Multi-objective optimization of an energy community: an integrated and dynamic approach for full decarbonisation in the European Alps

Supplementary material

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Supplementary Material A

Input data for the use of EnergyPLAN in the CEIS case study

Table 1: National electricity grid production mix. Electricity generation efficiency from fossil fuels considered equal to 45% in 2018, 53% in 2030 and 56% in 2050 (**[1]**, **[2]** *).*

	Coal (%)	Oil (%)	Gas (%)	Renewable & Nuclear (%)	Reference
2018	11.52	0.60	41.56	46.32	GSE [1]
2030	0.00	0.66	46.94	52.40	Italian NECP [2]
2050	0.00	0.00	25.00	75.00	Italian NECP [2]

Table 2: Efficiencies.

Technology	2018	2030	2050	Reference
Hydro Power (kWh/kW)	4632	4632	4632	CEIS
Small PV (kWh/kW)	1032	1074	1095	CEIS / IEA [3]
Biogas (el) (kWh/kW)	6171	6943	7714	CEIS / IEA [4]
Small Solar Thermal (kWh/m2)	678	705	720	IEA [5]
Individual Oil Boilers	0.84	0.87	0.88	IEA [5]
Individual LPG/Gas Boilers	0.94	0.97	0.98	IEA [5]
Individual Biomass Boilers	0.75	0.78	0.80	IEA [5]
Individual Hydrogen Boilers		0.97	0.98	IEA [5]
Individual Heat Pump (SPF)	2.8	3.04	3.31	IEA [5]
Small Gas CHP with DH (el)		0.38	0.40	IEA [4]
Small Gas CHP with DH (th)		0.48	0.50	IEA [4]
Small Bio CHP with DH (el)		0.16	0.18	IEA [4]
Small Bio CHP with DH (th)		0.60	0.63	IEA [4]
DH Losses (%)		20	20	AIRU [6]
Energy Efficient Building Envelopes LC (MWh)	16166	17826	21249	ENEA [7]
Alkaline Electrolyzer (%)		72.17	75.35	IEA [8]
Fuel Cell P2P (%)		50.80	53.04	IEA [8]

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Battery		0.9	0.94	IEA [9]
ICEV (kWh/km)	0.538	0.398	0.319	FIF [10]
BEV (kWh/km)		0.146	0.117	FIF [10]
FCEV (kWh/km)		0.239	0.181	FIF [10]

Table 3: CAPEX.

Technology	**Unit**	**2018 (MEuro/unit)**	**2030 (MEuro/unit)**	**2050 (MEuro/unit)**	**Reference**
Hydro Power	MWe	2.6	2.6	2.6	IEA [11] / EnergyPLAN [12]
Small PV	MWe	1.91	1.76	1.52	IEA [3] / EnergyPLAN [12]
Biogas (el)	MWe	5.93	5.50	5.30	IEA [4]
Small Solar Thermal	TWh/year	1236	1129	1066	IEA [5]
Solar Heat Storage	GWh	3	3	3	EnergyPLAN [12]
Individual Oil/LPG/Gas/Biomass Boilers	1000 Units*	3	3	3	IEA [5]
Individual Hydrogen Boilers	1000 Units*		3.725	3.725	IEA [5]
Individual Heat Pump	1000 Units*	11.8	10.8	10.3	IEA [5]
Small Gas CHP	MWe		0.9	0.9	IEA [4]
Small Bio CHP	MWe		6.6	6.4	IEA [4]
DH	TJ		0.174	0.174	EnergyPLAN [12]
Energy Efficient Building Envelopes LC (MWh)	MWh	0.0033	0.0033	0.0033	ENEA [7]
Alkaline Electrolyzer	MWe		0.742	0.598	IEA [8]
Fuel Cell P2P	MWe		1.392	1.121	IEA [8]
H2 Storage	GWh		13.93	11.21	IEA [8]
Battery	GWh		400	260	IEA [9]
ICEV + Ref. Station	1000 veh.	14.789	16.028	17.856	FIF [10]
BEV + Ch. Station	1000 veh.		28.602	24.921	FIF [10]
FCEV + Ref. Station	1000 veh.		34.191	27.461	FIF [10]

*Heating demand per unit = 15000 kWh/year

Table 4: OPEX.

Technology	**Unit**	**2018**	**2030**	**2050**	**Reference**
Hydro Power	% CAPEX	2.2	2.2	2.2	EnergyPLAN [12]
Small PV	% CAPEX	1.71	1.97	1.97	EnergyPLAN [12]
Biogas (el)	% CAPEX	0.77	0.83	0.85	EnergyPLAN [12]

Small Solar Thermal	% CAPEX	1.24	1.36	1.44	EnergyPLAN [12]
Solar Heat Storage	% CAPEX	0.7	0.7	0.7	EnergyPLAN [12]
Individual Oil/LPG/Gas/Biomass Boilers	% CAPEX	4.17	4.17	4.17	IEA [5]
Individual Hydrogen Boilers	% CAPEX		4.17	4.17	IEA [5]
Individual Heat Pump	% CAPEX	0.94	1.03	1.09	IEA [5]
Small Gas CHP	% CAPEX		3.91	3.99	EnergyPLAN [12]
Small Bio CHP	% CAPEX		0.83	0.85	EnergyPLAN [12]
DH	% CAPEX		0.76	0.76	EnergyPLAN [12]
Energy Efficient Building Envelopes LC (MWh)	% CAPEX	0	0	0	IEA [5]
Alkaline Electrolyzer	% CAPEX		9.0	11.0	IEA [8]
Fuel cell P2P	% CAPEX		9.0	11.0	IEA [8]
H2 Storage	% CAPEX		9.0	11.0	IEA [8]
Battery	% CAPEX		1.5	2.31	IEA [9]
ICEV + Ref. Station	% CAPEX	2.47	2.31	2.08	FIF [10]
BEV + Ch. Station	% CAPEX		1.19	1.36	FIF [10]
FCEV + Ref. Station	% CAPEX		2.5	3.04	FIF [10]

Table 5: Lifetimes.

Technology	Unit	2018	2030	2050	Reference
Hydro Power	years	50	50	50	EnergyPLAN [12]
Small PV	years	25	25	25	EnergyPLAN [12]
Biogas (el)	years	20	20	20	EnergyPLAN [12]
Small Solar Thermal	years	25	25	25	EnergyPLAN [12]
Solar Heat Storage	years	30	30	30	EnergyPLAN [12]
Individual Oil/LPG/Gas/Biomass Boilers	years	25	25	25	EnergyPLAN [12]
Individual Hydrogen Boilers	years		25	25	EnergyPLAN [12]
Individual Heat Pump	years	20	20	20	EnergyPLAN [12]

Small Gas CHP	years		20	20	EnergyPLAN [12]
Small Bio CHP	years		20	20	EnergyPLAN [12]
DH	years		40	40	EnergyPLAN [12]
Energy Efficient Building Envelopes LC (MWh)	years	30	30	30	IEA [5]
Alkaline Electrolyzer	years		13	13	IEA [8]
Fuel cell P2P	years		13	13	IEA [8]
H2 Storage	years		15	15	IEA [8]
Battery	years		15	15	IEA [9]
ICEV + Ref. Station	years	12	12	12	FIF [10]
BEV + Ch. Station	years		12	12	FIF [10]
FCEV + Ref. Station	years		12	12	FIF [10]

Table 6: Energy carriers cost.

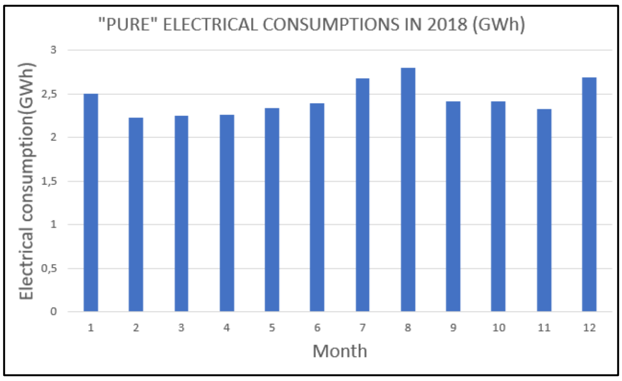
Energy carrier	Unit	2018	2030	2050	Reference
Diesel (for vehicles)	€/MWh	131.58	151.97	141.91	MISE [13] / IEA 2DS [14]
Oil (for boilers)	€/MWh	112.97	133.06	124.27	MISE [13] / IEA 2DS [14]
Gas	€/MWh		71.39	72.00	ARERA [15] / IEA 2DS [14]
LPG	€/MWh	101.12	118.08	119.09	MISE [13] / IEA 2DS [14]
Wood	€/MWh	37.33	42.98	47.48	AIEL [16]
Electricity (PUN) average	€/MWh	56	80	92	GME [17] / RSE [18] / EU STRATEGY [19]
Electrical grid distribution cost	€/MWh	158.20	213.61	236.31	ARERA [15] / RSE [20] / EU STRATEGY [19]

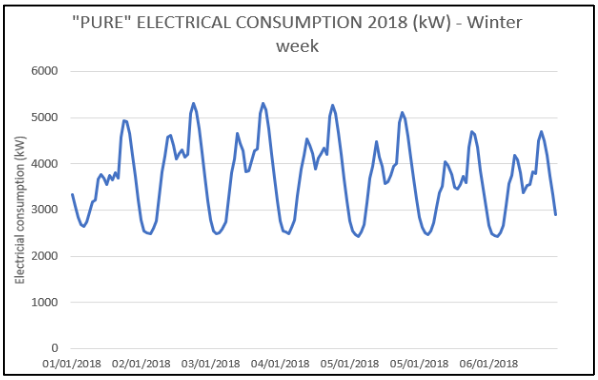
Table 7: CO_2 emissions of energy carriers.

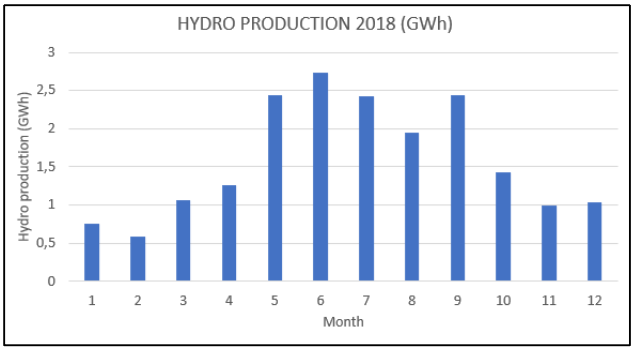
	tC02/MWh	Reference
Coal	0.341	Covenant of Mayors [21]
Oil	0.267	Covenant of Mayors [21]
Ngas	0.202	Covenant of Mayors [21]
LPG	0.231	Covenant of Mayors [21]

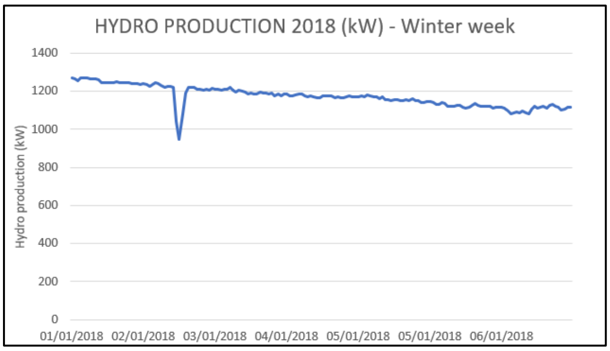
Supplementary Material B

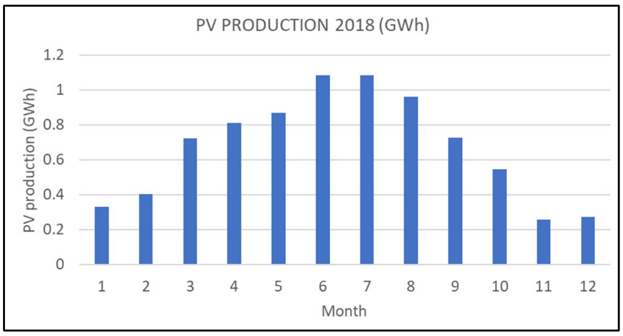
CEIS energy system: hourly profiling of productions, demands and national electricity market

