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A MULTI-OBJECTIVE OPTIMIZATION APPROACH IN DEFINING THE DECARBONIZATION STRATEGY OF A REFINERY – CASE STUDY OF SONATRACH RAFFINERIA ITALIANA – RAFFINERIA DI AUGUSTA

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Presenter: **Jacopo de Maigret** (Fondazione Bruno Kessler - Italy)

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Assessment Objective

What? Feasibility study of the decarbonization of a refinery's energy supply.

Why? In sight of the European and national decarbonization objectives. Which result in the increase of the price of CO_2 and therefore of the expenses related to the 'over free allowance'.

How? The study is based on the concept of smart energy system (EnergyPLAN) coupled with multi-objective optimization.

Expected results? In this case, the objectives are two: the minimization of the total annual costs and CO_2 emissions.

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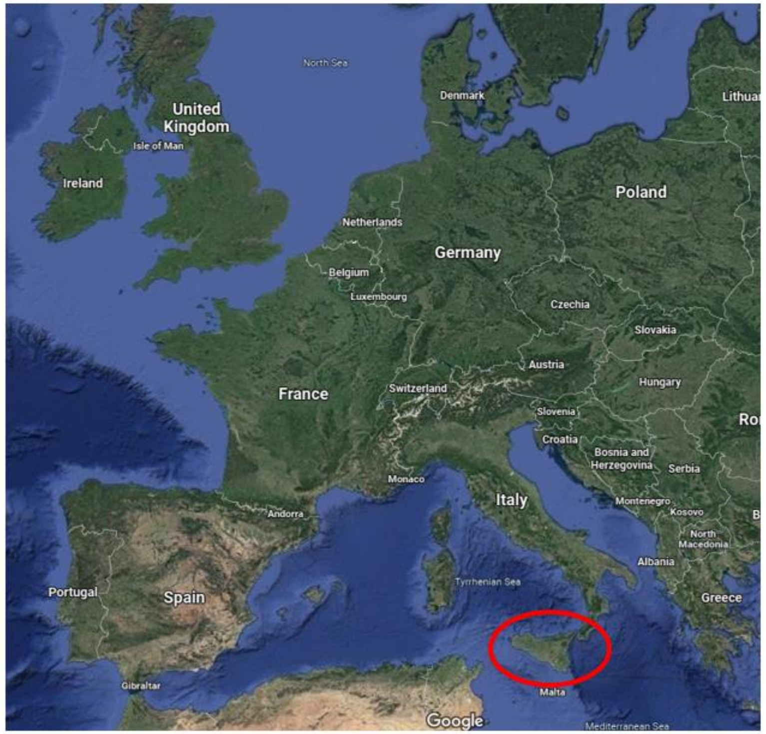
Case study: Sonatrach Raffineria Italiana – Raffineria di Augusta



			Macro-Areas and Functional Areas	Processes	
Main activities (AP)	On-site	Fuel plants	COMPLEX A	VPS-2	Vacuum pipe still 2.
				HF-1	Hydrofiner 1.
				LPGS	Low pressure gas scrubber.
				FCUU	Fluidized bed catalytic cracker.
			COMPLEX B	S-1	Sulfur recovery 1.
				S-2	Sulfur recovery 2.
				TGCU	Tail gas clean up.
				MEA REGEN	MEA regenerator.
				T-4	Topping 4.
				T-5	Topping 5.
				HF-T5	Hydrofiner topping 5.
			COMPLEX C	ALKY	Alkylation.
				C3/C4 Splitter	Propane & butane splitter.
				PP Splitter	Propane & propylene splitter.
				Blowdown&Gas flare	
				Butamer	Isomeriaztion
			COMPLEX D	R-4	Reforming 4.
				R-5	Reforming 5.
				PSU	Powerformer stripper unit.
				R-1	Hydrofiner R1.
				Scanfiner&splitter	Desulfurization della FCCU
				SWS	Sour water scrubber.
		Lube plants	LUBE 1	VPS-1	Vacuum pipe still 1.
				(P)DAU-1	(Propane) deasphalter unit-1.
				EFU-1	Exolfiner unit-1.
				PDU	Propane (Toluene) dewaxing unit.
			LUBE 2	(P)DAU-2	(Propane) deasphalter unit-2.
				EFU-2	Exolfiner unit-2.
				KDU	Ketone dewaxer unit.
	Off-site	Oil movement & blending.			

Data preparation – Reference year

Reference year of the analysis: 2017.

Refined goods throughput and energy dimension closest to the nominal conditions.

Year	Energy Dimension	Produced goods
	toe	tons
2014	580’341	8’231’200
2015	584’886	9’172’240
2016	611’290	9’146’716
2017	644’002	9’984’507
2018	586’492	8’405’155

Data preparation – 'Import-only' model

Not included: self produced energy vectors.

Included: imported energy vectors.

Acquired Energy Vectors	Analyzed Quantities GWh/year
Electric Energy HV	62.164(import)
Electric Energy MV	2.5
HP Natural Gas	973
LP Natural Gas	859.5
Crude	-
Hydrogen	123.6
Diesel	0.31
Petrol	0.28

'Import-only' model

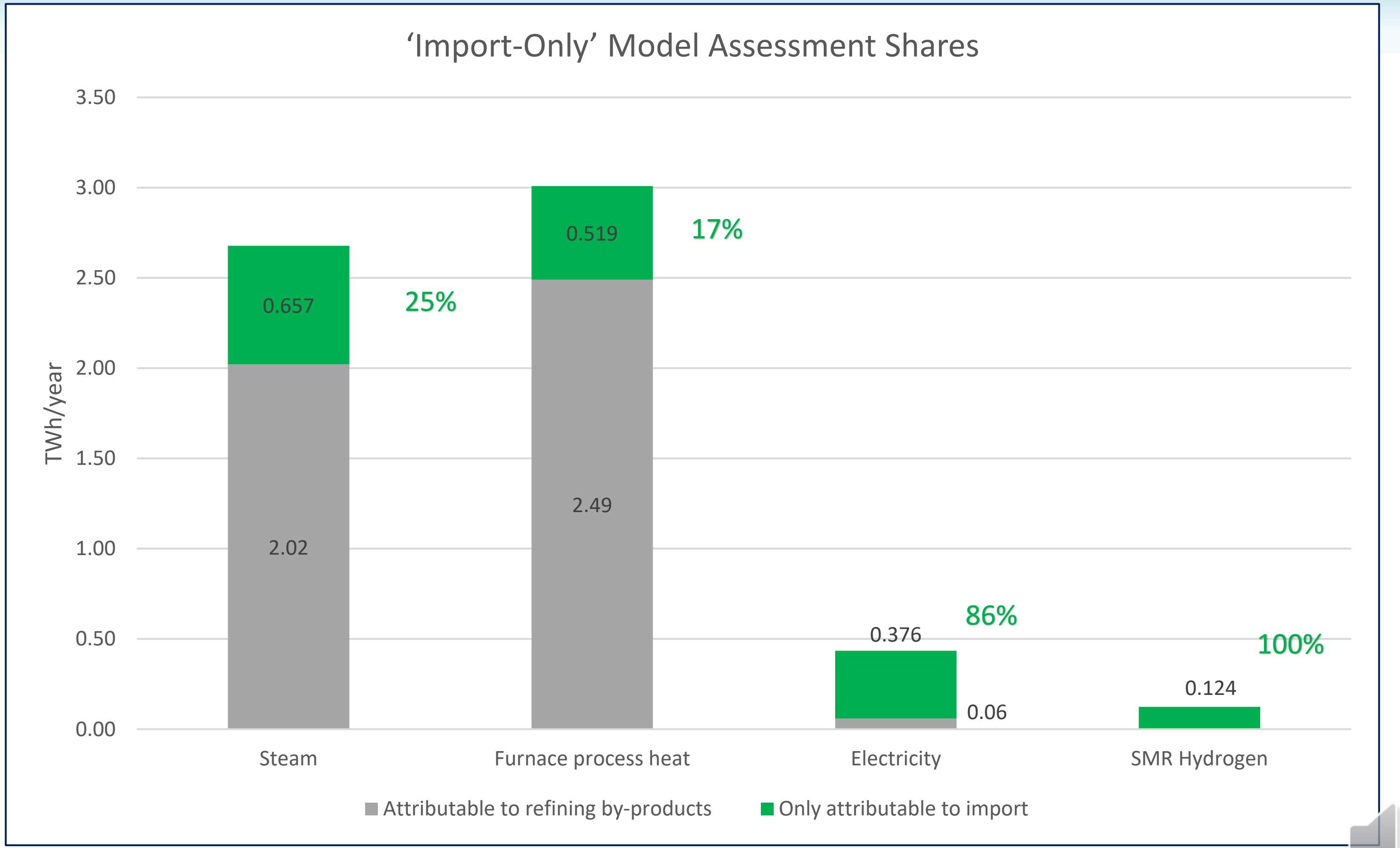
- Reported in green are the portions of the overall energy demand which are included in the analysis.
- Heat demand modelled:

  1177 GWh/year.
- Electric demand modelled:

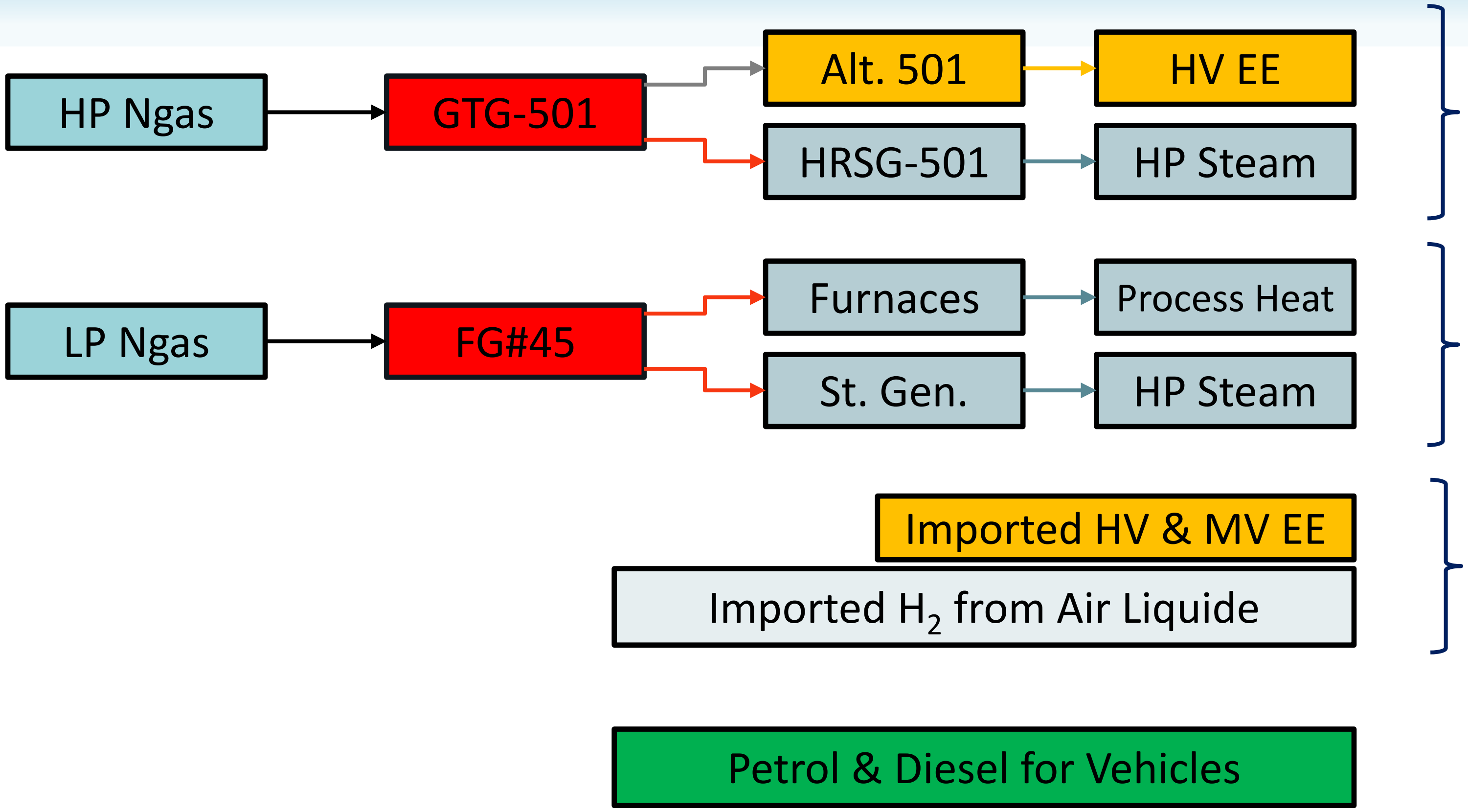
  375 GWh/year.
- Hydrogen demand modelled:

  123 GWh/year.
- Petrol and diesel demand modelled:

  0.68 GWh/year.



‘Import-only’ model



Annual consumptions and hourly profiles taken from provided data.

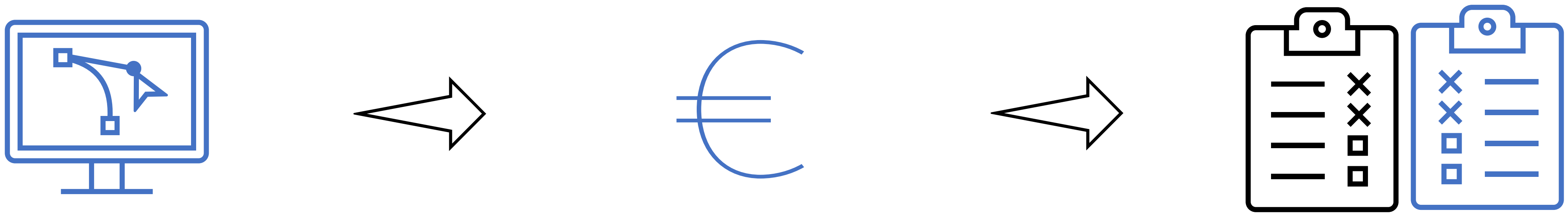
Annual consumptions taken from provided data. Hourly distribution derived as monthly aggregated percentage of the FG#45 network.

Annual consumptions and hourly profiles taken from provided data.

Annual consumptions taken from provided data:

- Petrol: 34’000 liters/year.
- Diesel: 30’000 liters/year.

Baseline 2017



1. Implementation import-only model in EnergyPLAN.

2. Annual emissions & Costs of the reference year import-only model.

3. Validation through comparison, were possible, between simulation output and refinery-provided data.

Baseline 2017

Yearly Total
- Demand (electrical, thermal, hydrogen, transport).
- Supply (electrical, gas, hydrogen, Diesel, petrol).

Hourly Profiles
- Demand (electrical, thermal, hydrogen, transport).
- National grid electricity cost (PUN).

Costs
- CAPEX & OPEX.
- CO_2.
- Energy vectors.

Technology characteristics
- Efficiencies and lifetimes.

National electric grid energy mix and generation efficiency.

Emission factors of energy vectors.

→ **EnergyPLAN** →

Total Annual Costs [k€/year]
- Annual energy vectors cost.
- Annual CO_2 cost.
- Annual CAPEX cost.
- Annual OPEX cost.

Annual Emissions [ktonCO_2/year]

Sustainability Vision 2025

Assumed year of sustainable interventions: 2025. → Planning steps. 2025 plant downtime.

Energy demands & technological mix of **2017**. → Costs and supplies foreseen for **2025**.

'Business-as-Usual' Scenario. → Refinery's performance if no interventions are made.

Implemented Sustainable Technologies

Thermal Sector:
- Concentrating solar thermal (LFR).
- Hydrogen blending.
- Biomass steam generators and furnaces.
- Electric steam generators and furnaces.

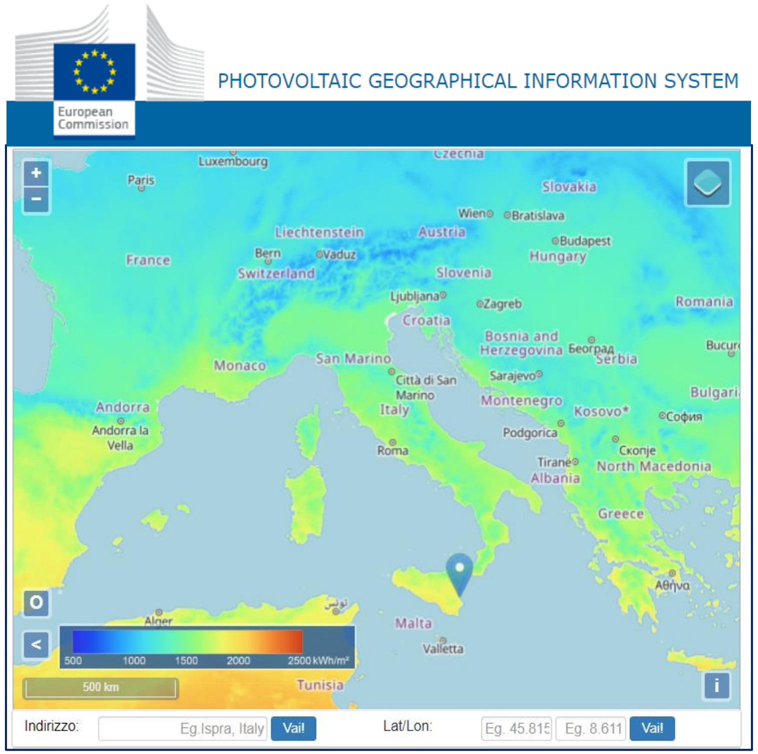
Electrical Sector:
- Solar photovoltaic.
- Wind power.
- Biomass ORC.
- Waste heat recovery ORC.

