

Modeling the Optimal Transition of an Urban Neighborhood Towards an Energy Community and a Positive Energy District

Supplementary Material

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Supplementary Material A

Input data for the use of EnergyPLAN in the Santa Chiara district case study

Table S1: Regional electricity grid production mix. Electricity generation efficiency from fossil fuels considered equal to 35% in 2024 and 40% in 2050.

	Import (%)	Renewable (%)	Biomass/Biofuel (%)	Gas (%)
2024	0.6%	81.6%	0.7%	17.1%
2050	5.4%	83.0%	0.8%	10.8%

Table S2: National electricity grid production mix. Electricity generation efficiency from fossil fuels considered equal to 48% in 2024 and 56% in 2050.

	Coal (%)	Oil (%)	Gas (%)	Renewable & Nuclear (%)
2024	5.07	0.88	48.13	45.92
2050	0.00	0.00	12.00	88.00

Table S3: Efficiencies.

Technology	2024	2050
Individual Gas Boilers	0.97	0.98
Individual Hydrogen Boilers	0.97	0.98
Individual Heat Pump (SCOP)	2.96	3.31
Individual Heat Pump (SEER)	4.00	4.48
Alkaline Electrolyzer (%)	70	75
Fuel Cell P2P (%)	45	55
Battery	0.89	0.94
ICEV (kWh/km)	0.422	0.319
BEV (kWh/km)	0.155	0.117
FCEV (kWh/km)	0.256	0.181

Table S4: CAPEX.

Technology	Unit	2024 (MEuro/unit)	2050 (MEuro/unit)
Small PV	MWe	1.88	1.52
Small Solar Thermal	TWh/year	1628	1116
Solar Heat Storage	GWh	3.00	3.00
Individual Gas Boilers	1000 Units*	2.00	2.00
Individual Hydrogen Boilers	1000 Units*	2.73	2.73
Individual Heat Pump	1000 Units*	10.95	10.30
Alkaline Electrolyzer	MWe	0.948	0.600
Fuel Cell P2P	MWe	2.940	1.815
H2 Storage	GWh	22	18
Battery	GWh	884	520
ICEV + Ref. Station	1000 veh.	15.48	17.86
BEV + Ch. Station	1000 veh.	29.71	24.92
FCEV + Ref. Station	1000 veh.	36.21	27.46

*Heating demand per unit = 15000 kWh/year

Table S5: OPEX.

Technology	Unit	2024	2050
Small PV	% CAPEX	1.97	1.97
Small Solar Thermal	% CAPEX	0.94	1.38
Solar Heat Storage	% CAPEX	0.70	0.70
Individual Gas Boilers	% CAPEX	4.17	4.17
Individual Hydrogen Boilers	% CAPEX	4.17	4.17
Individual Heat Pump	% CAPEX	1.00	1.09
Alkaline Electrolyzer	% CAPEX	4	4
Fuel cell P2P	% CAPEX	4	4
H2 Storage	% CAPEX	2	2
Battery	% CAPEX	1.26	2.31
ICEV + Ref. Station	% CAPEX	2.38	2.08
BEV + Ch. Station	% CAPEX	1.14	1.36
FCEV + Ref. Station	% CAPEX	2.30	3.04

Table S6: Lifetimes.

Technology	Unit	2024	2050
Small PV	years	25	25
Small Solar Thermal	years	25	25
Solar Heat Storage	years	30	30
Individual Gas Boilers	years	25	25
Individual Hydrogen Boilers	years	25	25
Individual Heat Pump	years	20	20
Alkaline Electrolyzer	years	13	13

Fuel cell P2P	years	10	10
H2 Storage	years	30	30
Battery	years	15	15
ICEV + Ref. Station	years	12	12
BEV + Ch. Station	years	12	12
FCEV + Ref. Station	years	12	12

Table S7: Energy carriers cost.

Energy carrier	Unit	2024	2050
Diesel (for vehicles)	€/GJ	42.78	39.42
Gas	€/GJ	22.65	17.55
Electricity PUN (average)	€/MWh	134	89
Electrical grid distribution cost	€/MWh	109.36	164.44
Energy Community incentive	€/MWh	110	110

Table S8: CO₂ emissions of energy carriers.

	tCO ₂ /MWh
Coal	0.341
Oil	0.267
Ngas	0.202

Supplementary Material B

MOEA boundaries in the four types of simulation scenarios

Table S9: MOEA boundaries of scenario S1. * thermal demand.