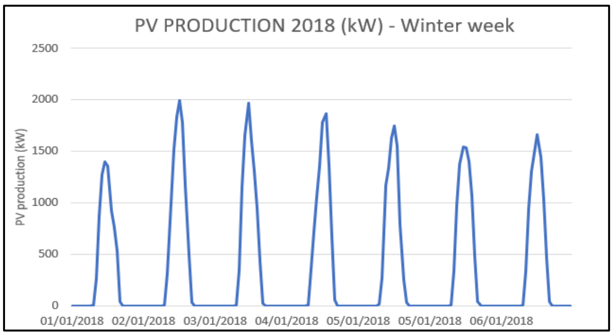


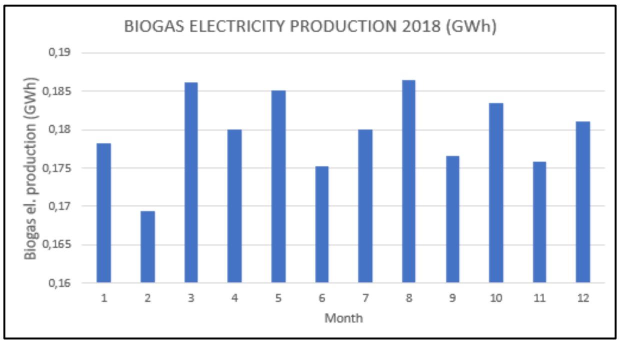


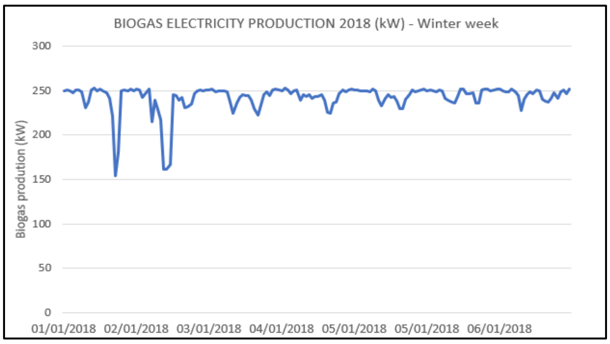


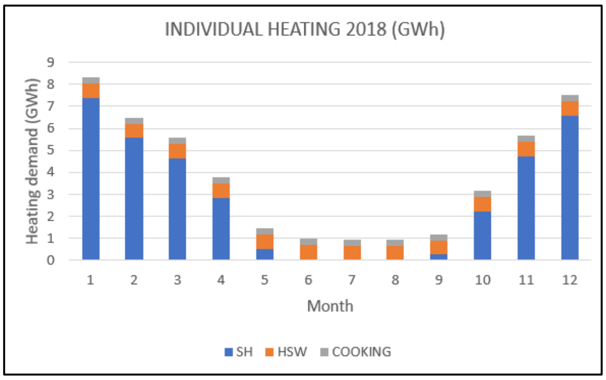


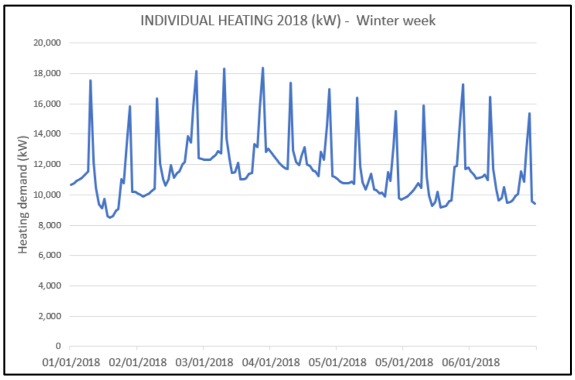


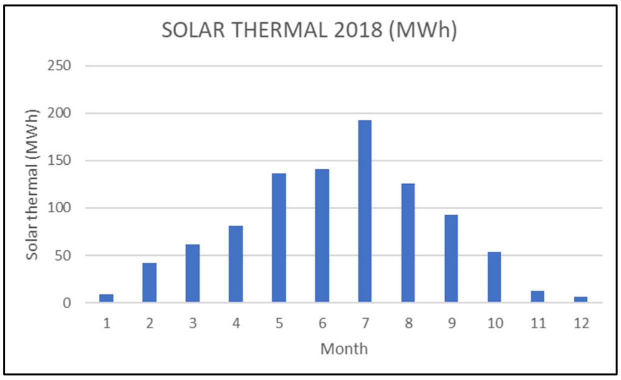


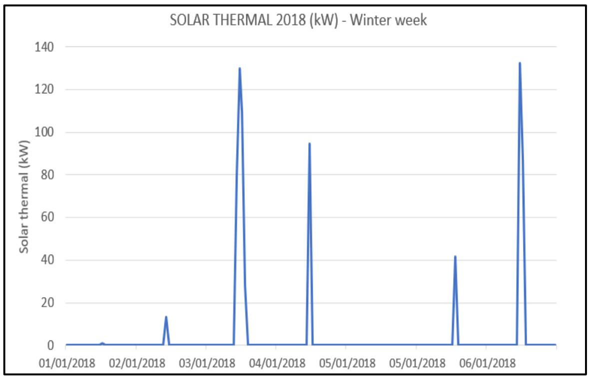


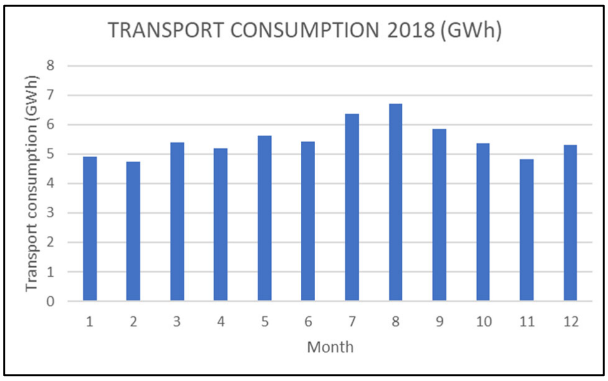


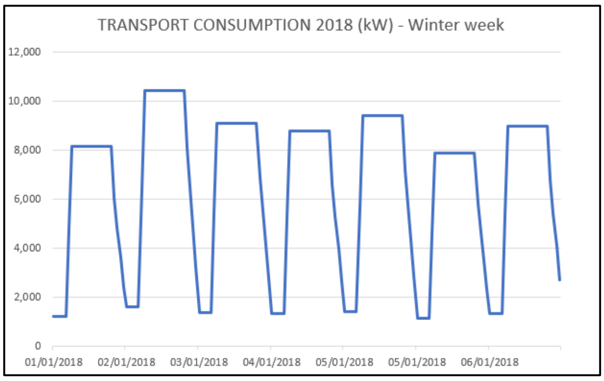

INDIVIDUAL HEATING 2018 (GWh)
Heating demand (GWh)
Month
SH
HSW
COOKING

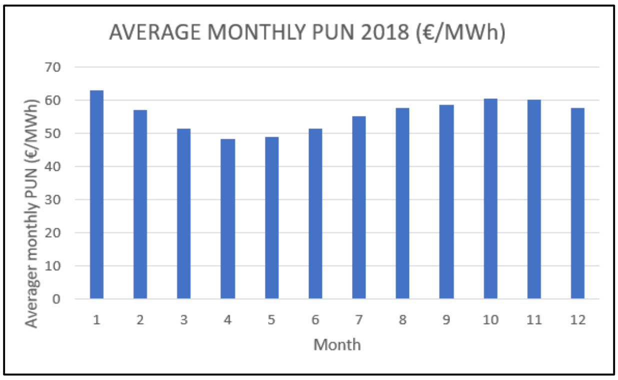

INDIVIDUAL HEATING 2018 (kW) - Winter week
Heating demand (kW)

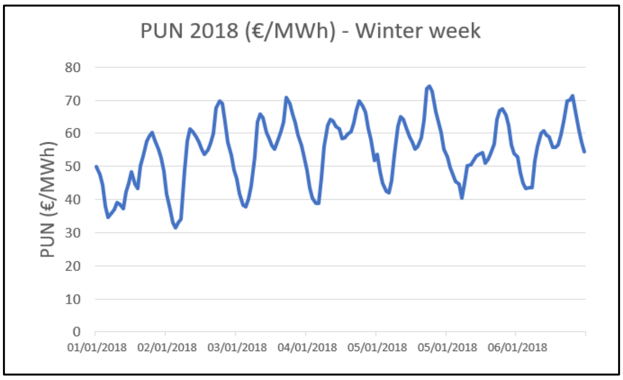

SOLAR THERMAL 2018 (MWh)
Solar thermal (MWh)
Month


SOLAR THERMAL 2018 (kW) - Winter week
Solar thermal (kW)


TRANSPORT CONSUMPTION 2018 (GWh)
Transport consumption (GWh)
Month


TRANSPORT CONSUMPTION 2018 (kW) - Winter week


AVERAGE MONTHLY PUN 2018 (€/MWh)
Averager monthly PUN (€/MWh)
Month


PUN 2018 (€/MWh) - Winter week
PUN (€/MWh)

Supplementary Material C

Input data for the years 2030 and 2050

To evaluate the CEIS decarbonisation scenarios for the years 2030 and 2050 with the framework EnergyPLAN+MOEA, it is necessary to provide the same type of input data of the Baseline 2018: energy demands in the three sectors (thermal, electrical, transport), available technologies (decision variables) for energy production, energy storage and energy efficiency, together with their respective efficiencies, CAPEX, OPEX, lifetimes, energy carriers cost and emission factors.

Concerning the energy demands, the input data for the years 2030 and 2050 is obtained considering the trend of the population, the reduction of the space heating demand due to building renovations and a projection of the historical trend of "pure" electricity consumption.

Starting from the thermal demand, its trend is linked to two factors: trend of the population and trend of the building renovations (Table 8). The trend of the population in the CEIS area is assumed to be the same of the Province of Trento which is provided by Istituto nazionale di statistica – ISTAT [22]. In a first analysis it is assumed that the thermal demand for SH, HSW and cooking follows the same trend of the population. Then, SH energy savings are considered in each year due to the renovation of the buildings, assuming the LC trend of the PEAP study for the Province of Trento [23].

Table 8: Analysis of the trend of the thermal demand in the CEIS area. Q_{SH} = thermal demand for space heating, Q_{HSW} = thermal demand for hot sanitary water, $Q_{COOKING}$ = thermal demand for cooking, Q_{TOT} = total thermal demand.

Year	2018	2020	2025	2030	2035	2040	2045	2050
CEIS population	8371	8426	8658	8878	9079	9246	9368	9433
Energy eff. build env. CEIS LC (GWh/year)	0.539	0.655	0.673	0.690	0.706	0.719	0.728	0.733
Q_{SH} (GWh/year)	36.11	35.03	32.63	30.01	27.16	24.07	20.74	17.22
Q_{HSW} (GWh/year)	8.30	8.36	8.59	8.81	9.01	9.17	9.29	9.36
$Q_{COOKING}$ (GWh/year)	3.38	3.40	3.50	3.59	3.67	3.74	3.79	3.81
Q_{TOT} (GWh/year)	47.79	46.79	44.72	42.41	39.84	36.98	33.82	30.39

Regarding the electrical demand, its trend is linked both to the demographic trend and to the projection of the historical trend of "pure" electricity consumption. This historical trend includes the effect of both electrical efficiency measures (e.g., LED lighting and more efficient household appliances), and the growing demand for "pure" electricity (e.g., for more lighting services, greater use of household appliances, electricity consumption in the artisan and industrial sectors). Considering the period 2010-2019, the electricity consumption grows from 28.18 GWh/year to 29.23 GWh/year (+0.413% per year) while the population decreases from 8369 to 8334 inhabitants (-0.042% per year). Therefore, the historical trend of increase in "pure" electricity consumption per capita is equal to +0.455% per year. In this way, starting from 2019 (which is the last year with available data that are not influenced by the COVID-19 pandemic) it is possible to reconstruct a prediction of the "pure" electrical demand in the CEIS area for the future years until 2050 (Table 9).

Table 9: Analysis of the trend of the "pure" electricity demand in the CEIS area. $E_{e,CEIS}$ = "pure" electricity demand.

Year	2019	2025	2030	2035	2040	2045	2050
$E_{e,CEIS}$ (GWh/year)	29.23	30.99	32.49	33.96	35.36	36.63	37.72

The transport energy demand is evaluated on the base of the annual distance in Mkm travelled by the vehicles of the CEIS area. In the Baseline 2018 this value is equal to:

$$d_{CEIS\ vehicles\ Base} = \frac{E_{P,trans\ CEIS\ tot\ Base}}{\eta_{diesel\ cars\ Base}} = \frac{65.73\ GWh}{0.538\ GWh/Mkm} = 122.17\ Mkm$$

where:

- $d_{CEIS\ vehicles\ Base}$ is the "ideal" distance (Mkm) travelled by the vehicles of the CEIS area in the Baseline 2018 in order to consume all the primary energy of the transport sector, if they would be all diesel cars
- $E_{P,trans\ CEIS\ tot\ Base}$ is the total primary energy of the transport sector in the CEIS area in the Baseline 2018 expressed in GWh
- $\eta_{diesel\ cars\ Base}$ is the average efficiency of the diesel cars in the Baseline 2018 expressed in GWh/Mkm.

Then, the annual distance travelled in the future by the vehicles of the CEIS area (Table 10) is projected following the trend of the population (+3.4% by 2030 and +11.9% by 2050).

The calculation of the number of km travelled in one year is done supposing that all the vehicles are cars and with this approach it is also possible to obtain the number of equivalent vehicles supposing that each car travels 12900 km/year. The number of equivalent vehicles (Table 10) is used for the analysis of CAPEX and OPEX.

Table 10: Analysis of the trend of the transport demand in the CEIS area. $d_{trans\ CEIS}$ = annual distance travelled by the vehicles of the CEIS area, $n_{equivalent\ vehicles}$ = number of equivalent vehicles.

Year	2018	2020	2025	2030	2035	2040	2045	2050
$d_{trans\ CEIS}$ (Mkm/year)	122.17	122.97	126.36	129.57	132.50	134.95	136.72	137.67
$n_{equivalent\ vehicles}$	9471	9532	9796	10044	10271	10461	10598	10672

Supplementary Material D

MOEA boundaries in the four types of simulation scenarios

*Table 11: MOEA boundaries of scenario S1. * thermal demand.*

TECHNOLOGY	2030		2050	
	MOEA LB	MOEA HB	MOEA LB	MOEA HB
ELECTRICAL SECTOR				
Hydro (kW)	0	4732	0	4732
PV (kW)	0	81256	0	88192
Biogas (kW)	0	350	0	350
Battery (kW)	0	20000	0	30000
Battery (MWh)	0	40	0	60
Import (kW)	0	9999999	0	9999999
Export (kW)	0	9999999	0	9999999
HYDROGEN SECTOR				
Bl-Tr Hydrogen Electrolyser (kW)	defined by EnergyPLAN		defined by EnergyPLAN	
Bl-Tr Hydrogen Storage (MWh)	0	100	0	100
P2P Hydrogen Electrolyser (kW)	0	2000	0	2000
P2P Hydrogen Fuel Cell (kW)	0	2000	0	2000
P2P Hydrogen Storage (MWh)	0	500	0	500
CHP + THERMAL SECTOR				
Energy eff. build. env. (GWh)	17.826		21.249	
Solar thermal* (GWh)	0	437.021	0	475.262
Heat Pump* (GWh)	0	42.407	0	30.391
CHP-DH biomass* (GWh)	0	42.407	0	30.391
CHP-DH gas* (GWh)	0	42.407	0	30.391
Boiler oil* (GWh)	0	42.407	0	30.391
Boiler LPG* (GWh)	0	42.407	0	30.391
Boiler gas* (GWh)	0	42.407	0	30.391
Boiler biomass* (GWh)	0	42.407	0	30.391
Boiler hydrogen* (GWh)	0	42.407	0	30.391
Solar Heat Storage (in days of average heat demand)	0	366	0	366
TRANSPORT SECTOR				
Transport el (Mkm)	0	129.572	0	137.674
Transport H2 (Mkm)	0	129.572	0	137.674
Transport diesel (Mkm)	0	129.572	0	137.674

*Table 12: MOEA boundaries of scenario S2. * thermal demand.*

TECHNOLOGY	2030		2050	
	MOEA LB	MOEA HB	MOEA LB	MOEA HB
ELECTRICAL SECTOR				
Hydro (kW)	3339	4732	2016	4732

PV (kW)	4820	81256	0	88192
Biogas (kW)	182	350	0	350
Battery (kW)	0	20000	0	30000
Battery (MWh)	0	40	0	60
Import (kW)	0	9999999	0	9999999
Export (kW)	0	9999999	0	9999999
HYDROGEN SECTOR				
Bl-Tr Hydrogen Electrolyser (kW)	defined by EnergyPLAN		defined by EnergyPLAN	
Bl-Tr Hydrogen Storage (MWh)	0	100	0	100
P2P Hydrogen Electrolyser (kW)	0	2000	0	2000
P2P Hydrogen Fuel Cell (kW)	0	2000	0	2000
P2P Hydrogen Storage (MWh)	0	500	0	500
CHP + THERMAL SECTOR				
Energy eff. build. env. (GWh)	17.826		21.249	
Solar thermal* (GWh)	0.523	437.021	0.000	475.262
Heat Pump* (GWh)	0.854	42.407	0.000	30.391
CHP-DH biomass* (GWh)	0.000	42.407	0.000	30.391
CHP-DH gas* (GWh)	0.000	42.407	0.000	30.391
Boiler oil* (GWh)	9.741	42.407	0.000	30.391
Boiler LPG* (GWh)	4.904	42.407	0.000	30.391
Boiler gas* (GWh)	0.000	42.407	0.000	30.391
Boiler biomass* (GWh)	9.944	16.142	0.000	11.568
Boiler hydrogen* (GWh)	0.000	42.407	0.000	30.391
Solar Heat Storage (in days of average heat demand)	0	2	0	2
TRANSPORT SECTOR				
Transport el (Mkm)	0	129.572	0	137.674
Transport H2 (Mkm)	0	129.572	0	137.674
Transport diesel (Mkm)	25.914	129.572	0	137.674

