Energy Systems

Supplementary Information

High-resolution modeling for the integrated planning of generation, storage, and transmission in energy networks

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S1. Existing Capacity

Existing generation and storage capacities are reported at the EMZ level in Tables S1 and S2.

Table S1. Existing generation capacity (expressed in MW) by technology and EMZ for the baseline scenario (reference year 2021). The values are based on [1–4].

EMZ	Natural Gas	Coal	Geothermal	Bioenergy	Hydropower	Wind Onshore	PV Residential	PV Utility
NORTH	23,223.0	976.0	0.0	2,405.4	16,700.1	165.8	8,368.9	1,827.4
C-NORTH	2,339.0	0.0	771.8	228.1	1,124.7	165.6	1,661.1	910.1
C-SOUTH	9,120.0	1,980.0	0.0	409.4	2,745.1	2,106.7	1,868.7	1,325.2
SOUTH	5,467.0	1,980.0	0.0	442.7	223.7	4,542.3	1,108.2	2,409.1
CALA	3,499.0	0.0	0.0	178.4	779.0	1,174.4	441.2	131.8
SICI	3,029.0	0.0	0.0	69.4	716.1	2,010.0	863.3	678.3
SARD	917.0	1,230.0	0.0	104.5	461.0	1,088.8	600.6	400.4

Table S2. Existing storage capacity by technology and EMZ for the baseline scenario (reference year 2021). The values are based on [4,5].

EMZ	BESS Small [MWh]	BESS Utility [MWh]	PHS [MW]
NORTH	600.0	3,200.0	5,016.0
C-NORTH	0.0	100.0	0.0
C-SOUTH	100.0	1,000.0	1,727.0
SOUTH	0.0	100.0	0.0
CALA	0.0	0.0	0.0
SICI	0.0	0.0	580.0
SARD	0.0	3,500.0	240.0

Existing thermal (non-renewable) and pumped hydro storage plants are clustered by technology type and EMZ, with units within each cluster assumed to be identical. The clustering is based on plant-level databases reporting the individual plants and their nominal capacities [3,4]. Accordingly, the number of units in each cluster is derived from the corresponding plant count, while the nominal unit size of the cluster is represented by the average nominal capacity of the plants belonging to that cluster. The number of existing thermal (non-renewable) and pumped hydro storage units and their average nominal capacity are reported at the EMZ level in Tables S3 and S4.

Table S3. Existing thermal (non-renewable) generation units and average nominal capacity (expressed in MW/unit) by EMZ for the baseline scenario (reference year 2021). The values are based on [3,4].

	CCGT		OCGT		Coal	
EMZ	Units	Avg. P_{nom}	Units	Avg. P_{nom}	Units	Avg. P_{nom}
NORTH	66.0	348.1	7.0	35.9	4.0	244.0
C-NORTH	12.0	182.4	3.0	50.0	0.0	0.0
C-SOUTH	21.0	428.5	4.0	30.5	3.0	660.0
SOUTH	12.0	357.3	10.0	118.0	3.0	660.0
CALA	9.0	363.9	4.0	56.0	0.0	0.0
SICI	9.0	307.6	3.0	87.0	0.0	0.0
SARD	3.0	225.0	4.0	60.5	4.0	307.5

Table S4. Existing pumped hydro storage units and average nominal capacity (expressed in MW/unit) by EMZ for the baseline scenario (reference year 2021). The values are based on [4].

	PHS	
EMZ	Units	Avg. P_{nom}
NORTH	12.0	418.0
C-NORTH	0.0	0.0
C-SOUTH	4.0	431.8
SOUTH	0.0	0.0
CALA	0.0	0.0
SICI	2.0	290.0
SARD	1.0	240.0

The transmission system is represented through the net transfer capacity between neighboring EMZs, as reported in Table S5. The length of each transmission connection is approximated as the straight-line distance between the geographic centers of the connected EMZs.

Table S5. Net transfer capacity (expressed in MW) between neighboring EMZs for the baseline scenario (reference year 2021). Data are taken from [5].

From / To	NORTH	C-NORTH	C-SOUTH	SOUTH	CALA	SICI	SARD
NORTH	-	4,300	-	-	-	-	-
C-NORTH	3,100	-	2,900	-	-	-	-
C-SOUTH	-	2,800	-	2,000	-	-	700
SOUTH	-	-	5,000	-	1,100	-	-
CALA	-	-	-	2,400	-	1,500	-
SICI	-	-	-	-	1,200	-	-
SARD	-	-	900	-	-	-	-

S2. Capacity Expansion Planning

Concerning the available generation, storage, and transmission capacity for new investment, guidance was drawn from the EU Fit-for-55 2030 package for the Italian electricity system [5]. These values do not reflect Italy's maximum technical potential. Rather, they are used as scenario-based limits for new investments, based on the additional capacity identified in the Fit-for-55 scenario.

Table S6 reports the maximum capacity available for new investment in renewable generation and storage technologies at the EMZ level. For natural gas technologies, only an aggregate national increase of about 5 GW is reported in [5], without any specification of zonal distribution. Therefore, we treat this additional gas-fired capacity as a national investment limit that can be allocated across EMZs. Offshore wind is not included, as its installation in Italy has so far encountered strong social resistance and significant bureaucratic obstacles [6]. Table S7 reports the maximum transmission capacity available for new investment between neighboring EMZs.

Table S6. Maximum capacity available for new investment in renewable generation (expressed in MW) and storage technologies (expressed in MWh) by EMZ for the considered future scenarios (reference year 2030). The values are based on [5,7].