TECHNOLOGY	2024		2050 ERY_h^I		2050 UC	
	MOEA LB	MOEA HB	MOEA LB	MOEA HB	MOEA LB	MOEA HB
ELECTRICAL SECTOR						
PV (kW)	0	772	0	935	0	870
Battery (kW)	0	500	0	500	0	500
Battery (MWh)	0	1	0	1	0	1
Import (kW)	0	9999999	0	9999999	0	9999999
Export (kW)	0	9999999	0	9999999	0	9999999
HYDROGEN SECTOR						
BI-Tr Hydrogen Electrolyser (kW)	defined by EnergyPLAN		defined by EnergyPLAN		defined by EnergyPLAN	
BI-Tr Hydrogen Storage (MWh)	0	10	0	10	0	10
P2P Hydrogen Electrolyser (kW)	0	500	0	500	0	500
P2P Hydrogen Fuel Cell (kW)	0	500	0	500	0	500
P2P Hydrogen Storage (MWh)	0	10	0	10	0	10
THERMAL SECTOR						
Solar thermal* (GWh)	0	2.322	0	3.336	0	2.466
Heat Pump (heating)* (GWh)	0	2.158	0	1.546	0	2.158

Heat Pump (cooling)* (GWh)	0.590	0.590	1.180	1.180	0.590	0.590
Boiler gas* (GWh)	0	2.158	0	1.546	0	2.158
Boiler hydrogen* (GWh)	0	2.158	0	1.546	0	2.158
Solar Heat Storage (in days of average heat demand)	0	1	0	1	0	1
TRANSPORT SECTOR						
Transport el (Mkm)	0	4.760	0	4.760	0	4.760
Transport H2 (Mkm)	0	4.760	0	4.760	0	4.760
Transport diesel (Mkm)	0	4.760	0	4.760	0	4.760

Table S10: MOEA boundaries of scenario S2. * thermal demand.

TECHNOLOGY	2024		2050 ERY_h^I		2050 UC	
	MOEA LB	MOEA HB	MOEA LB	MOEA HB	MOEA LB	MOEA HB
ELECTRICAL SECTOR						
PV (kW)	0	772	0	935	0	870
Battery (kW)	0	500	0	500	0	500
Battery (MWh)	0	1	0	1	0	1
Import (kW)	0	9999999	0	9999999	0	9999999
Export (kW)	0	9999999	0	9999999	0	9999999
HYDROGEN SECTOR						
Bl-Tr Hydrogen Electrolyser (kW)	defined by EnergyPLAN		defined by EnergyPLAN		defined by EnergyPLAN	
Bl-Tr Hydrogen Storage (MWh)	0	10	0	10	0	10
P2P Hydrogen Electrolyser (kW)	0	500	0	500	0	500
P2P Hydrogen Fuel Cell (kW)	0	500	0	500	0	500
P2P Hydrogen Storage (MWh)	0	10	0	10	0	10
THERMAL SECTOR						
Solar thermal* (GWh)	0	2.322	0	3.336	0	2.466
Heat Pump (heating)* (GWh)	0	2.158	0	1.546	0	2.158
Heat Pump (cooling)* (GWh)	0.590	0.590	1.180	1.180	0.590	0.590
Boiler gas* (GWh)	0	2.158	0	1.546	0	2.158
Boiler hydrogen* (GWh)	0	2.158	0	1.546	0	2.158
Solar Heat Storage (in days of average heat demand)	0	1	0	1	0	1
TRANSPORT SECTOR						
Transport el (Mkm)	0	4.760	0	4.760	0	4.760
Transport H2 (Mkm)	0	4.760	0	4.760	0	4.760
Transport diesel (Mkm)	0	4.760	0	4.760	0	4.760

Table S11: MOEA boundaries of scenario S3. * thermal demand.

TECHNOLOGY	2024		2050 ERY_h^I		2050 UC	
	MOEA LB	MOEA HB	MOEA LB	MOEA HB	MOEA LB	MOEA HB
ELECTRICAL SECTOR						
PV (kW)	0	772	0	935	0	870
Battery (kW)	0	500	0	500	0	500
Battery (MWh)	0	1	0	1	0	1
Import (kW)	0	9999999	0	9999999	0	9999999
Export (kW)	0	9999999	0	9999999	0	9999999
HYDROGEN SECTOR						
Bl-Tr Hydrogen Electrolyser (kW)	defined by EnergyPLAN		defined by EnergyPLAN		defined by EnergyPLAN	
Bl-Tr Hydrogen Storage (MWh)	0	10	0	10	0	10
P2P Hydrogen Electrolyser (kW)	0	500	0	500	0	500
P2P Hydrogen Fuel Cell (kW)	0	500	0	500	0	500
P2P Hydrogen Storage (MWh)	0	10	0	10	0	10
THERMAL SECTOR						
Solar thermal* (GWh)	0	2.322	0	3.336	0	2.466
Heat Pump (heating)* (GWh)	0	2.158	0	1.546	0	2.158
Heat Pump (cooling)* (GWh)	0.590	0.590	1.180	1.180	0.590	0.590
Boiler gas* (GWh)	0	2.158	0	1.546	0	2.158
Boiler hydrogen* (GWh)	0	2.158	0	1.546	0	2.158
Solar Heat Storage (in days of average heat demand)	0	1	0	1	0	1
TRANSPORT SECTOR						
Transport el (Mkm)	0	0	0	0	0	0
Transport H2 (Mkm)	0	0	0	0	0	0
Transport diesel (Mkm)	0	0	0	0	0	0

Table S12: MOEA boundaries of scenario S4. * thermal demand.