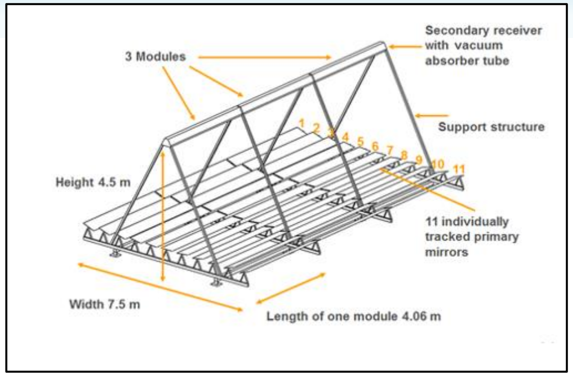
Hydrogen Sector:
- Electrolytic hydrogen.

Energy Storage Sector:
- Thermal energy storage.
- Electrical storage.
- Hydrogen gas storage.

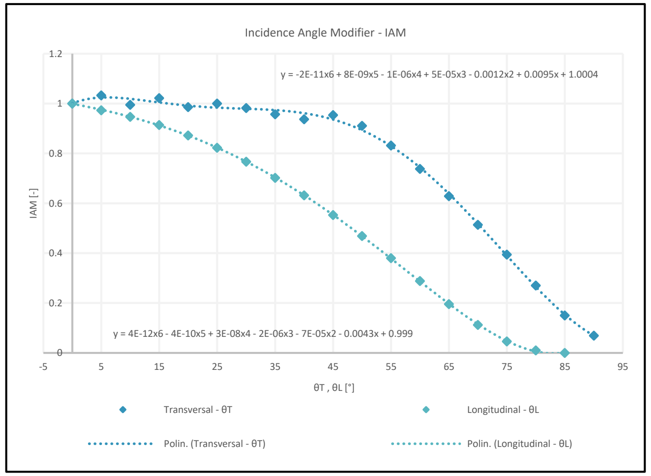
Transport Sector:
- Battery electric vehicles.

Implemented Sustainable Technologies – Solar thermal

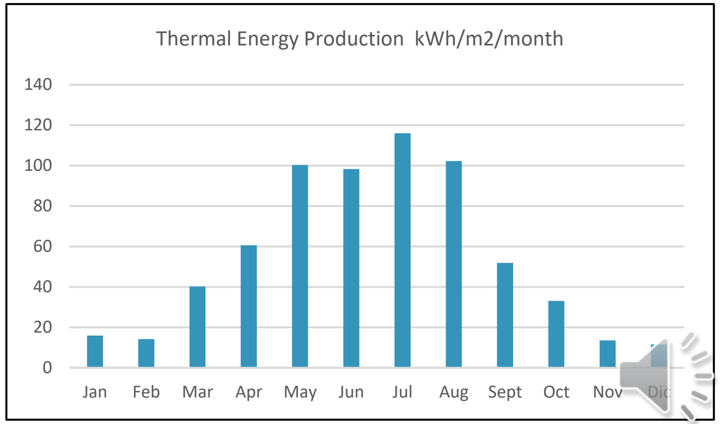




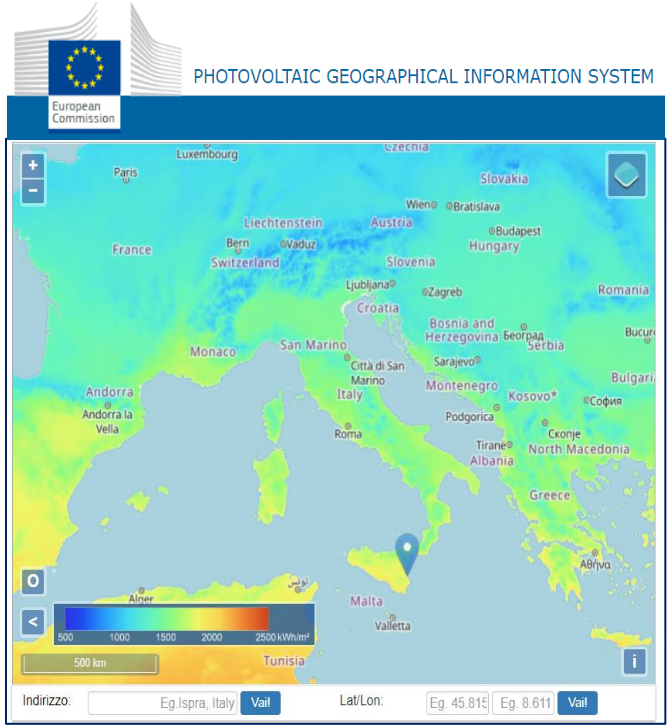
n_0	a_1 (W/m^2K)	a_2 (W/m^2K^2)
0.635	0.0265	0.00043

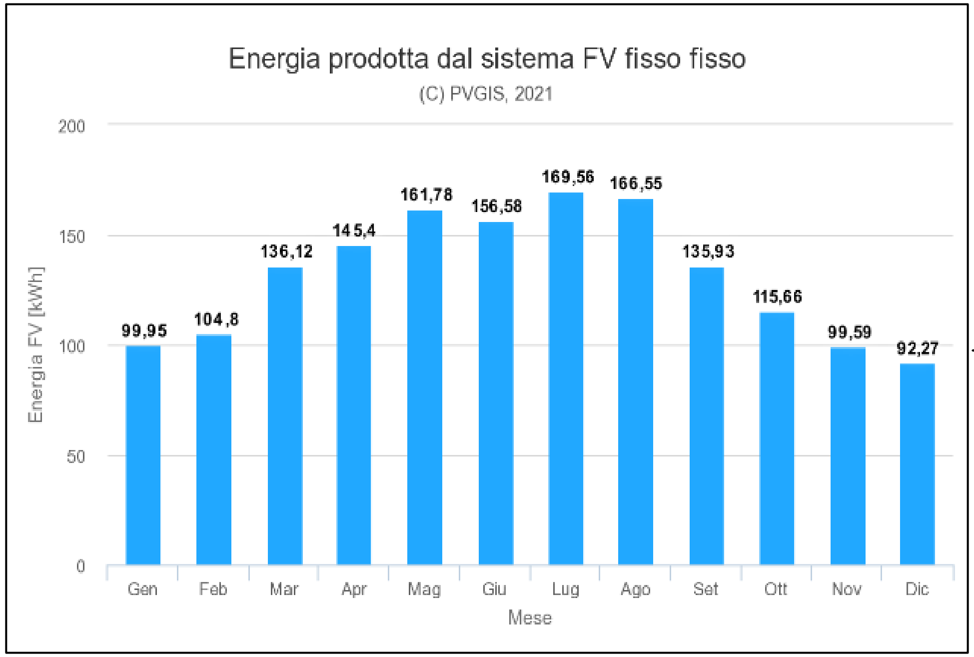


For every sq. meter of collector, the energy collected is:
661 kWh/m²year.