EMZ	Wind Onshore	PV Residential	PV Utility	BESS Small	BESS Utility	PHS
NORTH	134.2	3,631.1	8,172.6	8,400.0	0.0	0.0
C-NORTH	234.4	738.9	1,889.9	1,400.0	0.0	0.0
C-SOUTH	993.3	1,931.3	9,774.8	3,300.0	3,520.0	880.0
SOUTH	3,457.7	491.8	12,090.9	800.0	26,800.0	6,700.0
CALA	625.6	58.8	968.2	300.0	4,480.0	1,120.0
SICI	990.0	336.7	7,221.7	800.0	16,320.0	4,080.0
SARD	811.2	0.0	5,199.6	300.0	5,520.0	1,380.0

Table S7. Maximum transmission capacity available for new investment between neighboring EMZs for the considered future scenarios (reference year 2030). The values are based on [5].

Connection	Capacity [MW]
NORTH ↔ C-NORTH	3,500
C-NORTH ↔ C-SOUTH	3,500
C-SOUTH ↔ SOUTH	4,000
C-SOUTH ↔ SARD	1,000
SOUTH ↔ CALA	3,000
CALA ↔ SICI	3,000

S3. Techno-economic characteristics

The economic characteristics of generation, storage, and transmission technologies are reported in Tables S8–S10. Additionally, fuel prices are reported in Table S11. In the numerical application, investment costs are annualized assuming a 5% discount rate [8]. Furthermore, the model permits procurement below the required reserve levels or even load shedding. However, cost penalties of 3,000 €/MWh and 10,000 €/MWh are applied for reserve shedding and load shedding, respectively [9]. These penalty values are assumed to be constant across nodes and time steps.

Table S8. Economic characteristics of generation technologies. Data are taken from [8,10].

Technology	Investment cost [k€/MW]	FOM [k€/MW]	VOM [€/MWh]	Lifetime [years]
CCGT	690.0	15.0	2.31	30
OCGT	570.0	17.0	4.0	15
Coal	1,600.0	25.6	2.40	40
Geothermal	3,198.0	95.0	0.32	35
Bioenergy	1,800.0	40.1	3.56	40
Hydropower	2,400.0	8.2	0.0	50
Wind Onshore	988.0	18.0	0.0	25
PV Residential	930.0	17.0	0.0	25
PV Utility	645.0	12.2	0.0	25

Table S9. Economic characteristics of storage technologies. The values are based on [7,10,11].

Economic characteristic	BESS Small	BESS Utility	PHS
Investment cost power [k€/MW]	162.8	133.0	1,300.0
Investment cost energy [k€/MWh]	215.0	190.0	50.0
FOM [k€/MW]	6.3	15.0	20.3
Lifetime [years]	13	13	65
Discharge duration [h]	2	8	8

Table S10. Economic characteristics of transmission connections. The values are based on [12,13].

Economic characteristic	Transmission connection
Investment cost [€/MW·km]	310.0
FOM [€/MW·km]	0.93
Losses [%/1000km]	2
Lifetime [years]	40

Table S11. Fuel prices. Data are taken from [5].

Fuel	Price [€/MWh]
Natural Gas	45
Coal	9

The technical characteristics of thermal (non-renewable) and storage technologies are presented in Tables S12 and S13.

Table S12. Technical characteristics of thermal (non-renewable) generators. Data are taken from [8, 9].

Technical characteristic	CCGT	OCGT	Coal
MSOP [%/P_{nom}]	30	20	25
Efficiency loss at MSOP [%pt]	3.2	9	2
Ramp rate [%/P_{nom}/min]	10	25	4
Ramp cost [€/ΔMW]	0.22	0.68	1.09
MUT [h]	1	0	6
MDT [h]	1	0	3
Start-up energy [MWh/ΔMW]	1.5	0.0	3.6
Start-up depreciation [€/ΔMW]	24.5	19.4	45.1
Start-up time [h]	1	0.17	2
Efficiency [%]	64	45	49
Availability [%]	85	85	85

Table S13. Technical characteristics of energy storage technologies. Data are taken from [8].

Technical characteristic	BESS	PHS
MSOP while charging [%/P_{nom}]	0	60
MSOP while discharging [%/P_{nom}]	0	30
Ramp rate [%/P_{nom}/min]	100	20
Start-up time charging [min]	0	15
Start-up time discharging [min]	0	5
Shut-down time charging [min]	0	5
Shut-down time discharging [min]	0	10
Round-trip efficiency [%]	90	75
Availability [%]	97	97

An overview of the adopted reserve requirements is presented in Table S14. For storage technologies, in addition to cycling constraints, it is assumed that upward reserves can only be supplied when sufficient stored energy is available for twice the activation time [14].

Table S14. Reserve requirements. The values are based on [8,14].

Type	Activation time	Sizing criterion
Regulation reserves	< 5 min, 100% spin	1% of demand
Spinning contingency reserves	10 min, 50% spin	6% of demand
Flexibility reserves	1 h, 100% spin	10% of wind generation + 7.5% of solar generation

S4. Renewable generation potential and load profiles

The spatially explicit characterization of renewable generation is based on capacity factor time series defined for each EMZ. The capacity factor time series used in the numerical case study are obtained from [1]. Additionally, load profiles for each Italian EMZ are based on [1,2], with electricity demand assumed to be inflexible. For the baseline scenario, the time series refer to the historical year 2021, consistently with the model validation. For the future scenarios considered, a representative weather year is used instead. According to Lombardi et al. [15], the year 2016 is chosen as the most typical reference weather year for Italy.

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