*Table 13: MOEA boundaries of scenario S3. * thermal demand.*

TECHNOLOGY	**2030**		**2050**	
	MOEA LB	**MOEA HB**	**MOEA LB**	**MOEA HB**
ELECTRICAL SECTOR				
Hydro (kW)	3339	4732	2016	4732
PV (kW)	4820	81256	0	88192
Biogas (kW)	182	350	0	350
Battery (kW)	0	20000	0	30000
Battery (MWh)	0	40	0	60
Import (kW)	0	9999999	0	9999999
Export (kW)	0	9999999	0	9999999
HYDROGEN SECTOR				
Bl-Tr Hydrogen Electrolyser (kW)	defined by EnergyPLAN		defined by EnergyPLAN	
Bl-Tr Hydrogen Storage (MWh)	0	100	0	100
P2P Hydrogen Electrolyser (kW)	0	2000	0	2000

P2P Hydrogen Fuel Cell (kW)	0	2000	0	2000
P2P Hydrogen Storage (MWh)	0	500	0	500
CHP + THERMAL SECTOR				
Energy eff. build. env. (GWh)	17.826		21.249	
Solar thermal* (GWh)	0.523	437.021	0.000	475.262
Heat Pump* (GWh)	0.854	42.407	0.000	30.391
CHP-DH biomass* (GWh)	0.000	0.000	0.000	0.000
CHP-DH gas* (GWh)	0.000	0.000	0.000	0.000
Boiler oil* (GWh)	9.741	42.407	0.000	30.391
Boiler LPG* (GWh)	4.904	42.407	0.000	30.391
Boiler gas* (GWh)	0.000	42.407	0.000	30.391
Boiler biomass* (GWh)	9.944	16.142	0.000	11.568
Boiler hydrogen* (GWh)	0.000	42.407	0.000	30.391
Solar Heat Storage (in days of average heat demand)	0	2	0	2
TRANSPORT SECTOR				
Transport el (Mkm)	0	129.572	0	137.674
Transport H2 (Mkm)	0	129.572	0	137.674
Transport diesel (Mkm)	25.914	129.572	0	137.674

*Table 14: MOEA boundaries of scenario S4. * thermal demand.*

TECHNOLOGY	2030		2050	
	MOEA LB	**MOEA HB**	**MOEA LB**	**MOEA HB**
ELECTRICAL SECTOR				
Hydro (kW)	3339	4732	2016	4732
PV (kW)	4820	81256	0	88192
Biogas (kW)	182	350	0	350
Battery (kW)	0	0	0	0
Battery (MWh)	0	0	0	0
Import (kW)	0	9999999	0	9999999
Export (kW)	0	9999999	0	9999999
HYDROGEN SECTOR				
Bl-Tr Hydrogen Electrolyser (kW)	defined by EnergyPLAN		defined by EnergyPLAN	
Bl-Tr Hydrogen Storage (MWh)	0	500	0	500
P2P Hydrogen Electrolyser (kW)	0	2000	0	2000
P2P Hydrogen Fuel Cell (kW)	0	2000	0	2000
P2P Hydrogen Storage (MWh)	0	500	0	500
CHP + THERMAL SECTOR				
Energy eff. build. env. (GWh)	17.826		21.249	
Solar thermal* (GWh)	0.523	0.523	0.000	0.000
Heat Pump* (GWh)	0.854	0.854	0.000	0.000
CHP-DH biomass* (GWh)	0.000	0.000	0.000	0.000
CHP-DH gas* (GWh)	0.000	42.407	0.000	30.391
Boiler oil* (GWh)	9.741	42.407	0.000	30.391
Boiler LPG* (GWh)	4.904	42.407	0.000	30.391

Boiler gas* (GWh)	0.000	42.407	0.000	30.391
Boiler biomass* (GWh)	9.944	9.944	0.000	0.000
Boiler hydrogen* (GWh)	0.000	42.407	0.000	30.391
Solar Heat Storage (in days of average heat demand)	0	2	0	2
TRANSPORT SECTOR				
Transport el (Mkm)	0.000	0.000	0.000	0.000
Transport H2 (Mkm)	0.000	129.572	0.000	137.674
Transport diesel (Mkm)	25.914	129.572	0.000	137.674

Supplementary Material E

MOEA boundaries

Here below are reported some general considerations that are valid for all scenarios. Moreover, Supplementary Materials D details the MOEA boundaries of the four types of simulation scenarios, each with two time steps corresponding to 2030 and 2050.

For what concerns the productions and the storage of the electrical sector, the choices are as follows:

- The higher boundary of the hydroelectric power is equal to the sum of the Baseline 2018 (4132 kW) and one possible future plant with a power of 600 kW
- The higher boundary of the PV power is calculated considering a maximum potential installation in the CEIS area based on 50% of the available roofs surface[1] and a local yield in kW/m^2
- The higher boundary of the biogas power is set at the Baseline 2018 level since there is no expansion planned
- The higher boundary of the battery storage capacity (MWh) is considered initially equal to the annual electricity export of the CEIS area in the Baseline 2018 and then reduced to a value close to the optimal results of some preliminary tests (in order to reduce the search space of the MOEA to values close to the optimized ones), the only exception is S4 where batteries are not considered
- The battery storage power (kW) is set to be half of the battery storage capacity in S1, S2 and S3
- The higher boundaries of the electrical import and export are considered practically unlimited (9999999 kW), to enable the simulation of energy systems free to exchange electricity with the external grid.

The higher boundaries for the hydrogen sector are defined in this way:

- For the power of the electrolyser for boilers (blending) and transport (FCEV) these are defined autonomously by EnergyPLAN as the minimum size to meet the demand for hydrogen boilers and FCEVs, considering also the storage size (the decision variable of the next point)

For the storage of hydrogen for boilers (blending) and transport (FCEV) these are considered initially equal to the annual electricity export of the CEIS area in the Baseline 2018 and then reduced to a value close to the optimal results of some preliminary tests (in order to reduce the search space of the MOEA to values close to the optimized ones)

- For the power of the electrolyser for power to power (P2P) these are considered initially equal to the maximum power exported from the CEIS grid in the Baseline 2018 and then reduced to a value close to the optimal results of some preliminary tests (in order to reduce the search space of the MOEA to values close to the optimized ones)
- For the power of the fuel cell for P2P these are considered initially equal to the maximum power imported to the CEIS grid in the Baseline 2018 and then reduced to a value close to the optimal results of some preliminary tests (in order to reduce the search space of the MOEA to values close to the optimized ones)
- For the storage of hydrogen for P2P these are considered initially equal to the annual electricity export of the CEIS area in the Baseline 2018 and then reduced to a value close to the optimal results of some preliminary tests (in order to reduce the search space of the MOEA to values close to the optimized ones).

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[1] With a conservative approach, it is considered that only 50% of the roofs surface in the CEIS area can be used for the installation of PV or solar thermal. The remaining 50% is deemed unsuitable for unfavorable exposure or other obstacles (e.g., chimneys). Moreover, following the current legislation in the Province of Trento, PV or solar thermal systems on the ground are not allowed; the only exception is 1 existing CEIS PV plant called "Sol de Ise" with a power of 637 kW.

As regards CHP and the thermal sector, the following considerations are made:

- The energy savings from the renovation of the building envelopes have no lower or higher boundaries but a single value calculated as explained in the Supplementary Materials C , assuming the LC trend of the PEAP for the Province of Trento [23]
- The higher boundary of the solar thermal is calculated considering a maximum potential installation in the CEIS area based on 50% of the available roofs surface and a local yield in kWh/m^2, the only exception is S4 where is the residual installed capacity considering the lifetime and the replacement rate
- The heat pump higher boundary is the total thermal demand both in 2030 and 2050 for scenarios S1, S2 and S3, while in S4 is the residual installed capacity considering the lifetime and the replacement rate
- The biomass CHP with DH higher boundary is the total thermal demand both in 2030 and 2050 for scenarios S1 and S2, while in S3 and S4 is not considered (no DH)
- The natural gas CHP with DH higher boundary is the total thermal demand both in 2030 and 2050 for scenarios S1, S2 and S4, while in S3 is not considered (no DH)
- The higher boundaries for all the types of boilers (oil, LPG, gas, hydrogen), except the biomass boilers, are the total thermal demand both in 2030 and 2050 in all scenarios
- The biomass boilers higher boundary is calculated, both in 2030 and 2050, in a different way: in S1 is the total thermal demand, in S2 and S3 maintain the same percentage of the Baseline 2018 (38% of the total thermal demand), in S4 is the residual installed capacity considering the lifetime and the replacement rate
- The solar thermal storage, expressed in days of average heat demand, can range from zero to the whole year in S1 and from zero to two days in S2, S3 and S4.

For the transport sector the boundaries are set in terms of Mkm/year for each considered technology:

- BEV: the higher boundary is the total transport demand, both in 2030 and 2050, for scenarios S1, S2 and S3, while in S4 is not considered (only FCEV vs ICEV)
- FCEV: the higher boundary is the total transport demand, both in 2030 and 2050, for all scenarios
- ICEV: the higher boundary is the total transport demand, both in 2030 and 2050, for all scenarios.

Supplementary Materials F

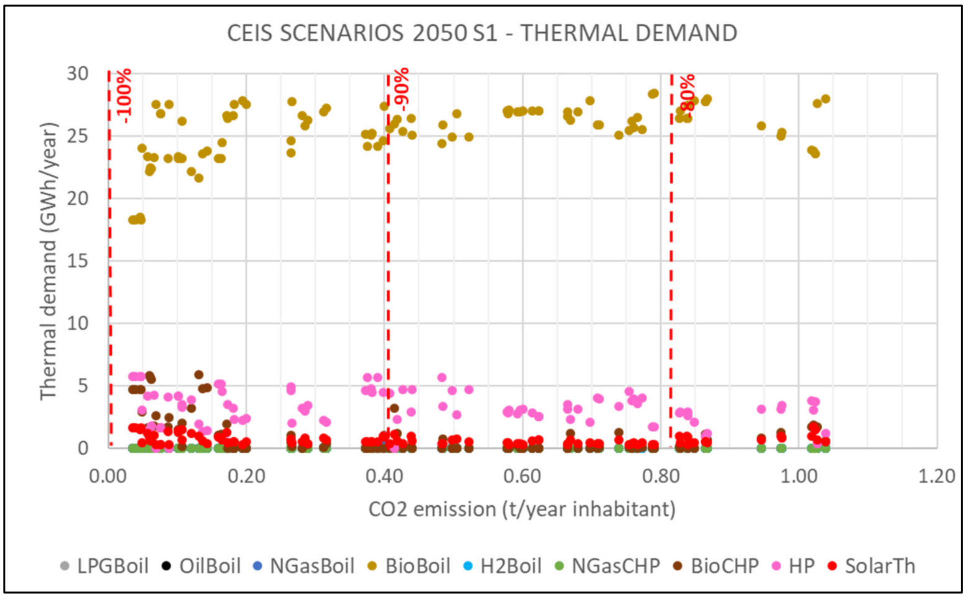
Extra formulas (additional algorithms for model adjustment)

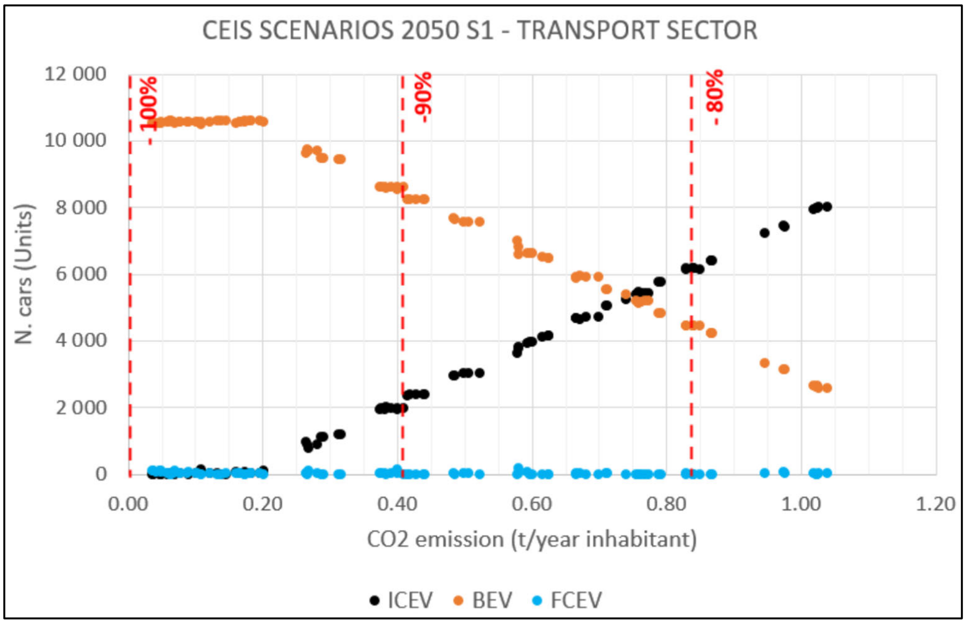
In order to accurately evaluate total annual costs and CO_2 emissions of CEIS energy scenarios in 2030 and 2050, it is necessary to include some extra formulas (additional algorithms) in the EnergyPLAN+MOEA framework to overcome some limitations of EnergyPLAN:

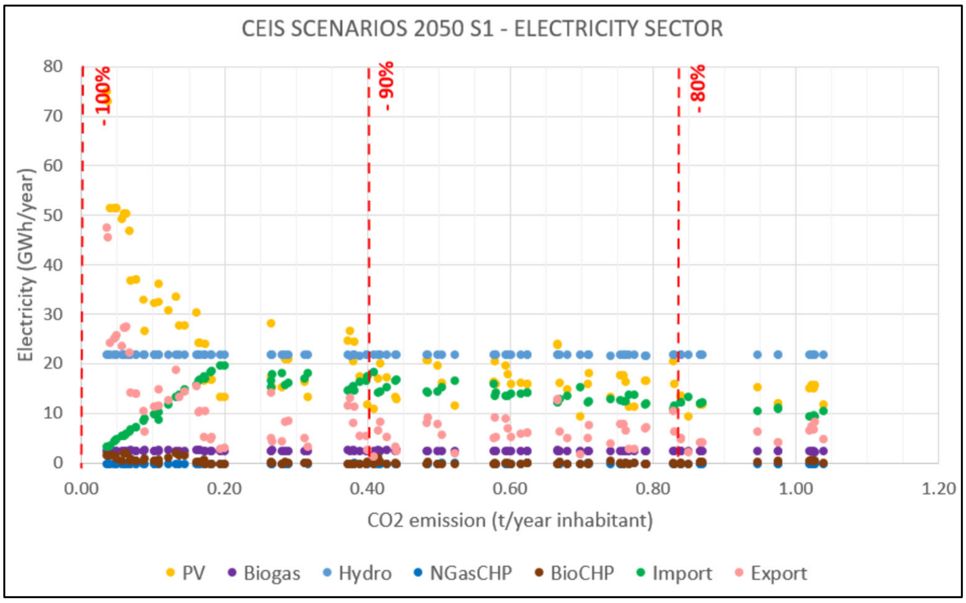
- The CAPEX and OPEX of the two types of CHP connected to DH (biomass and gas) in EnergyPLAN are set to zero and they are calculated using extra formulas. This is done in order to differentiate the costs of these two types of CHP, something not possible with EnergyPLAN in the individual heating screen
- The hydrogen boilers are considered in EnergyPLAN as "H2 micro-CHP", with CAPEX and OPEX set to zero and calculated using extra formulas (for the same reasons mentioned above)
- For FCEV, solar thermal storage and building energy efficiency there are no direct ways to consider CAPEX and OPEX in EnergyPLAN, these are therefore included with specific extra-formulas
- Electricity distribution costs are considered as variable costs with a specific extra formula that includes a 41% discount for locally produced and self-consumed electricity (this discount is not activated on imports)
- H2 distribution costs are considered as variable costs with a specific extra formula, a function of the hydrogen demand of the H2 boilers and of the same distribution cost considered at national level for natural gas
- Two specific extra formulas consider the CO_2 emissions related to oil and gas included in the national electricity generation mix and associated with the CEIS import
- Finally, an extra formula is dedicated to a particular constraint to be respected: the sum of the surfaces of PV and solar thermal installations cannot exceed 50% of the surface of the roofs in the CEIS area (higher boundary). Therefore, PV and solar thermal are two competing technologies to occupy the same roofs of the CEIS buildings.

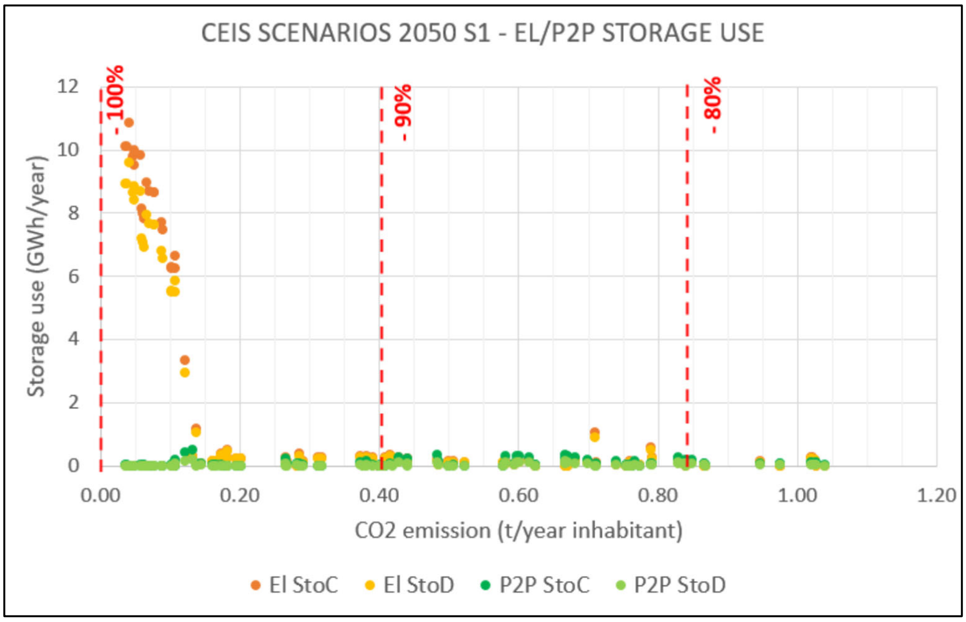
Supplementary Material G

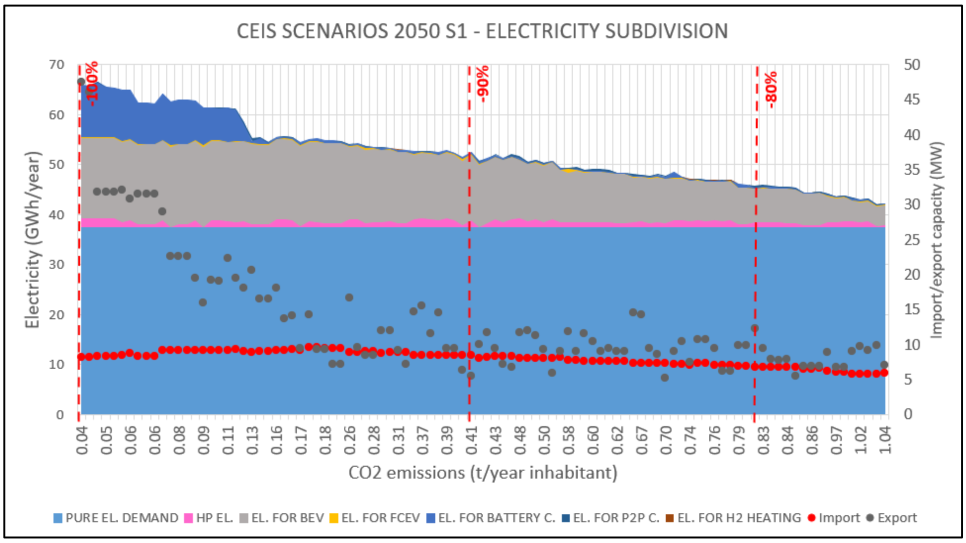
CEIS energy system: results of the EnergyPLAN+MOEA scenarios in S1 2050, S2 2030, S2 2050, S3 2030, S3 2050, S4 2030, S4 2050

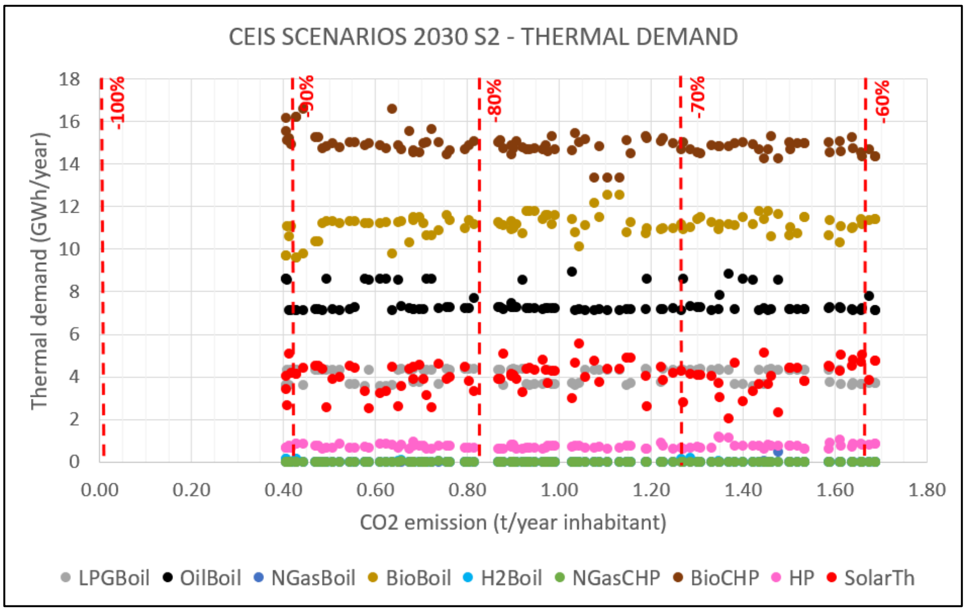


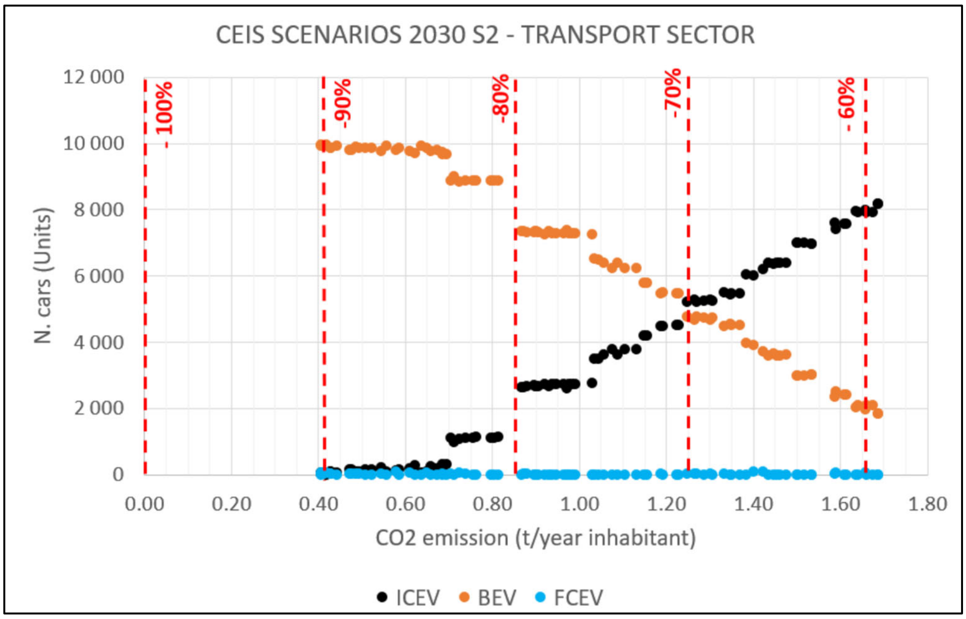


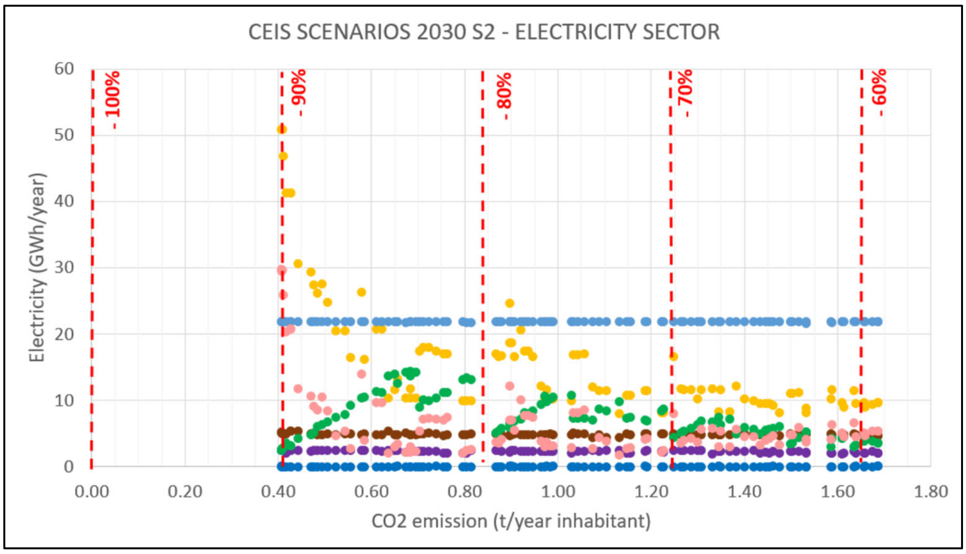

CEIS SCENARIOS 2050 S1 - ELECTRICITY SECTOR
Electricity (GWh/year)
CO2 emission (t/year inhabitant)
- 100%
- 90%
- 80%
PV
Biogas
Hydro
NGasCHP
BioCHP
Import
Export

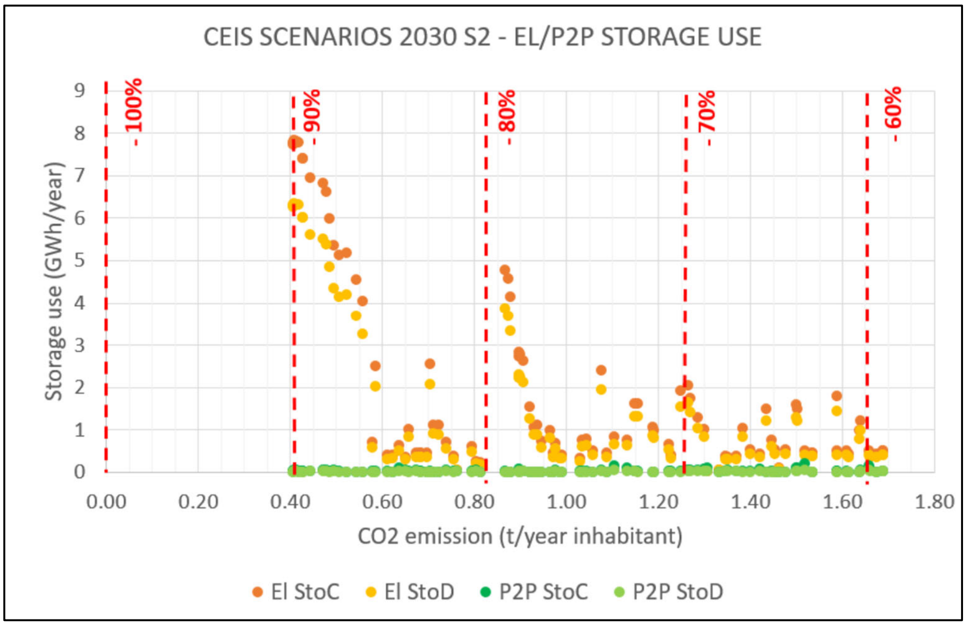

CEIS SCENARIOS 2050 S1 - EL/P2P STORAGE USE
Storage use (GWh/year)
CO2 emission (t/year inhabitant)
- 100%
- 90%
- 80%
El StoC
El StoD
P2P StoC
P2P StoD