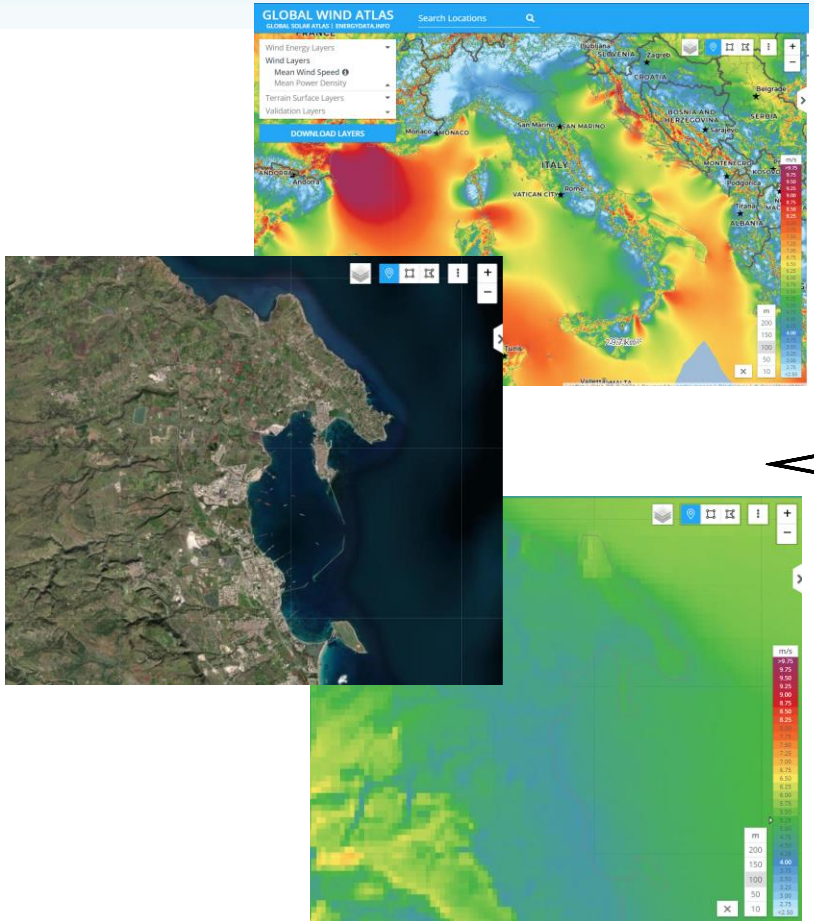
Implemented Sustainable Technologies – Solar PV

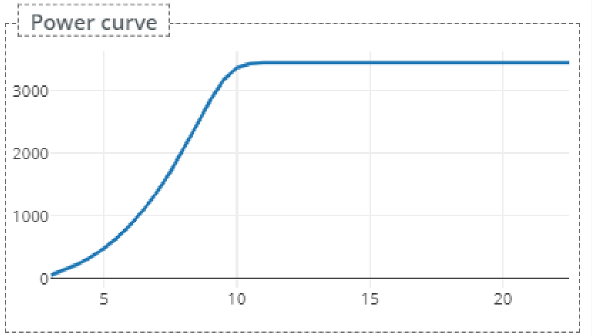




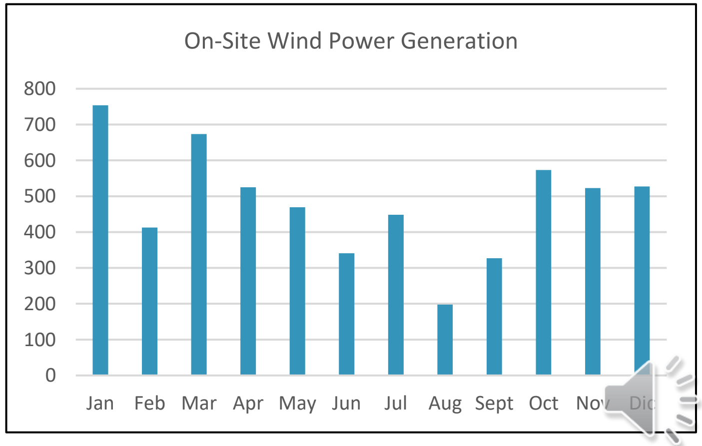
For every kW of PV installed, the electrical energy obtained is: **1538 kWh/year.**

Implemented Sustainable Technologies

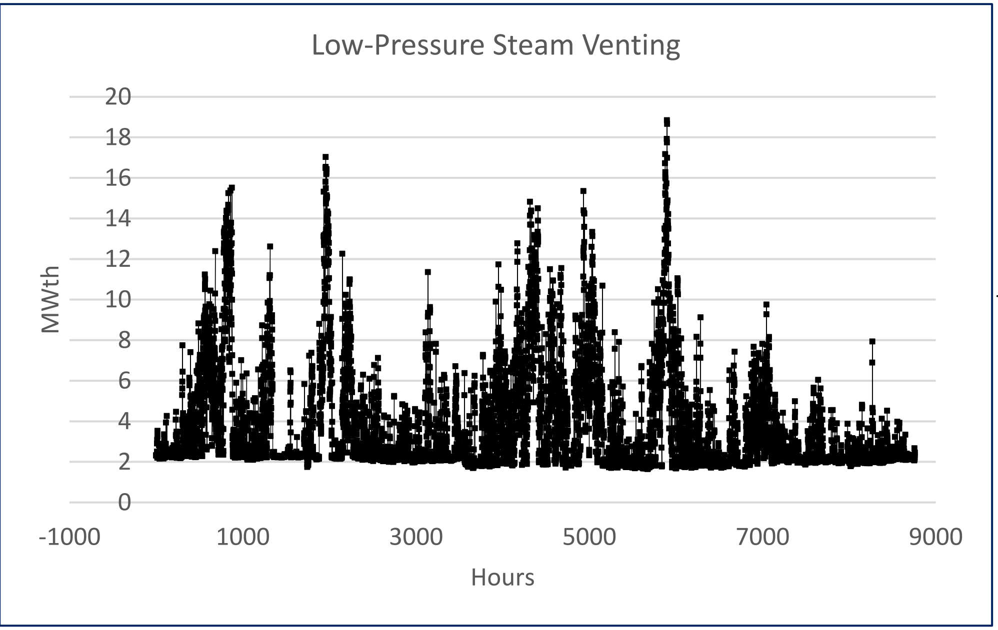


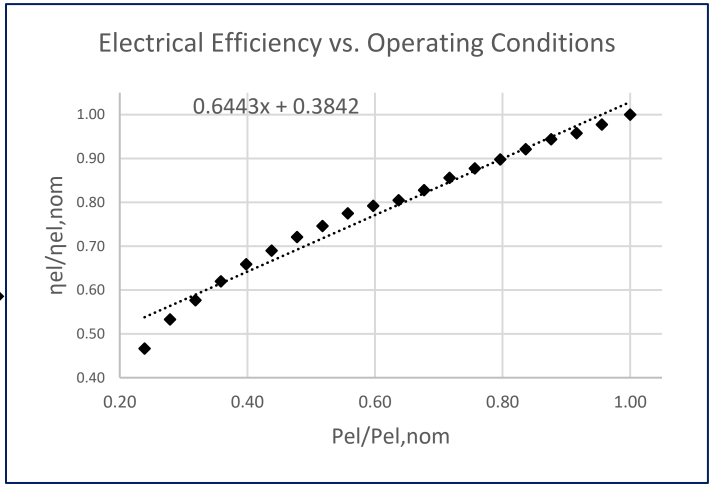


For every installed MW, a production of **1683 MWh/year** is estimated.
Presenting a utilization factor of **20%.**



Implemented Sustainable Technologies – WHR ORC





With respect to the operating conditions suggested by the manufacturer, a production of **2780 MWh/year** is foreseen. Having installed an ORC capacity of 400kW_{el}.

Decision Variables

Decision variables: **capacities.**

Manually change the decision variables to find the optimal combination?

Unfeasible strategy…

Intermittent Renewable Electricity

Renewable Energy Source	Capacity: kW	Stabilisation share	Distribution profile		Estimated Production GWh/year	Correction factor	Estimated Post Correction production
Photo Voltaic	0	0	Change	V3_SRI_PV.txt	0.00	0	0.00
Wave Power	0	0	Change	V3_SRI_ORC_W	0.00	0	0.00
Wind	0	0	Change	V3_SRI_Wind_0	0.00	0	0.00
Tidal	0	0	Change	V3_SRI_ORC_Bi	0.00	0	0.00
CSP Solar Power	0	0	Change	hour_tidal_power	0.00	0	0.00
CSP Solar Power	0	0	Change	Hour_wave_200	0.00	0	0.00
CSP Solar Power	0	0	Change	Hour_solar_prod1	0.00	0	0.00

