB	1.9%	7.8%	0%
CNOR	5.2%	2.6%	4.7%
CSUD	21.5%	13.0%	10.6%
NORD	23.7%	2.6%	7.0%
SARD	9.7%	10.4%	16.5%
SICI	14.2%	14.3%	16.5%
SUD	23.8%	49.3%	44.7%

Table 2 - Annual distribution limits for solar PV, wind and BESS additions by power zone.

We do not model any retirement of solar or wind capacity and assume that the capacity reaching end of life will be repowered.

Low Carbon Thermal Generation

In each scenario, besides the renewable capacity there will also be a need for additional low-carbon thermal generation to ensure system reliability through provision of sufficient capacity and flexibility while delivering the net zero target.

The NECP in Italy recognises the role of Hydrogen, Carbon Capture and Storage (CCS) as well as nuclear Small Modular Reactors (SMRs) for achieving net zero. Where captured CO_2 can be repurposed for other industries like production of chemicals or cement, it is also referred to as Carbon Capture, Utilisation and Storage (CCUS). However, all of these technologies have limitations and cost related uncertainties. This study provides a clear roadmap for deploying each of these technologies in a cost-effective manner that is aligned with emission reduction targets. Moreover, it examines the effect of existing and planned transmission capacity in Italy and recommends the optimal siting for new generation.

We have considered thermal power plants that are zero or low-carbon to meet the net zero target. This includes new and retrofitted combined cycle gas turbines (CCGTs) with carbon capture and storage (CCS) and Hydrogen-capable units. We have also considered nuclear as Small Modular Reactor (SMRs) which were included as an option after 2030 in the final NECP.

For the CCS units, an important consideration is the infrastructure for transporting and storing CO_2. CCS injection capacity is one of the key factors that will limit how much can be generated by Natural Gas while meeting emission targets. For example, the proposed EU Net-Zero Industry Act (NZIA) targets hard-to-abate emissions in energy-intensive industries as a priority for the deployment of CCS, as opposed to its deployment for electricity generation.[20] Nevertheless, the final NECP puts the CCS technology as one of the key elements of the electricity sector decarbonisation after 2030.

It was assumed that the CO_2 injection capacity in Italy will be 1 $MTCO_2$ per year from 2030 based on the Ravenna cluster potential, excluding initial 4 $MTCO_2$ per year reserved for industrial sectors. This is then increased to 20 $MTCO_2$ per year by 2040 and 40 $MTCO_2$ per year by 2050, in line with the range included in the Italy Long Term Strategy plan.[21]

Cross-Border Interconnection

Italy has about 10.8 GW of interconnection import capacity with its neighbouring countries that is expected to grow by about 2.5 GW by 2035. The model includes between Italy and other countries that are currently under construction as well as future interconnectors considered under the Projects of Common Interest (PCI) as shown in Table 3. Only the maximum import capacities are shown for brevity, however seasonal variations in this capacity as well as export limits are modelled. Generally, we assume slightly higher transmission line capacity in Winter reflecting higher thermal limits. We also take into account the reduction in transfer capacities during off-peak hours.

Country	Current Import Capacity	Expansion
Austria (AT)	600 MW	900 MW from 2029 1400 MW from 2035
France (FR)	4500 MW	
Switzerland (CH)	4500 MW	
Greece (GR)	500 MW	1500 MW from 2031
Slovenia (SL)	700 MW	
Tunisia (TN)		600 MW from 2028

Table 3 - Physical capacity of the interconnectors between Italy and other countries.

[20] https://ec.europa.eu/commission/presscorner/detail/en/ip_24_680
[21] https://www.mase.gov.it/sites/default/files/lts_gennaio_2021.pdf

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FORWARD LOOKING STATEMENTS

This paper contains forward-looking statements – that is, statements related to future events that by their nature address matters that are, to different degrees, uncertain. These forward-looking statements often address GE Vernova's expected future business and financial performance and financial condition, and the expected performance of its products, the impact of its services and the results they may generate or produce, often contain words such as "expect," "anticipate," "intend," "plan," "believe," "seek," "see," "will," "would," "estimate," "forecast," "target," "preliminary," or "range." Forward-looking statements by their nature address matters that are, to different degrees, uncertain, such as statements about planned and potential transactions, investments or projects and their expected results and the impacts of macroeconomic and market conditions and volatility on the Company's business operations, financial results and financial position and on the global supply chain and world economy.

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