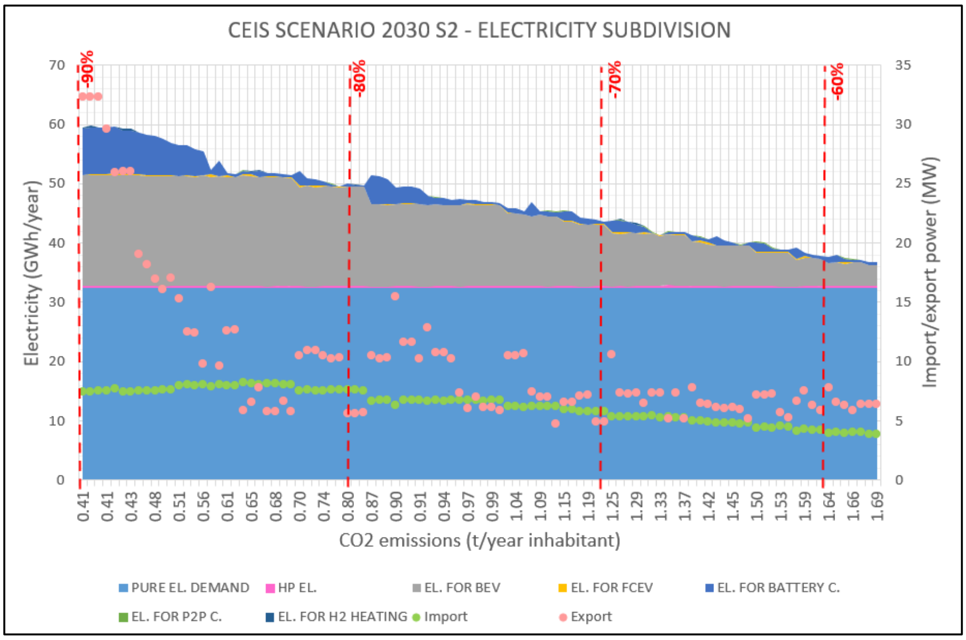

CEIS SCENARIOS 2050 S1 - ELECTRICITY SUBDIVISION
Electricity (GWh/year)
Import/export capacity (MW)
CO2 emissions (t/year inhabitant)
-100%
-90%
-80%
PURE EL. DEMAND
HP EL.
EL. FOR BEV
EL. FOR FCEV
EL. FOR BATTERY C.
EL. FOR P2P C.
EL. FOR H2 HEATING
Import
Export

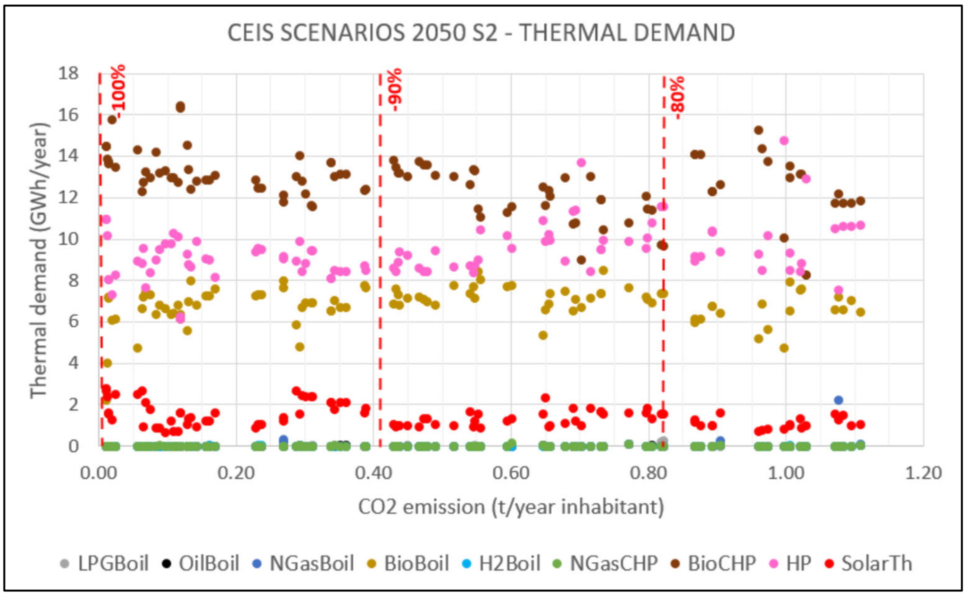

CEIS SCENARIOS 2030 S2 - THERMAL DEMAND
Thermal demand (GWh/year)
CO2 emission (t/year inhabitant)
-100%
-90%
-80%
-70%
-60%
LPGBoil
OilBoil
NGasBoil
BioBoil
H2Boil
NGasCHP
BioCHP
HP
SolarTh


CEIS SCENARIOS 2030 S2 - TRANSPORT SECTOR
N. cars (Units)
12 000
10 000
8 000
6 000
4 000
2 000
0
-100%
-90%
-80%
-70%
-60%
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
1.60
1.80
CO2 emission (t/year inhabitant)
ICEV
BEV
FCEV

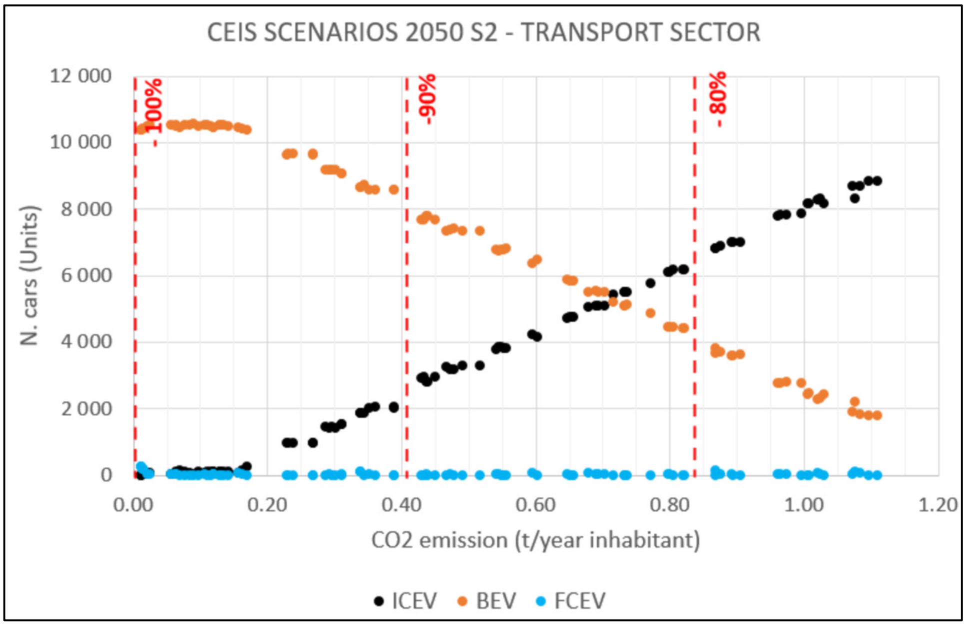

CEIS SCENARIOS 2030 S2 - ELECTRICITY SECTOR
Electricity (GWh/year)
60
50
40
30
20
10
0
-100%
-90%
-80%
-70%
-60%
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
1.60
1.80
CO2 emission (t/year inhabitant)


CEIS SCENARIOS 2030 S2 - EL/P2P STORAGE USE
Storage use (GWh/year)
CO2 emission (t/year inhabitant)
- 100%
- 90%
- 80%
- 70%
- 60%
El StoC
El StoD
P2P StoC
P2P StoD

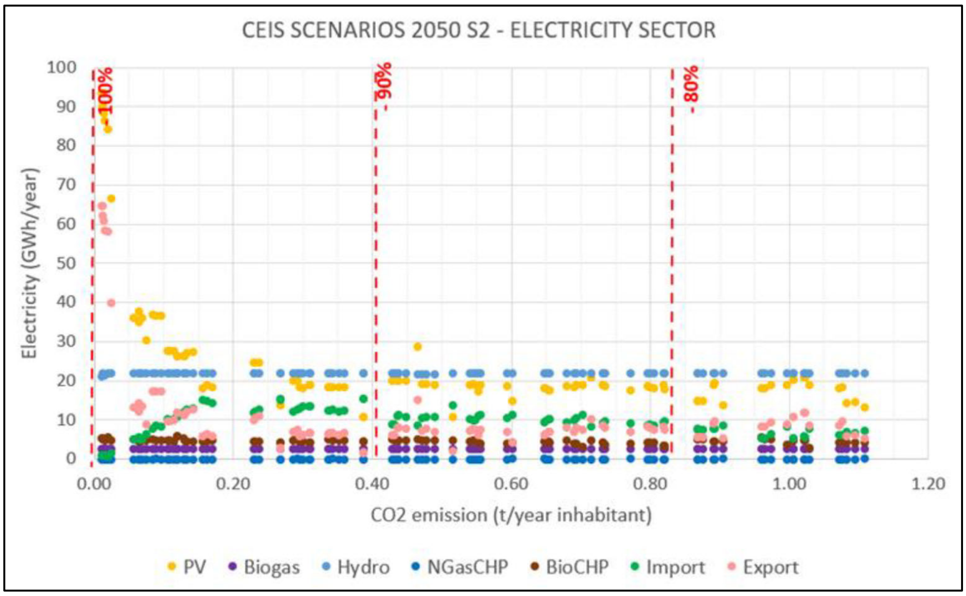

CEIS SCENARIO 2030 S2 - ELECTRICITY SUBDIVISION
Electricity (GWh/year)
Import/export power (MW)
CO2 emissions (t/year inhabitant)
-90%
-80%
-70%
-60%
PURE EL. DEMAND
HP EL.
EL. FOR BEV
EL. FOR FCEV
EL. FOR BATTERY C.
EL. FOR P2P C.
EL. FOR H2 HEATING
Import
Export

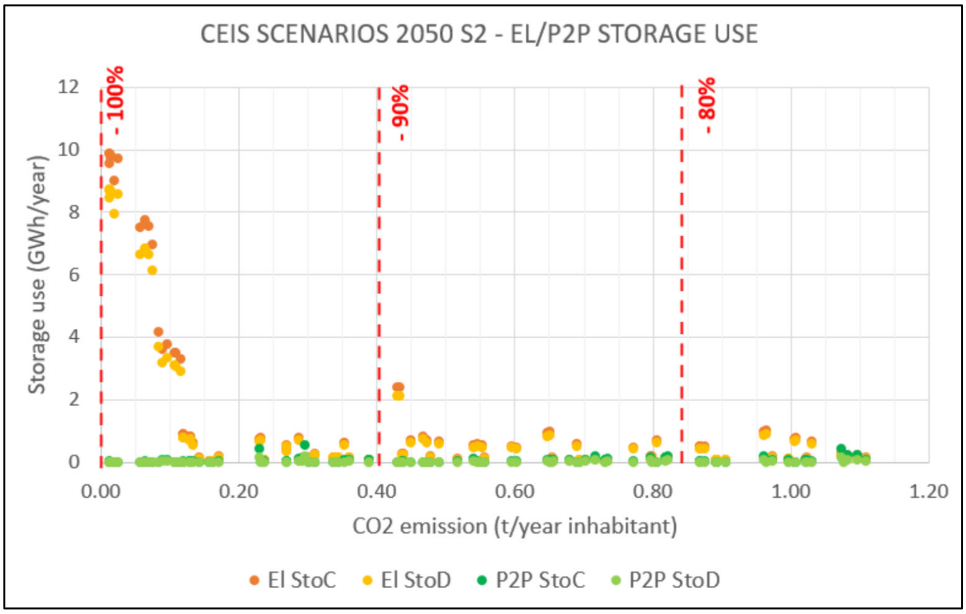


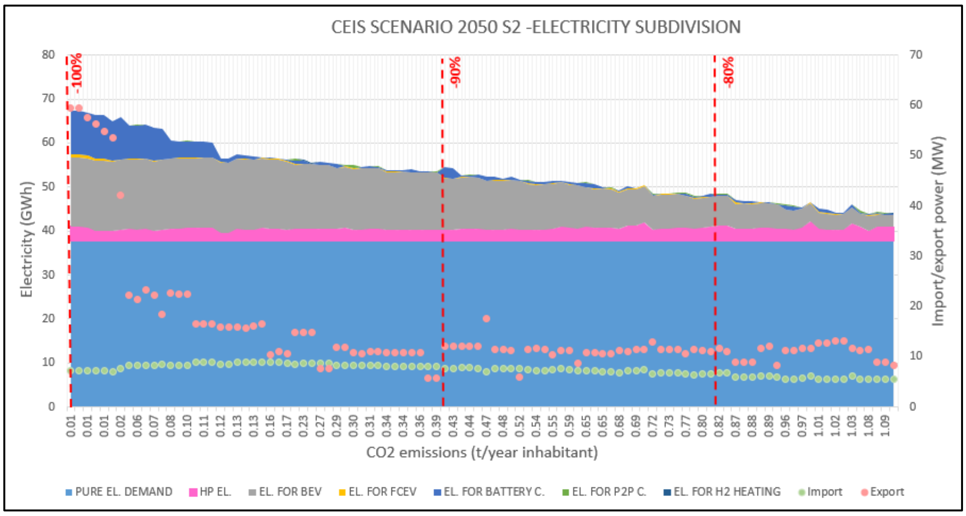
CEIS SCENARIOS 2050 S2 - THERMAL DEMAND
Thermal demand (GWh/year)
CO2 emission (t/year inhabitant)
-100%
-90%
-80%
LPGBoil
OilBoil
NGasBoil
BioBoil
H2Boil
NGasCHP
BioCHP
HP
SolarTh