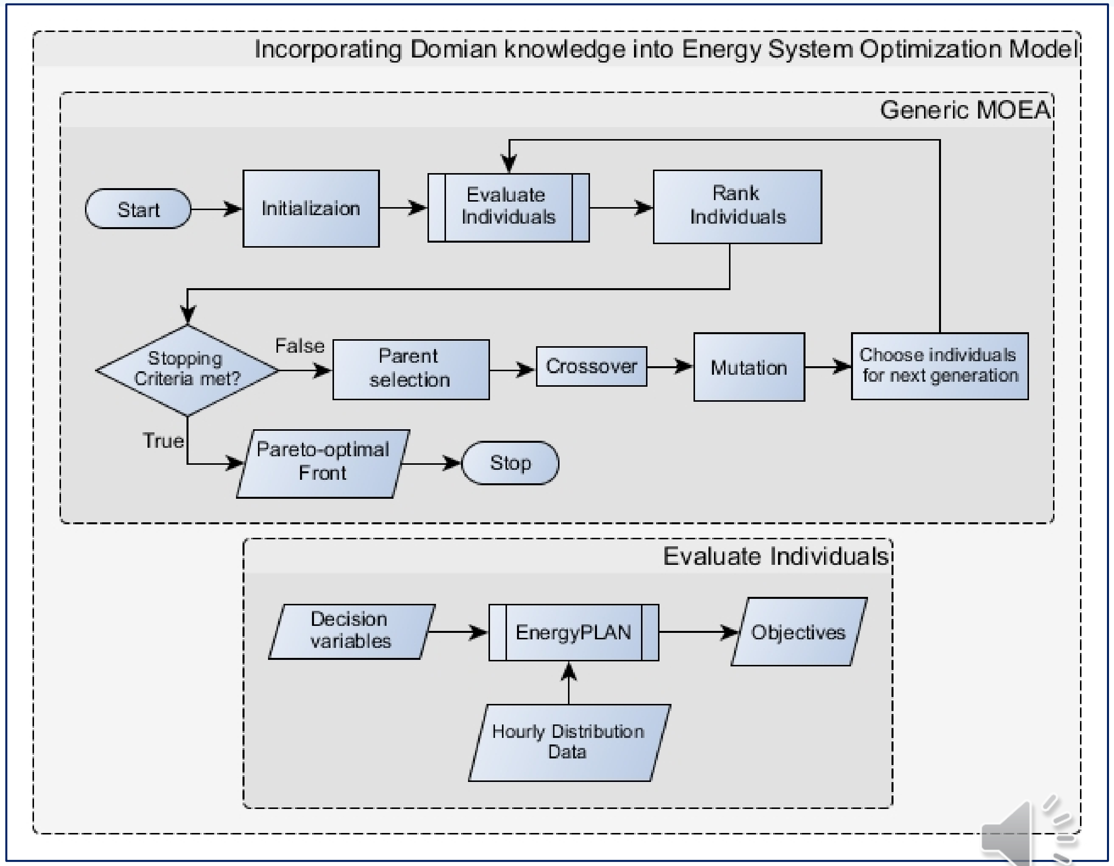
Multi-Objective Evolutionary Algorithm

Automation of the generation of scenarios

Inspired by natural evolution, the algorithm only **promotes** those scenarios which **outperform** others in terms of annual costs and emissions.

After 100 generations, and 10’000 simulated solutions, convergence is reached.

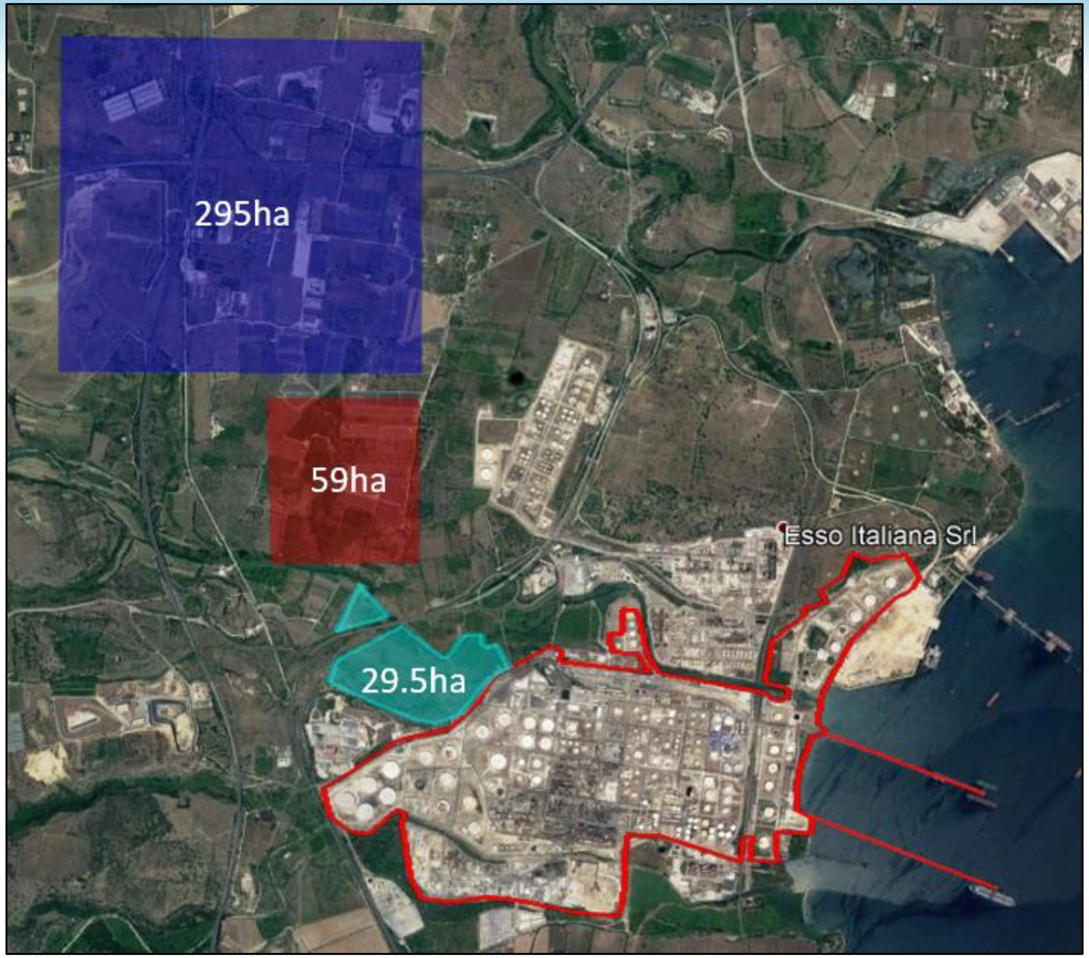
Optimized scenario: 100 solutions defined by **minimal annual cost** and **minimum annual emissions**.



Boundary Conditions

As first approach, we considered the area available suggested by the refinery.

We subsequently increased the area to investigate greater capacities of concentrating solar thermal and PV.



Boundary Conditions: diverse scenarios

Boundary Conditions

- **Low surface availability – 29.5 ha — S1X**: Yes Biomass S1A; No Biomass S1B; Only H2 S1C
- **Medium surface availability – 59 ha (x2) — S2X**: Yes Biomass S2A; No Biomass S2B; Only H2 S2C
- **High surface availability – 259 ha (x10) — S3X**: Yes Biomass S3A; No Biomass S3B; Only H2 S3C