TECHNOLOGY	2024		2050 ERY_h^I		2050 UC	
	MOEA LB	MOEA HB	MOEA LB	MOEA HB	MOEA LB	MOEA HB
ELECTRICAL SECTOR						
PV (kW)	0	772	0	935	0	870
Battery (kW)	0	0	0	0	0	0
Battery (MWh)	0	0	0	0	0	0
Import (kW)	0	9999999	0	9999999	0	9999999
Export (kW)	0	9999999	0	9999999	0	9999999
HYDROGEN SECTOR						
Bl-Tr Hydrogen Electrolyser (kW)	defined by EnergyPLAN		defined by EnergyPLAN		defined by EnergyPLAN	
Bl-Tr Hydrogen Storage (MWh)	0	10	0	10	0	10
P2P Hydrogen Electrolyser (kW)	0	500	0	500	0	500
P2P Hydrogen Fuel Cell (kW)	0	500	0	500	0	500

P2P Hydrogen Storage (MWh)	0	10	0	10	0	10
THERMAL SECTOR						
Solar thermal* (GWh)	0	0	0	0	0	0
Heat Pump (heating)* (GWh)	0	0	0	0	0	0
Heat Pump (cooling)* (GWh)	0.590	0.590	1.180	1.180	0.590	0.590
Boiler gas* (GWh)	0	2.158	0	1.546	0	2.158
Boiler hydrogen* (GWh)	0	2.158	0	1.546	0	2.158
Solar Heat Storage (in days of average heat demand)	0	0	0	0	0	0
TRANSPORT SECTOR						
Transport el (Mkm)	0	0	0	0	0	0
Transport H2 (Mkm)	0	4.760	0	4.760	0	4.760
Transport diesel (Mkm)	0	4.760	0	4.760	0	4.760

Supplementary Material C

Extra formulas (additional algorithms for model adjustment)

for 2024:

- CAPEX: FCEV=Transport H2 km/12900*36.21*0.05/(1-(1+0.05)^(-12))
- OPEX: FCEV=Transport H2 km/12900*0.023*36.21
- CAPEX: Heat storage=heat storage in days of heat demand*heat demand/366*3000*0.05/(1-(1+0.05)^(-30))
- OPEX: Heat storage=heat storage in days of heat demand*0.007*heat demand/366*3000
- VARIABLE COST: electrical grid distribution cost=109.36*(Pure el demand+El for BEV Transport+El for Heat Pumps+El for battery charge+ El for H2 P2P+El for H2 for transport+ El for H2 heat)
- VARIABLE COST: Energy Communities incentive =110*(PV production - El export)

If HP_heat_demand > HP_cooling_demand

- CAPEX: HP=(HP_heat_demand *10^6/15000)*10.95*0.05/(1-(1+0.05)^(-20))
- OPEX: HP=(HP_heat_demand *10^6/15000)*0.01*10.95

Else

- CAPEX: HP=(HP_cooling_demand*10^6/15000)*10.95*0.05/(1-(1+0.05)^(-20))
- OPEX: HP=(HP_cooling_demand*10^6/15000)*0.01*10.95

eff_gas_nat = 0.482

eff_gas_reg = 0.35

- CO2 EMISSION: National electricity =elecImport * 0.006

- CO2 EMISSION: Regional gas = elecImport * 0.171
- CO2 EMISSION: National gas = National electricity * 0.4813
- CO2 EMISSION: National oil = National electricity * 0.0088
- CO2 EMISSION: National coal = National electricity * 0.0507
- CO2 EMISSION: CO2InImportedEleGas = (National gas/eff_gas_nat*0.202)
- CO2 EMISSION: CO2InImportedEleOil = (National oil /eff_gas_nat*0.267)
- CO2 EMISSION: CO2InImportedEleCoal = (National coal /eff_gas_nat*0.341)
- CO2 EMISSION: CO2RegionalEleGas = (Regional gas/ eff_gas_reg *0.202)
- CO2 EMISSION:
TOTlocalCO2emission=localCO2emission+CO2InImportedEleOil+CO2InImportedEleNGas
+CO2InImportedEleCoal + CO2RegionalEleGas
- CONSTRAINT: (PV_capacity*6.28)+((Solar_input_annual*10^6)/ 478)<= 4849

for 2050 ERY_h^I :