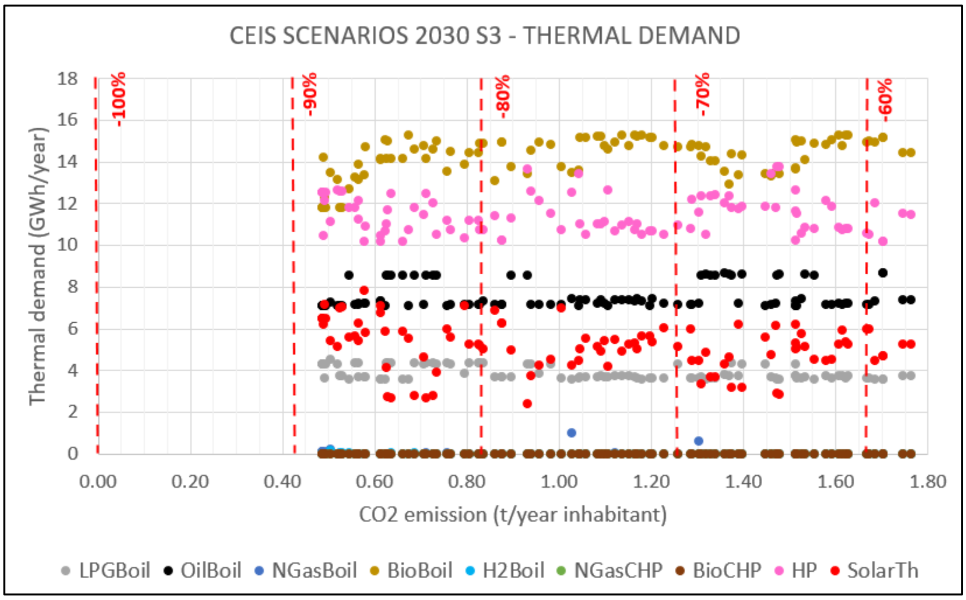


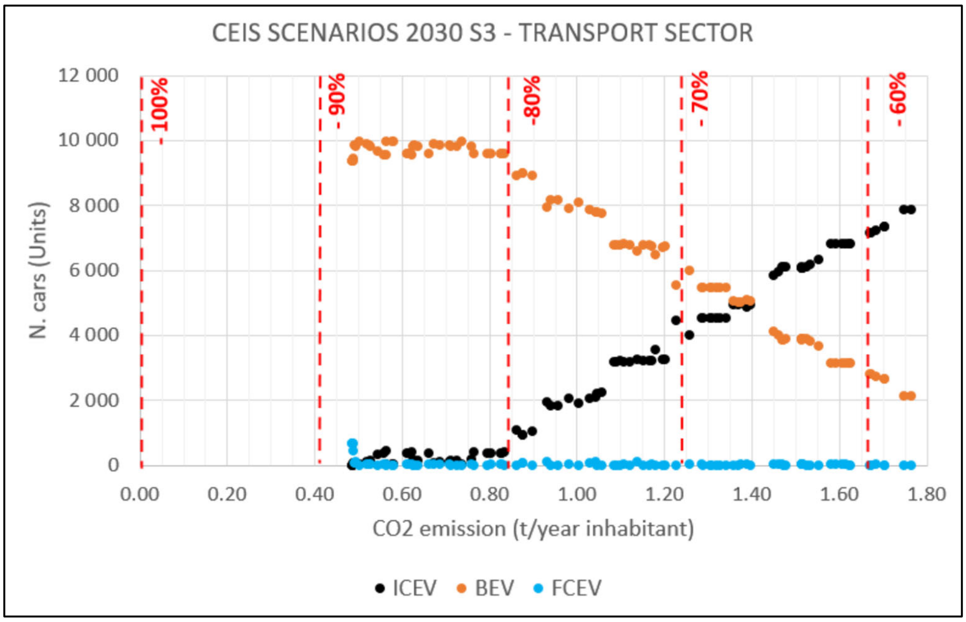
CEIS SCENARIOS 2050 S2 - TRANSPORT SECTOR
N. cars (Units)
CO2 emission (t/year inhabitant)
-100%
-90%
-80%
ICEV
BEV
FCEV

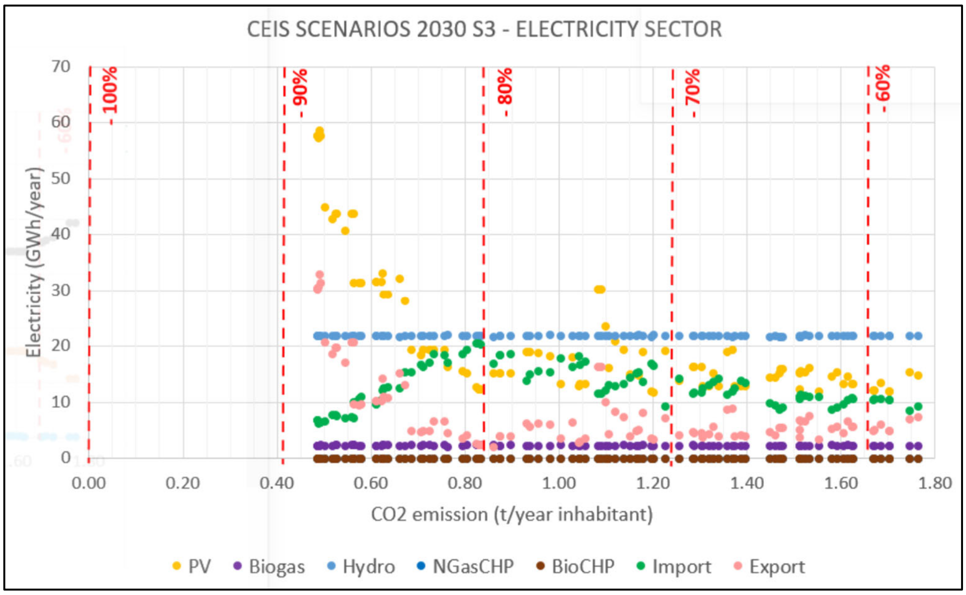

CEIS SCENARIOS 2050 S2 - ELECTRICITY SECTOR
-100%
-90%
- 80%
Electricity (GWh/year)
CO2 emission (t/year inhabitant)
PV
Biogas
Hydro
NGasCHP
BioCHP
Import
Export

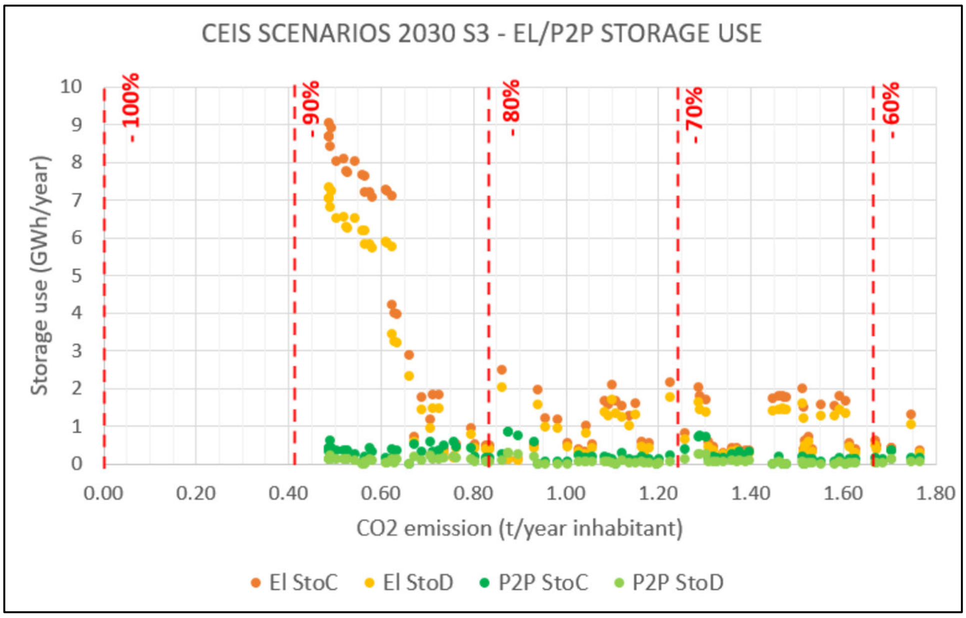

CEIS SCENARIOS 2050 S2 - EL/P2P STORAGE USE
- 100%
- 90%
- 80%
Storage use (GWh/year)
CO2 emission (t/year inhabitant)
El StoC
El StoD
P2P StoC
P2P StoD

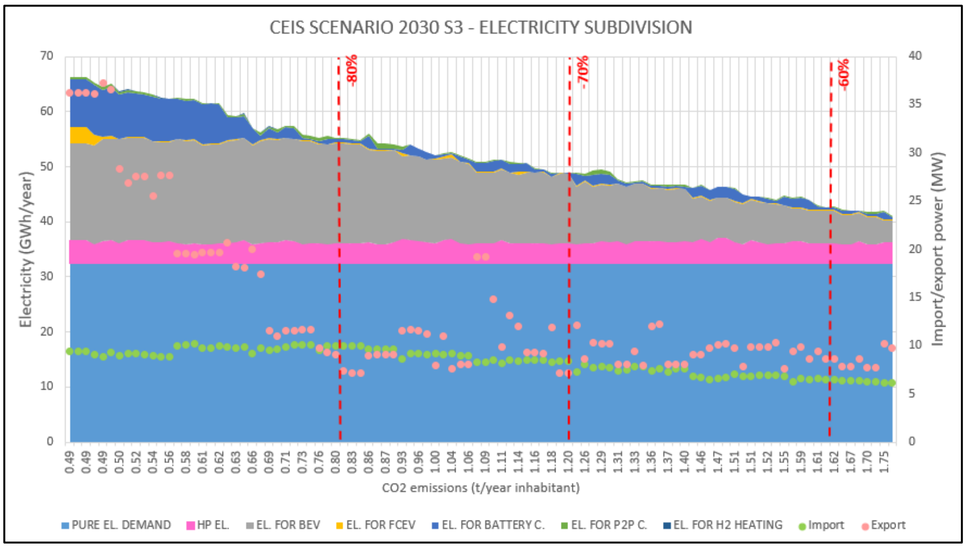

CEIS SCENARIO 2050 S2 -ELECTRICITY SUBDIVISION
Electricity (GWh)
Import/export power (MW)
-100%
-90%
-80%
CO2 emissions (t/year inhabitant)
PURE EL. DEMAND
HP EL.
EL. FOR BEV
EL. FOR FCEV
EL. FOR BATTERY C.
EL. FOR P2P C.
EL. FOR H2 HEATING
Import
Export

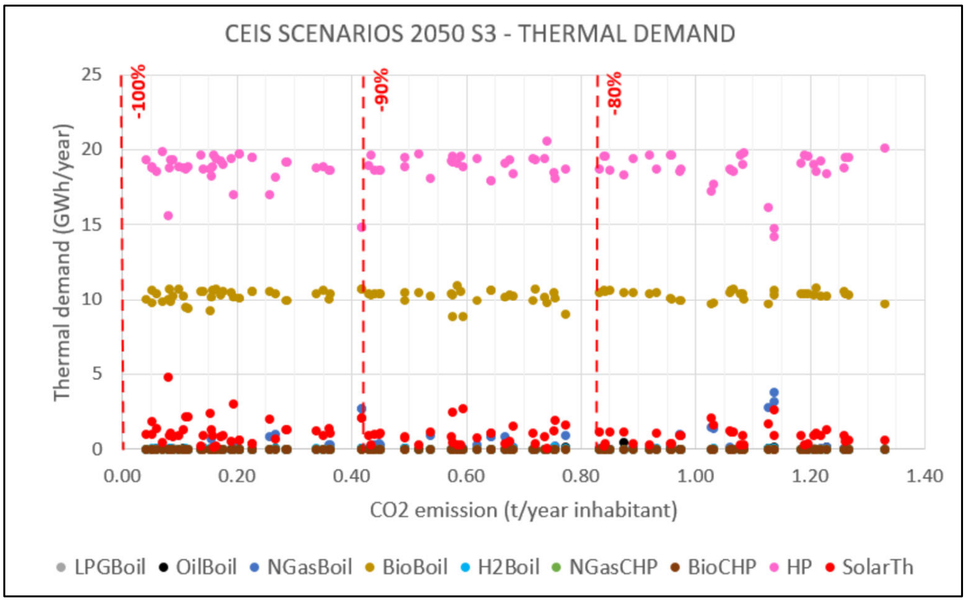

CEIS SCENARIOS 2030 S3 - THERMAL DEMAND
Thermal demand (GWh/year)
-100%
-90%
-80%
-70%
-60%
CO2 emission (t/year inhabitant)
LPGBoil
OilBoil
NGasBoil
BioBoil
H2Boil
NGasCHP
BioCHP
HP
SolarTh

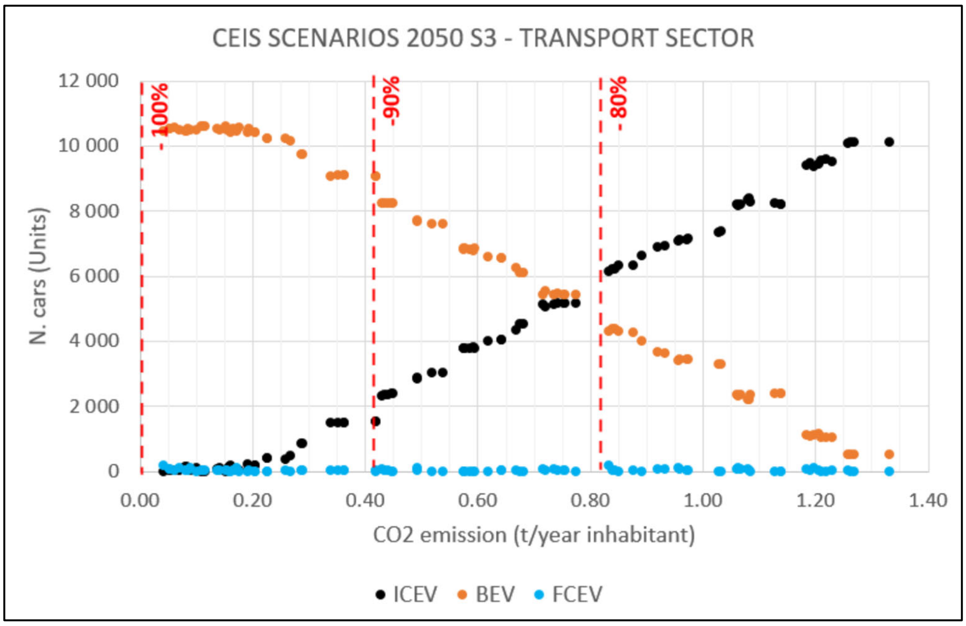

CEIS SCENARIOS 2030 S3 - TRANSPORT SECTOR
N. cars (Units)
CO2 emission (t/year inhabitant)
- 100%
- 90%
- 80%
- 70%
- 60%
ICEV
BEV
FCEV