Upper boundaries

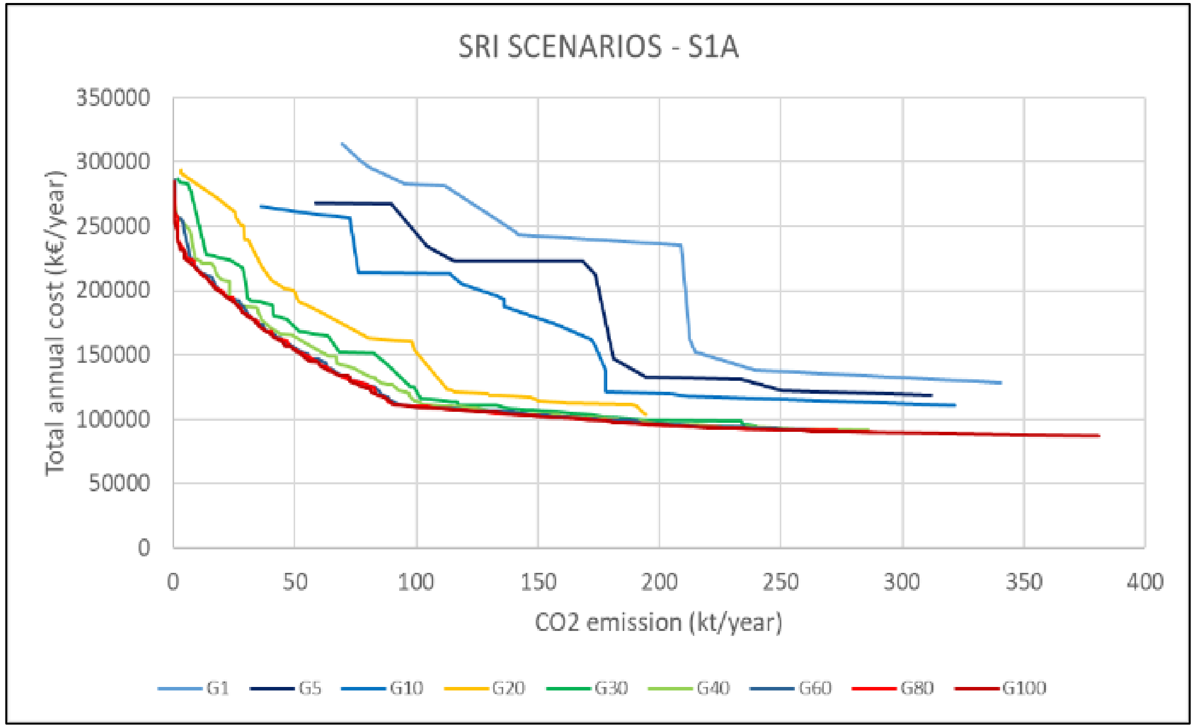
		Yes Biomass S1A	No Biomass S1B	Only H2 S1C	Yes Biomass S2A	No Biomass S2B	Only H2 S2C	Yes Biomass S3A	No Biomass S3B	Only H2 S3C
PV.	MW	38.35	38.35	38.35	76.7	76.7	76.7	383.5	383.5	383.5
Wind.	MW	6.9	6.9	6.9	13.8	13.8	13.8	31.05	31.05	31.05
Biomass St. Gen./Furnaces	GWh/year	1177.06	0	0	1177.06	0	0	1177.06	0	0
Biomass ORC.	MW	101.38	0	0	101.38	0	0	101.38	0	0
Electric St. Gen./Furnaces.	GWh/year	1177.06	1177.06	0	1177.06	1177.06	0	1177.06	1177.06	0
Solar thermal.	GWh/year	128.6	128.6	0	257.2	257.2	0	1286	1286	0
Solar thermal.	%	11%	11%	0	22%	22%	0	0	0	0
Battery.	MWh	362	362	362	724	724	724	3316.4	3316.4	3316.4

Boundary Conditions: Decision variables & value ranges

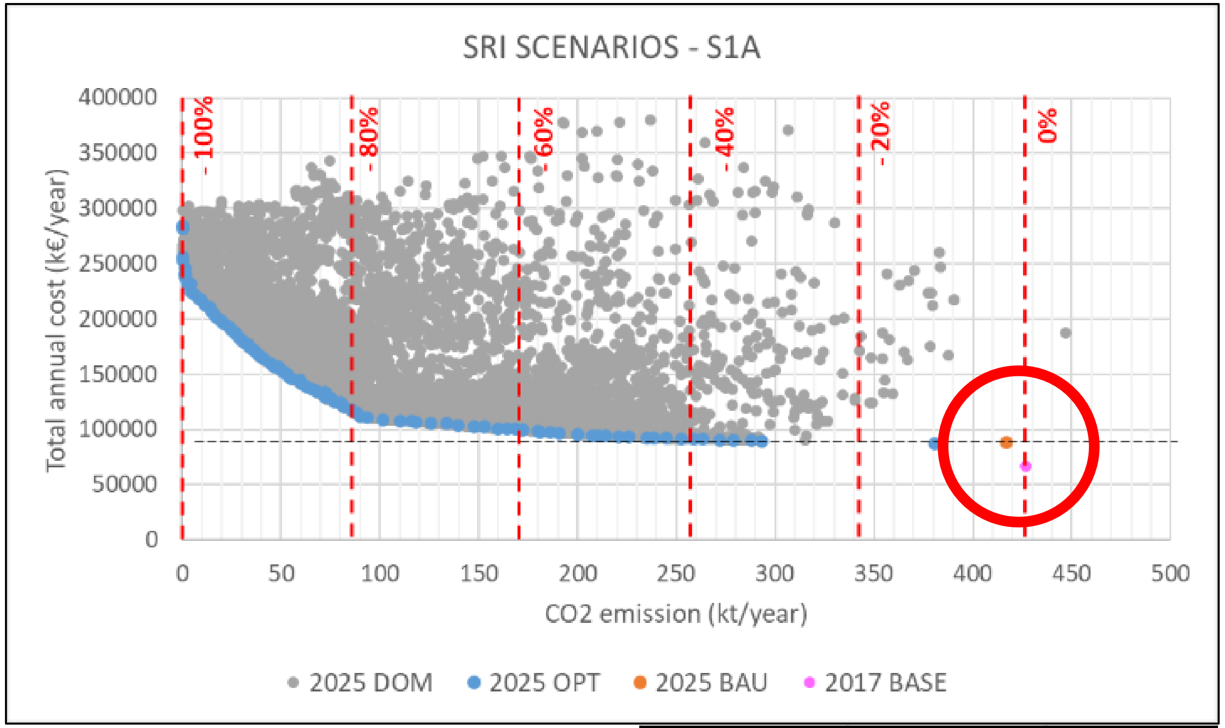
2025			
Technology	**Min**	**Max**	**Unit**
Electric Energy Production			
Photovoltaic.	0	See scenario chart.	kW
Wind.	0	See scenario chart.	kW
Waste heat ORC.	0	406	kW
Biomass ORC.	0	See scenario chart.	kW
National electric grid.	Calc. by EP, no grid constr.		GWh/year
Cogeneration			
Natural gas CHP.	0	1177.06	GWh/year
Thermal Energy Production			
Natural gas steam generators/furnaces.	0	1177.06	GWh/year
Hydrogen steam generators/furnaces.	0	1177.06	GWh/year
Biomass steam generators/furnaces.	0	See scenario chart.	GWh/year
Electric steam generators/furnaces.	0	See scenario chart.	GWh/year
Concentrating solar thermal.	0	See scenario chart.	GWh/year
Hydrogen			
Electrolytic feedstock H_2 demand.	0	123.62	GWh/year
Steam methane reforming feedstock H_2 demand.	0	123.62	GWh/year
Electrolytic production for H_2 steam generators/furnaces.	Calc. by EP as min cap. needed		kW
Electrolytic production for feedstock H_2	Calc. by EP as min cap. needed		kW
Trasportation			
Petrol vehicles demand.	0	1152001	km/year
Diesel vehicles demand.	0	1152001	km/year
Battery electric vehicles demand.	0	1152001	km/year
Storage			
Electric storage - Batteries.	0	See scenario chart.	MWh
Thermal energy storage for concentrating solar thermal.	Cons. cap. of 1 day of av. heat dem.		MWh
H_2 gas storage for H_2 steam generators/furnaces.	Cons. cap. of 1 day of av. H2 dem.		MWh
H_2 gas storage for H_2 as feedstock.	Cons. cap. of 1 day of av. H2 dem.		MWh

Results – Convergence and simulated scenarios.

Progression to convergence of the Pareto fronts as a function of generations.

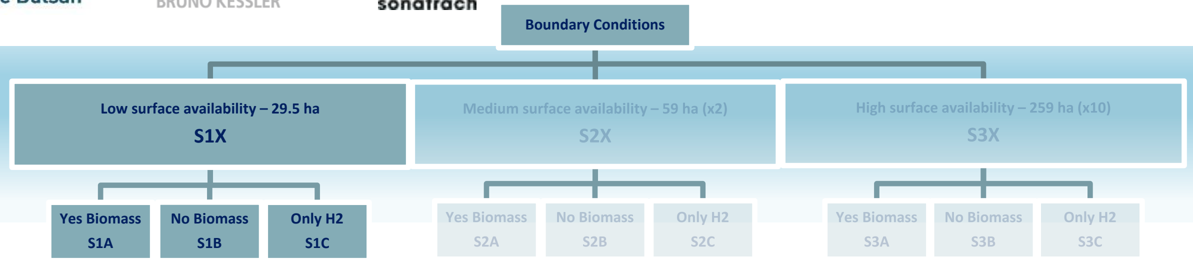


Example of Pareto front (blue) and dominated scenarios (grey).