- CAPEX: FCEV=Transport H2 km/12900*27.461*0.05/(1-(1+0.05)^(-12))
- OPEX: FCEV=Transport H2 km/12900*0.0304*27.461
- CAPEX: Heat storage=heat storage in days of heat demand*heat demand/366*3000*0.05/(1-(1+0.05)^(-30))
- OPEX: Heat storage=heat storage in days of heat demand*0.007*heat demand/366*3000
- VARIABLE COST: electrical grid distribution cost=164.44*(Pure el demand+El for BEV Transport+El for Heat Pumps+El for battery charge+ El for H2 P2P+El for H2 for transport+ El for H2 heat)
- VARIABLE COST: Energy Communities incentive =110*(PV production - El export)

If HP_heat_demand > HP_cooling_demand

- CAPEX: HP=(HP_heat_demand *10^6/15000)*10.3*0.05/(1-(1+0.05)^(-20))
- OPEX: HP =(HP_heat_demand *10^6/15000)*0.0109*10.3

Else

- CAPEX: HP=(HP_cooling_demand*10^6/15000)*10.3*0.05/(1-(1+0.05)^(-20))
- OPEX: HP =(HP_cooling_demand*10^6/15000)*0.0109*10.3

eff_gas_nat = 0.56

eff_gas_reg = 0.4

- CO2 EMISSION: National electricity =elecImport * 0.054

- CO2 EMISSION: Regional gas = elecImport * 0.108
- CO2 EMISSION: National gas = National electricity * 0.12
- CO2 EMISSION: CO2InImportedEleGas = (National gas/eff_gas_gas*0.202)
- CO2 EMISSION: CO2RegionalEleGas = (Regional gas/ eff_gas_reg *0.202)
- CO2 EMISSION: TOTlocalCO2emission=localCO2emission+CO2InImportedEleNGas + CO2RegionalEleGas
- CONSTRAINT: (PV_capacity*5.18+[(Solar_input_annual*10^6)/ 730]<= 4849

for 2050 UC:

- CAPEX: FCEV=Transport H2 km/12900*27.461*0.05/(1-(1+0.05)^(-12))
- OPEX: FCEV=Transport H2 km/12900*0.0304*27.461
- CAPEX: Heat storage=heat storage in days of heat demand*heat demand/366*3000*0.05/(1-(1+0.05)^(- 30))
- OPEX: Heat storage=heat storage in days of heat demand*0.007*heat demand/366*3000
- VARIABLE COST: electrical grid distribution cost=164.44*(Pure el demand+El for BEV Transport+El for Heat Pumps+El for battery charge+ El for H2 P2P+El for H2 for transport+ El for H2 heat)
- VARIABLE COST: Energy Communities incentive =110*(PV production - El export)

If HP_heat_demand > HP_cooling_demand

- CAPEX: HP=(HP_heat_demand *10^6/15000)*10.3*0.05/(1-(1+0.05)^(-20))
- OPEX: HP =(HP_heat_demand *10^6/15000)*0.0109*10.3

Else

- CAPEX: HP=(HP_cooling_demand*10^6/15000)*10.3*0.05/(1-(1+0.05)^(-20))
- OPEX: HP =(HP_cooling_demand*10^6/15000)*0.0109*10.3

eff_gas_nat = 0.56

eff_gas_reg = 0.4

- CO2 EMISSION: National electricity =elecImport * 0.054
- CO2 EMISSION: Regional gas =elecImport * 0.108
- CO2 EMISSION: National gas = National electricity * 0.12
- CO2 EMISSION: CO2InImportedEleGas = (National gas/eff_gas_gas*0.202)
- CO2 EMISSION: CO2RegionalEleGas = (Regional gas/ eff_gas_reg *0.202)

- CO2 EMISSION: $TOTlocalCO2emission = localCO2emission + CO2InImportedEleNGas + CO2RegionalEleGas$
- CONSTRAINT: $(PV_capacity * 5.57 + [(Solar_input_annual * 10^6) / 508]) \leq 4849$

Supplementary Material D

Santa Chiara district energy system: results of the EnergyPLAN+MOEA scenarios in S1 2050 ERY_h^I , S1 2050 UC, S2 2024, S2 2050 ERY_h^I , S2 2050 UC, S3 2024, S3 2050 ERY_h^I , S3 2050 UC, S4 2024, S4 2050 ERY_h^I , S4 2050 UC

