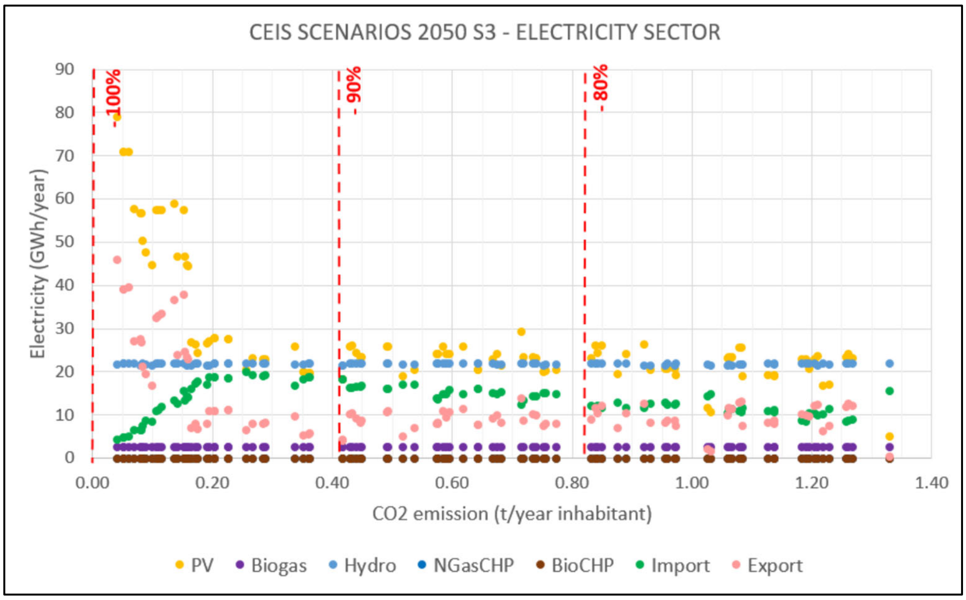

CEIS SCENARIOS 2030 S3 - ELECTRICITY SECTOR
Electricity (GWh/year)
CO2 emission (t/year inhabitant)
- 100%
- 90%
- 80%
- 70%
- 60%
PV
Biogas
Hydro
NGasCHP
BioCHP
Import
Export

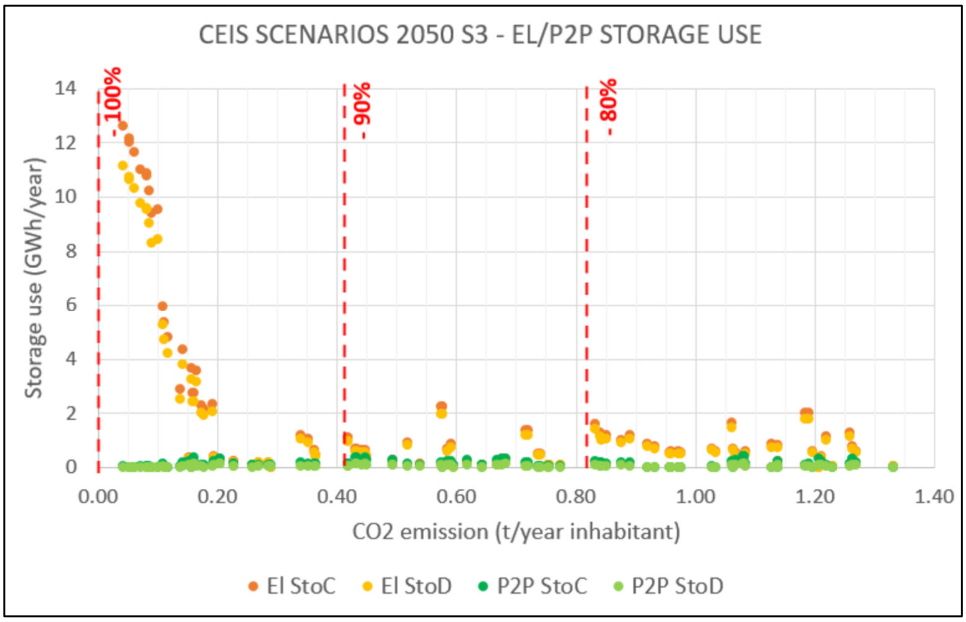

CEIS SCENARIOS 2030 S3 - EL/P2P STORAGE USE
Storage use (GWh/year)
CO2 emission (t/year inhabitant)
- 100%
- 90%
- 80%
- 70%
- 60%
El StoC
El StoD
P2P StoC
P2P StoD

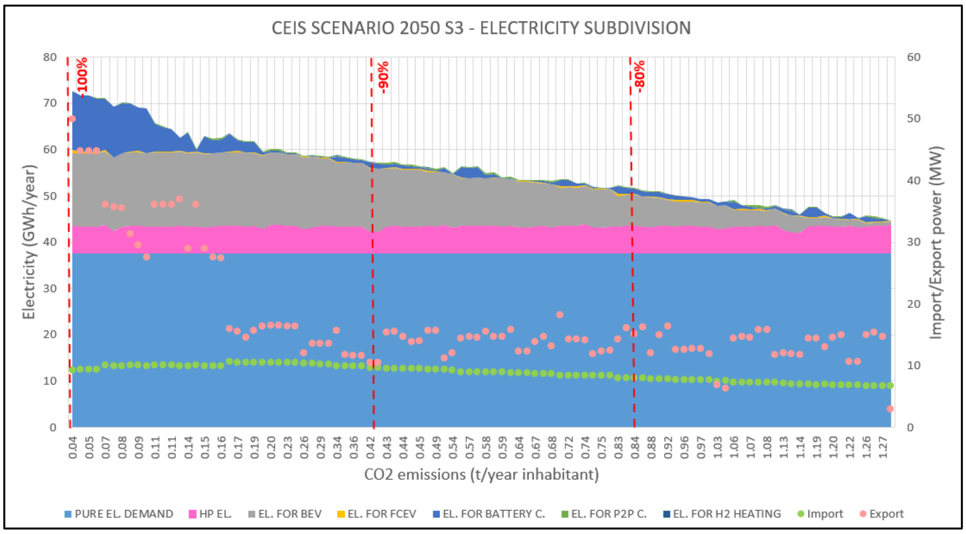

CEIS SCENARIO 2030 S3 - ELECTRICITY SUBDIVISION
Electricity (GWh/year)
Import/export power (MW)
CO2 emissions (t/year inhabitant)
-80%
-70%
-60%
PURE EL. DEMAND
HP EL.
EL. FOR BEV
EL. FOR FCEV
EL. FOR BATTERY C.
EL. FOR P2P C.
EL. FOR H2 HEATING
Import
Export

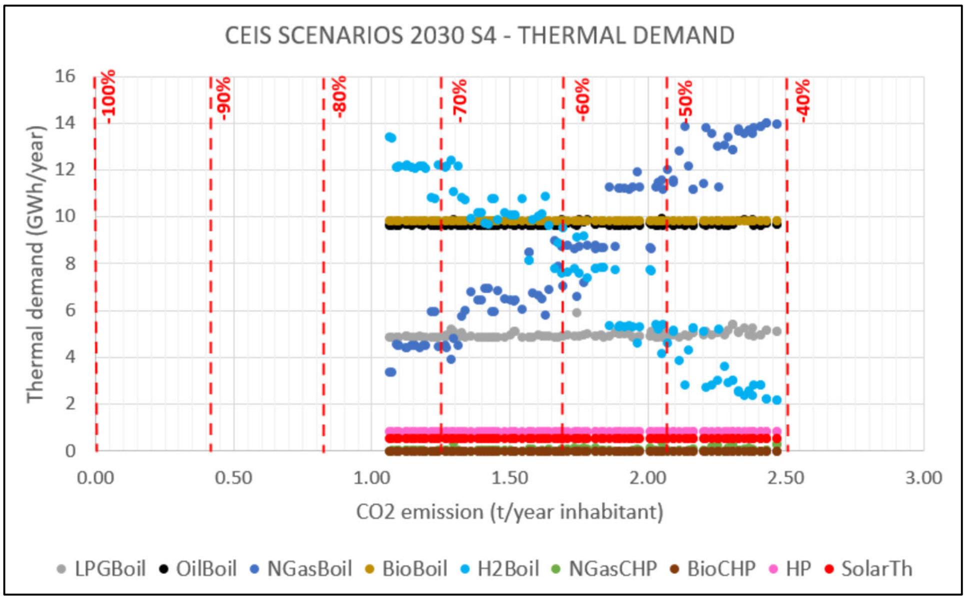

CEIS SCENARIOS 2050 S3 - THERMAL DEMAND
Thermal demand (GWh/year)
CO2 emission (t/year inhabitant)
-100%
-90%
-80%
0
5
10
15
20
25
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
LPGBoil
OilBoil
NGasBoil
BioBoil
H2Boil
NGasCHP
BioCHP
HP
SolarTh

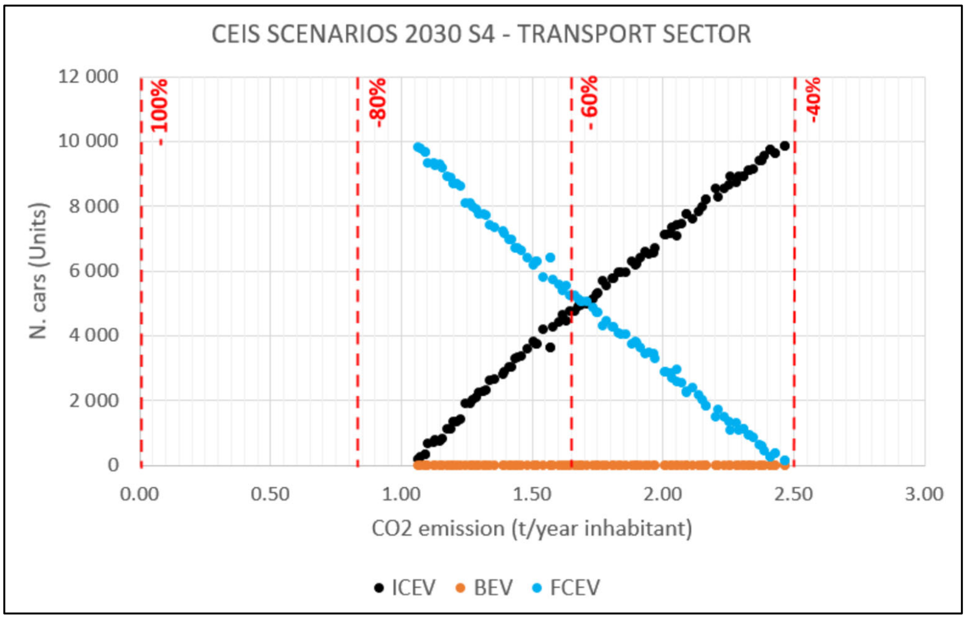

CEIS SCENARIOS 2050 S3 - TRANSPORT SECTOR
N. cars (Units)
CO2 emission (t/year inhabitant)
-100%
-90%
-80%
0
2 000
4 000
6 000
8 000
10 000
12 000
0.00
0.20
0.40
0.60
0.80
1.00
1.20
1.40
ICEV
BEV
FCEV

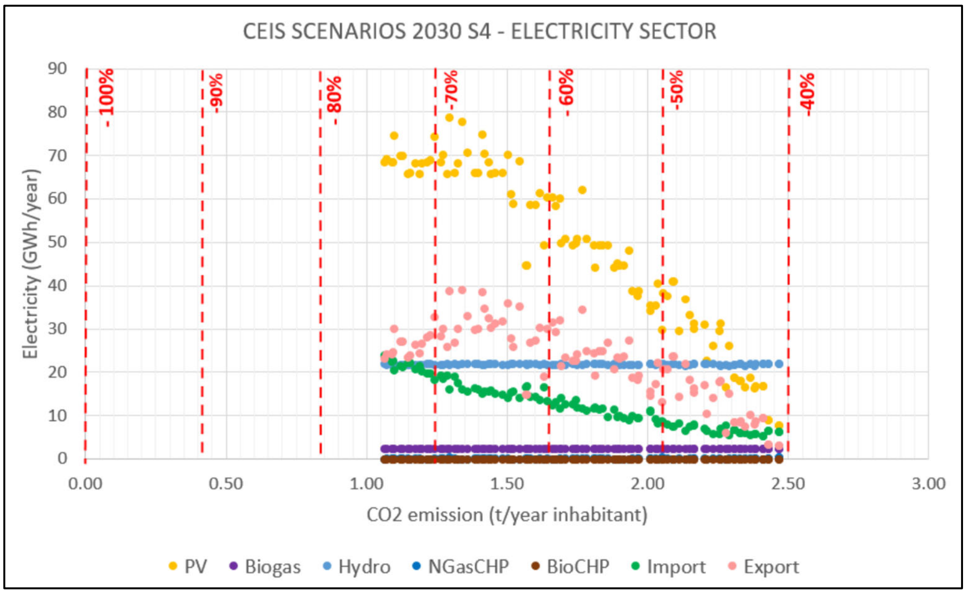

CEIS SCENARIOS 2050 S3 - ELECTRICITY SECTOR
Electricity (GWh/year)
CO2 emission (t/year inhabitant)
-100%
-90%
-80%
PV
Biogas
Hydro
NGasCHP
BioCHP
Import
Export

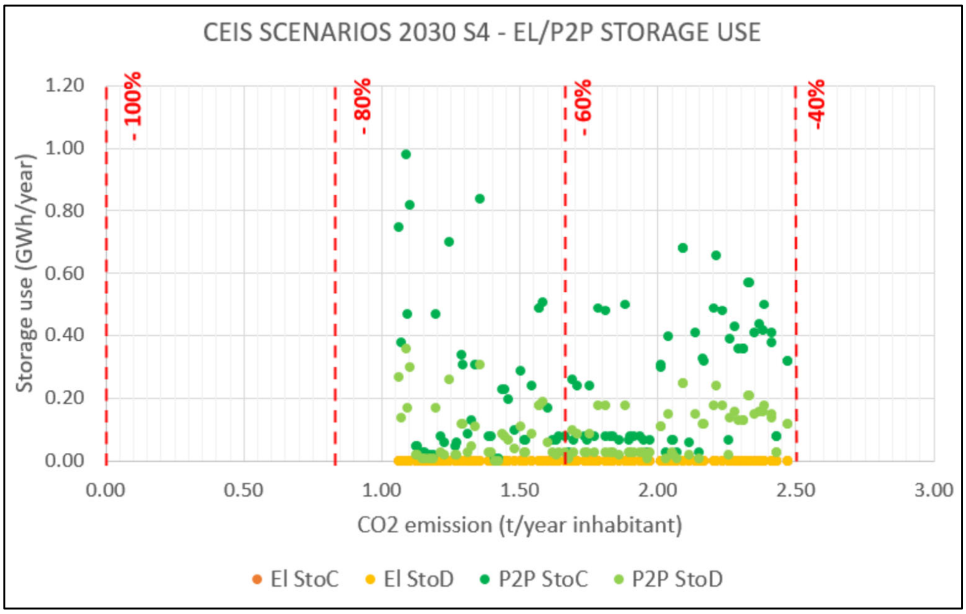

CEIS SCENARIOS 2050 S3 - EL/P2P STORAGE USE
Storage use (GWh/year)
CO2 emission (t/year inhabitant)
-100%
-90%
-80%
El StoC
El StoD
P2P StoC
P2P StoD