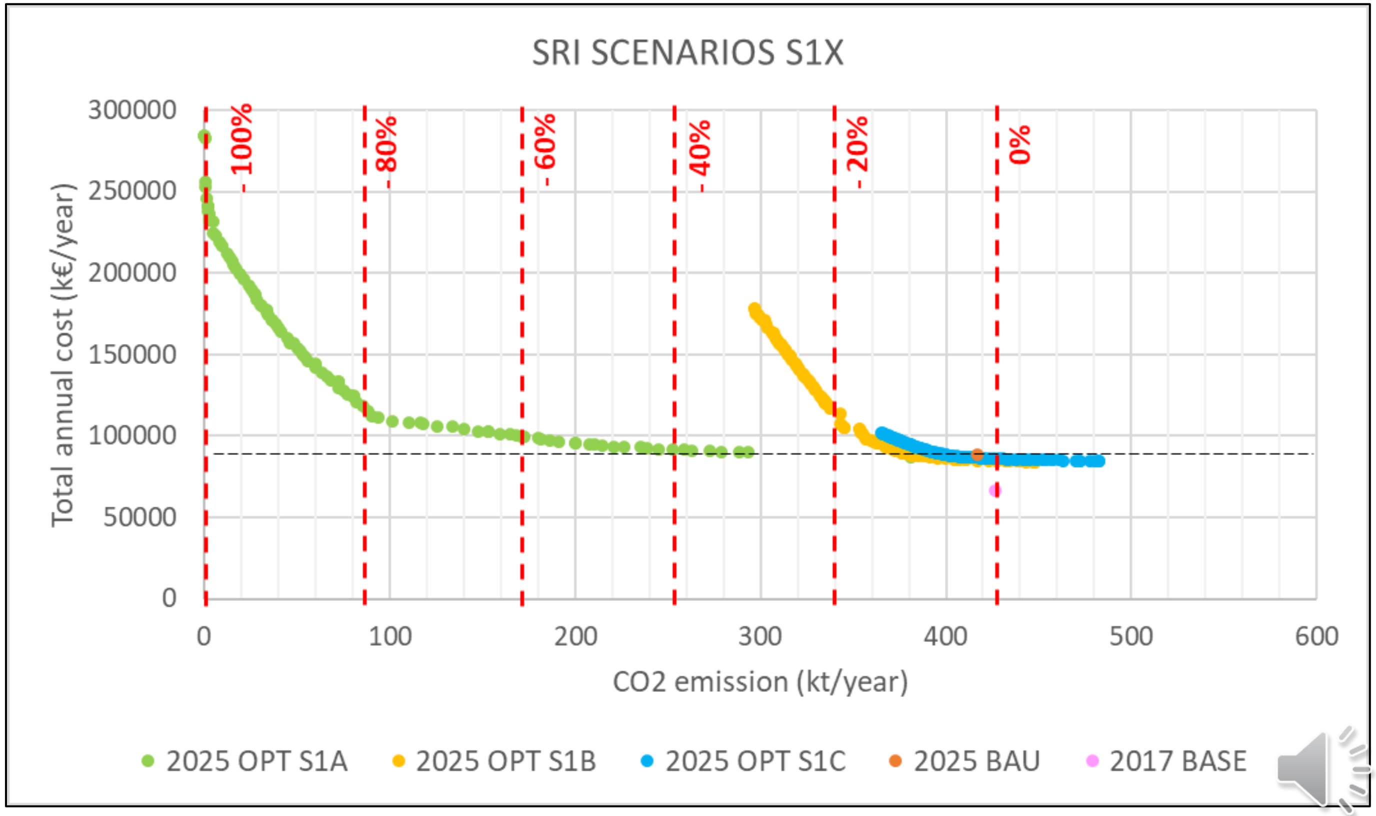
	CO2-Emission	Annual Cost
	ktonCO2/year	K€/year
2017 Baseline	427	66’525
2025 BAU	417	88’604

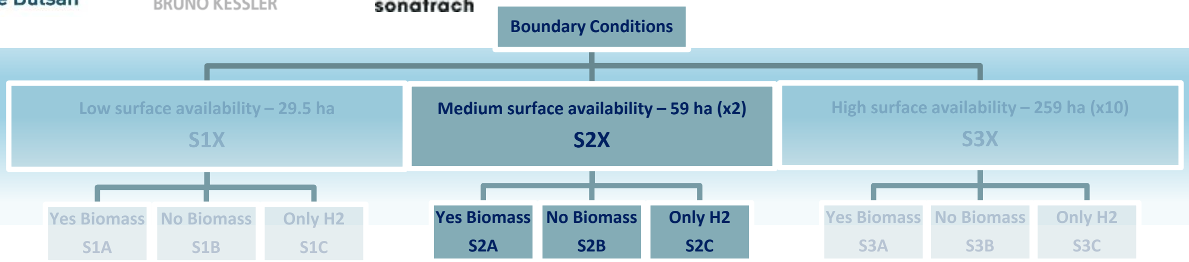
Results – S1X Pareto fronts



	CO2-Emission	Annual Cost
	ktonCO2/year	K€/year
2017 Baseline	427	66’525
2025 BAU	417	88’604

With low surface availability, deep decarbonizations are only achievable through the employment of biomass.

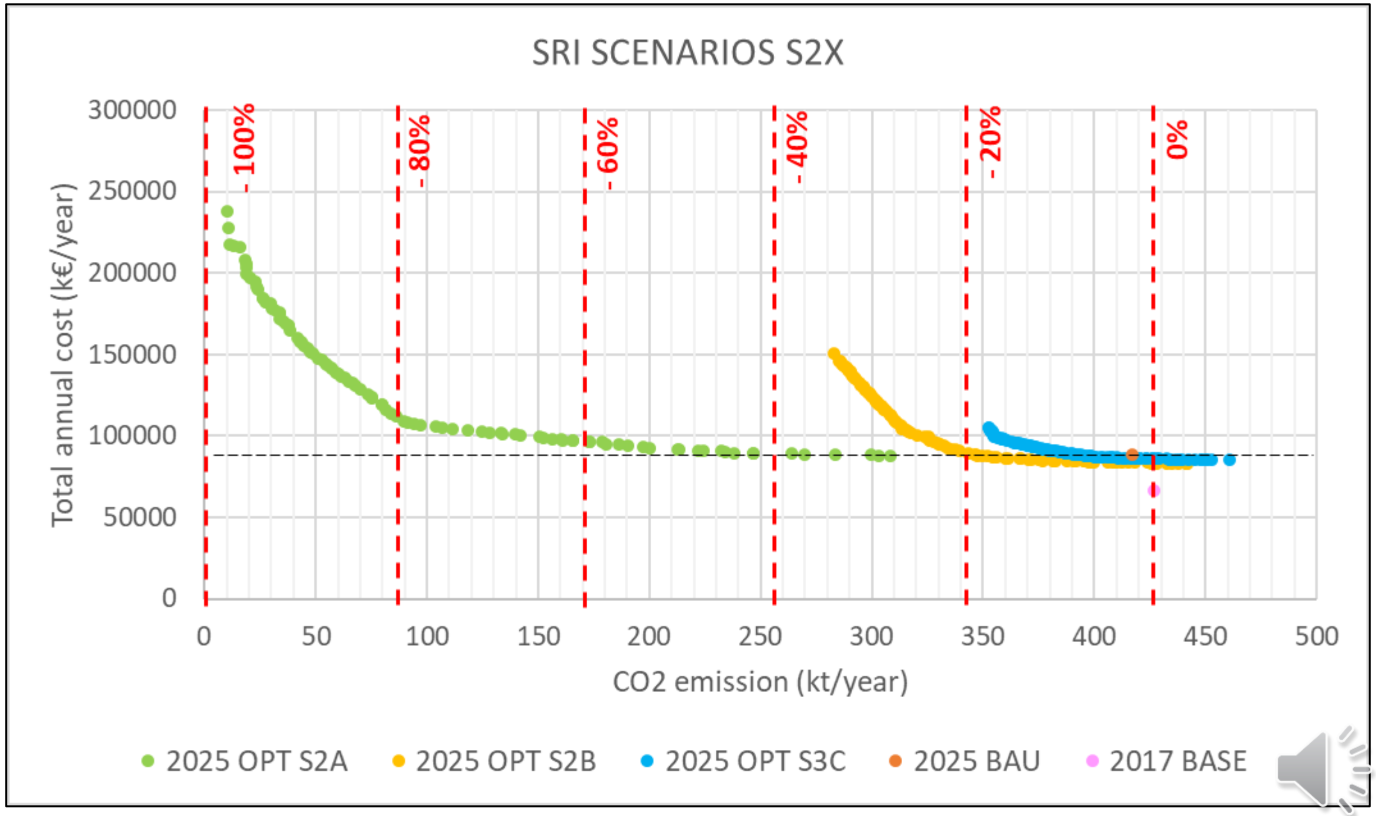




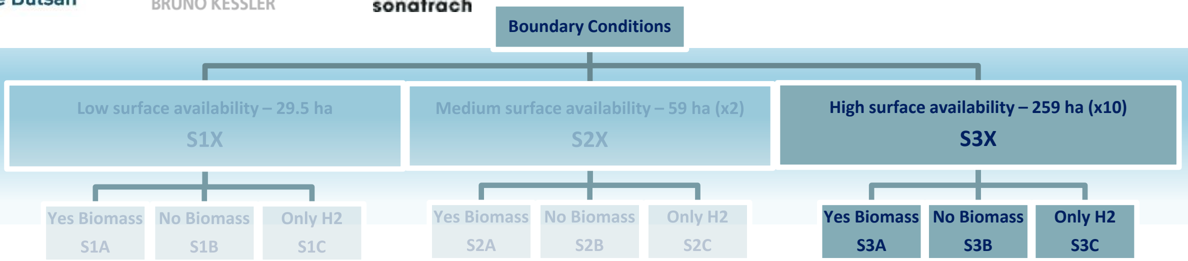
Results – S2X Pareto fronts

	CO2-Emission	Annual Cost
	ktonCO2/year	K€/year
2017 Baseline	427	66’525
2025 BAU	417	88’604