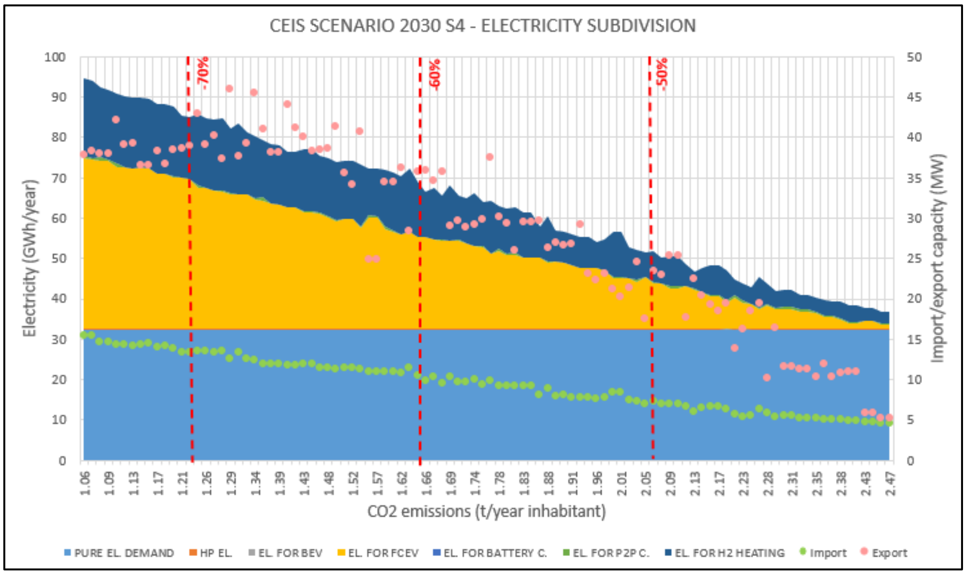

CEIS SCENARIO 2050 S3 - ELECTRICITY SUBDIVISION
Electricity (GWh/year)
Import/Export power (MW)
CO2 emissions (t/year inhabitant)
-100%
-90%
-80%
PURE EL. DEMAND
HP EL.
EL. FOR BEV
EL. FOR FCEV
EL. FOR BATTERY C.
EL. FOR P2P C.
EL. FOR H2 HEATING
Import
Export

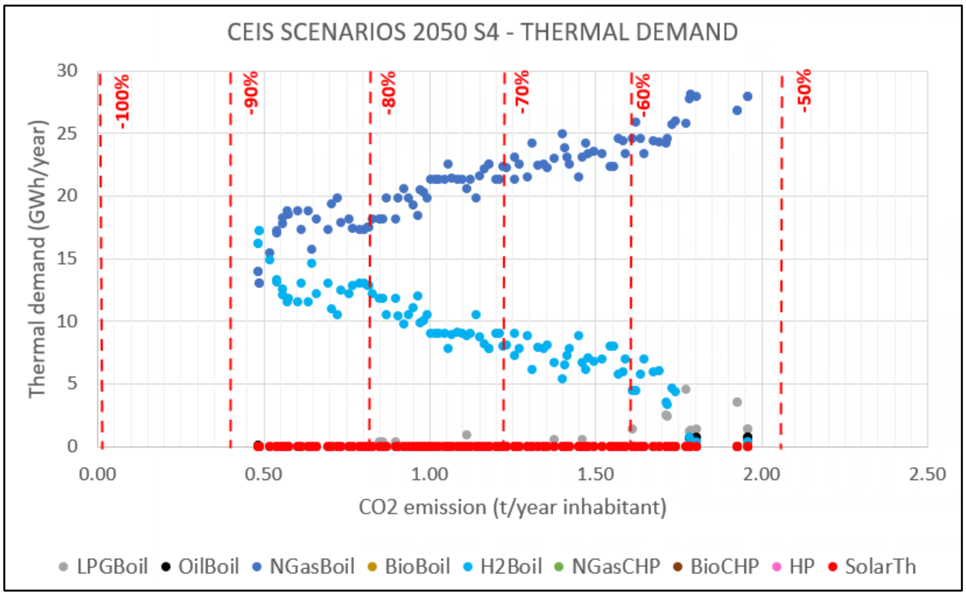

CEIS SCENARIOS 2030 S4 - THERMAL DEMAND
Thermal demand (GWh/year)
CO2 emission (t/year inhabitant)
-100%
-90%
-80%
-70%
-60%
-50%
-40%
LPGBoil
OilBoil
NGasBoil
BioBoil
H2Boil
NGasCHP
BioCHP
HP
SolarTh

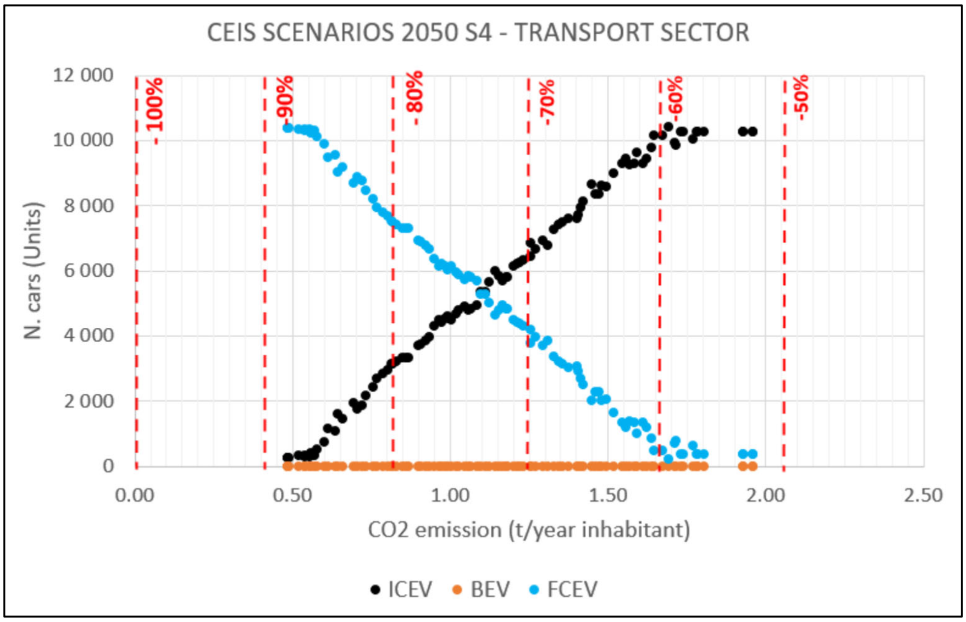

CEIS SCENARIOS 2030 S4 - TRANSPORT SECTOR
N. cars (Units)
CO2 emission (t/year inhabitant)
- 100%
-80%
- 60%
-40%
ICEV
BEV
FCEV

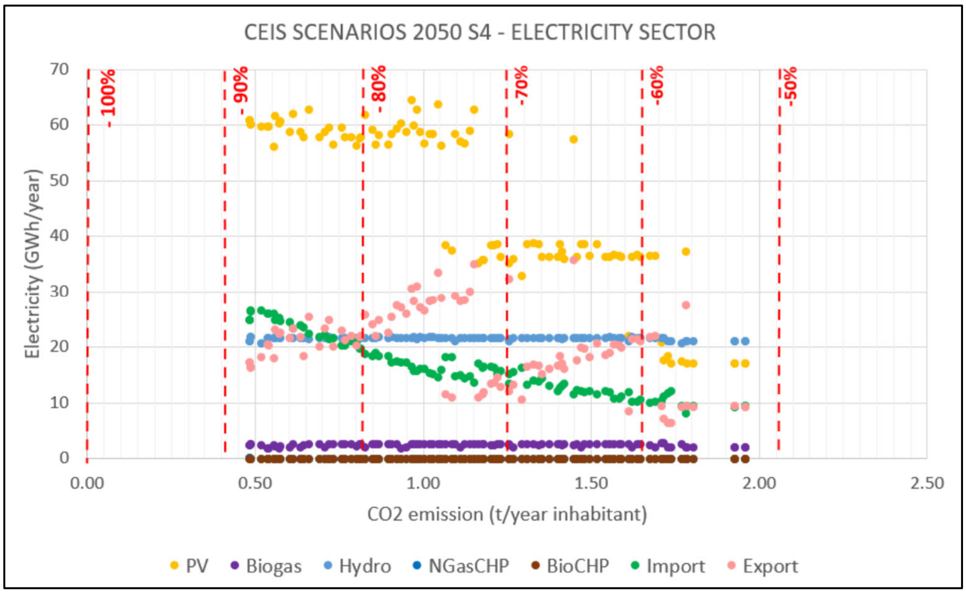

CEIS SCENARIOS 2030 S4 - ELECTRICITY SECTOR
Electricity (GWh/year)
CO2 emission (t/year inhabitant)
- 100%
-90%
- 80%
-70%
- 60%
-50%
-40%
PV
Biogas
Hydro
NGasCHP
BioCHP
Import
Export

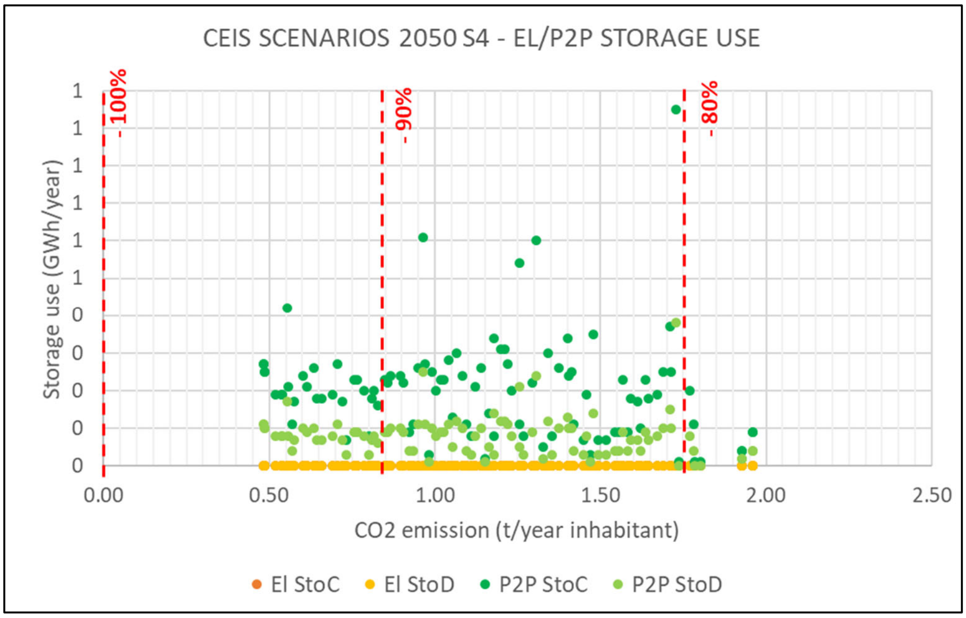

CEIS SCENARIOS 2030 S4 - EL/P2P STORAGE USE
Storage use (GWh/year)
1.20
1.00
0.80
0.60
0.40
0.20
0.00
- 100%
- 80%
- 60%
-40%
0.00
0.50
1.00
1.50
2.00
2.50
3.00
CO2 emission (t/year inhabitant)
El StoC
El StoD
P2P StoC
P2P StoD

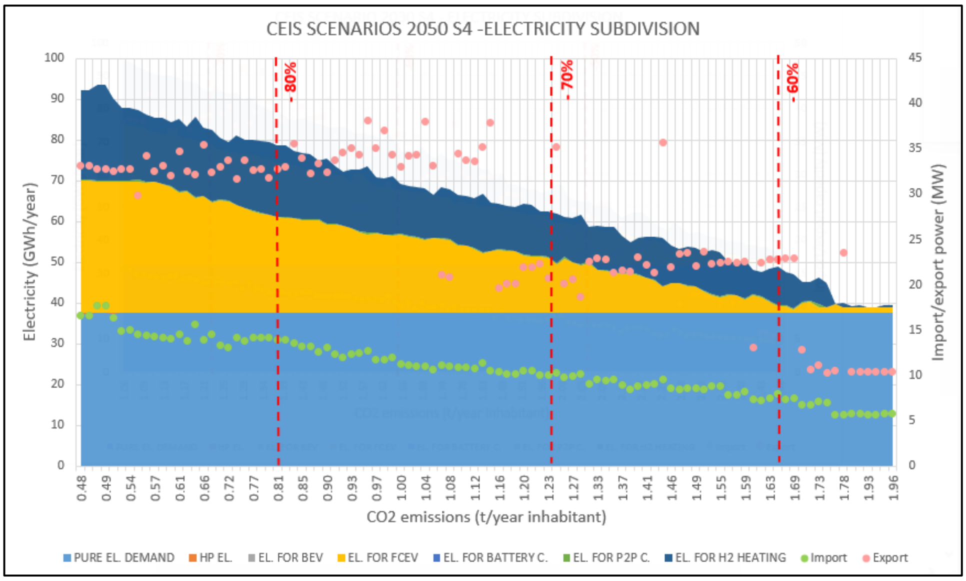

CEIS SCENARIO 2030 S4 - ELECTRICITY SUBDIVISION
Electricity (GWh/year)
Import/export capacity (MW)
-70%
-60%
-50%
CO2 emissions (t/year inhabitant)
PURE EL. DEMAND
HP EL.
EL. FOR BEV
EL. FOR FCEV
EL. FOR BATTERY C.
EL. FOR P2P C.
EL. FOR H2 HEATING
Import
Export


CEIS SCENARIOS 2050 S4 - THERMAL DEMAND
Thermal demand (GWh/year)
CO2 emission (t/year inhabitant)
-100%
-90%
-80%
-70%
-60%
-50%
LPGBoil
OilBoil
NGasBoil
BioBoil
H2Boil
NGasCHP
BioCHP
HP
SolarTh


CEIS SCENARIOS 2050 S4 - TRANSPORT SECTOR
N. cars (Units)
CO2 emission (t/year inhabitant)
-100%
-90%
-80%
-70%
-60%
-50%
ICEV
BEV
FCEV


CEIS SCENARIOS 2050 S4 - ELECTRICITY SECTOR
Electricity (GWh/year)
CO2 emission (t/year inhabitant)
-100%
-90%
-80%
-70%
-60%
-50%
PV
Biogas
Hydro
NGasCHP
BioCHP
Import
Export


CEIS SCENARIOS 2050 S4 - EL/P2P STORAGE USE
Storage use (GWh/year)
CO2 emission (t/year inhabitant)
-100%
-90%
-80%
El StoC
El StoD
P2P StoC
P2P StoD


CEIS SCENARIOS 2050 S4 -ELECTRICITY SUBDIVISION
Electricity (GWh/year)
Import/export power (MW)
CO2 emissions (t/year inhabitant)
- 80%
- 70%
- 60%
PURE EL. DEMAND
HP EL.
EL. FOR BEV
EL. FOR FCEV
EL. FOR BATTERY C.
EL. FOR P2P C.
EL. FOR H2 HEATING
Import
Export

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