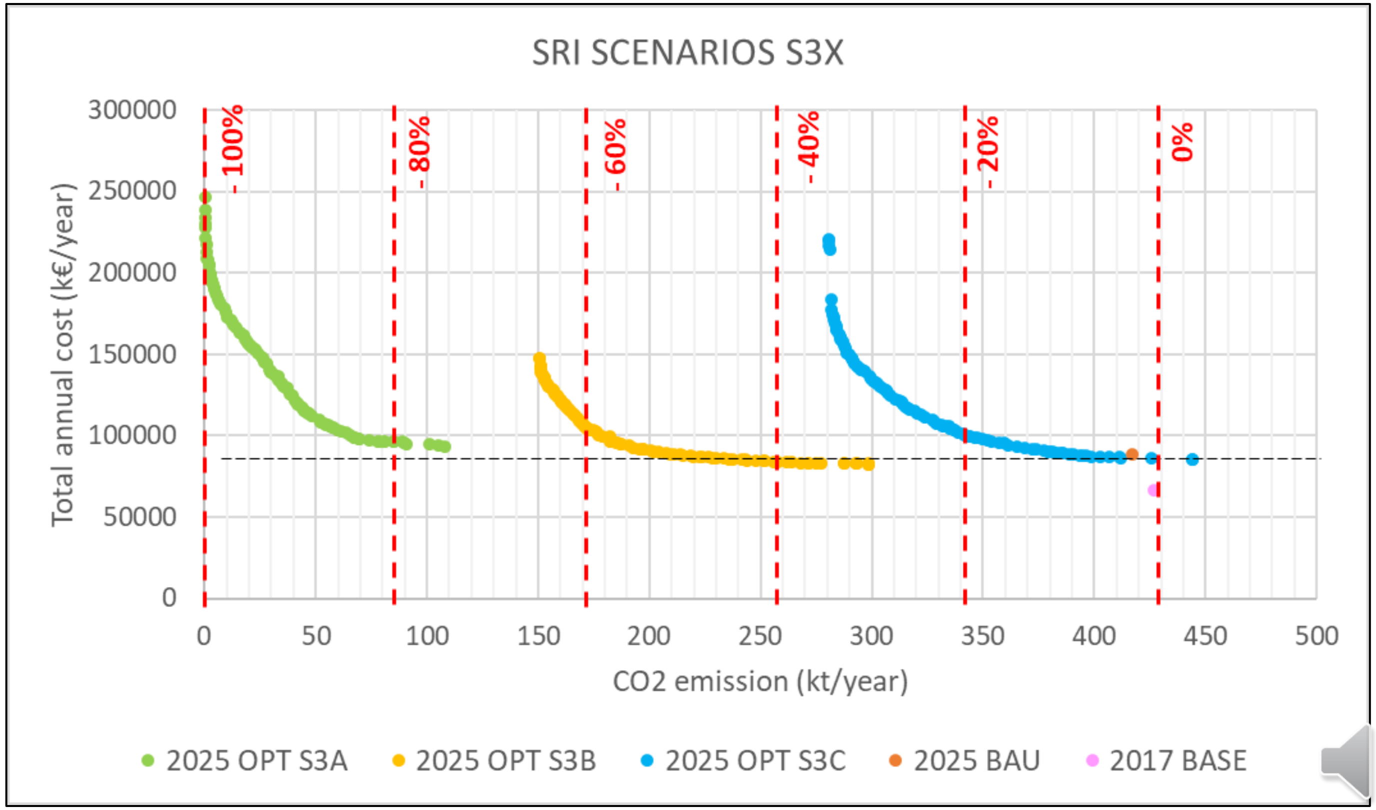
By doubling the available surface, the increase in decarbonization potential is negligible.



Results – S3X Pareto fronts

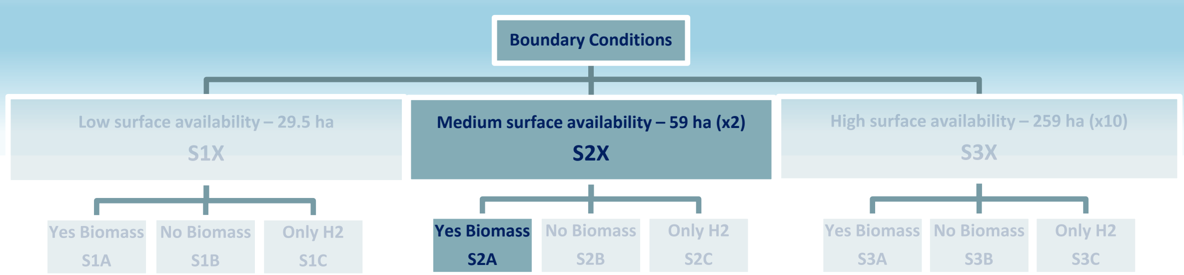


	CO2-Emission	Annual Cost
	ktonCO2/year	K€/year
2017 Baseline	427	66’525
2025 BAU	417	88’604

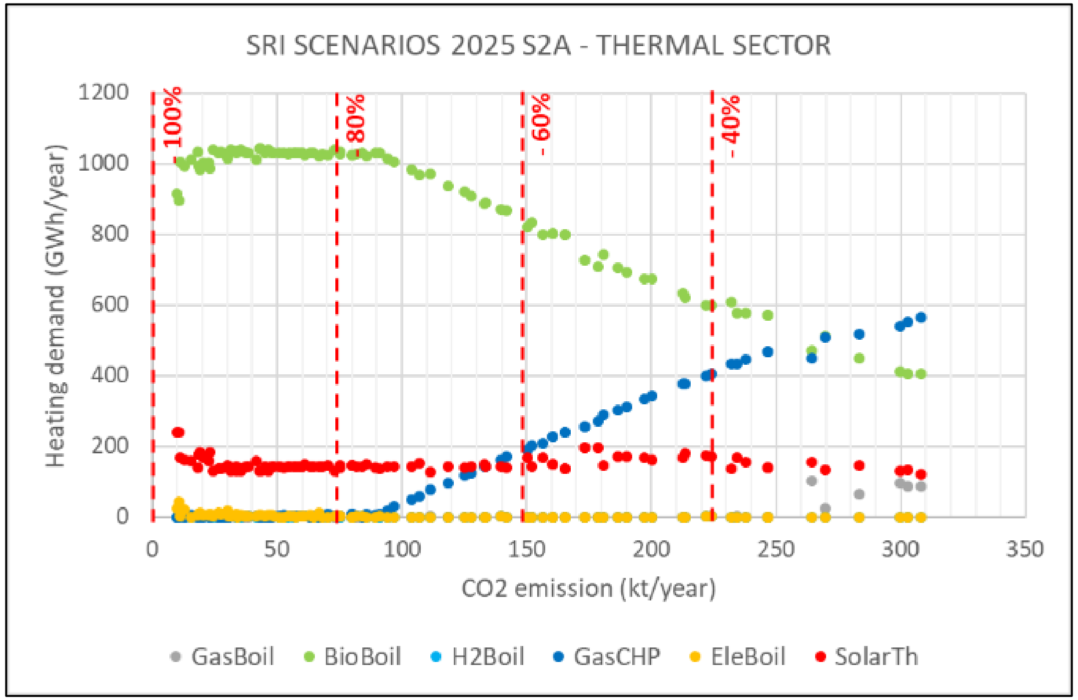


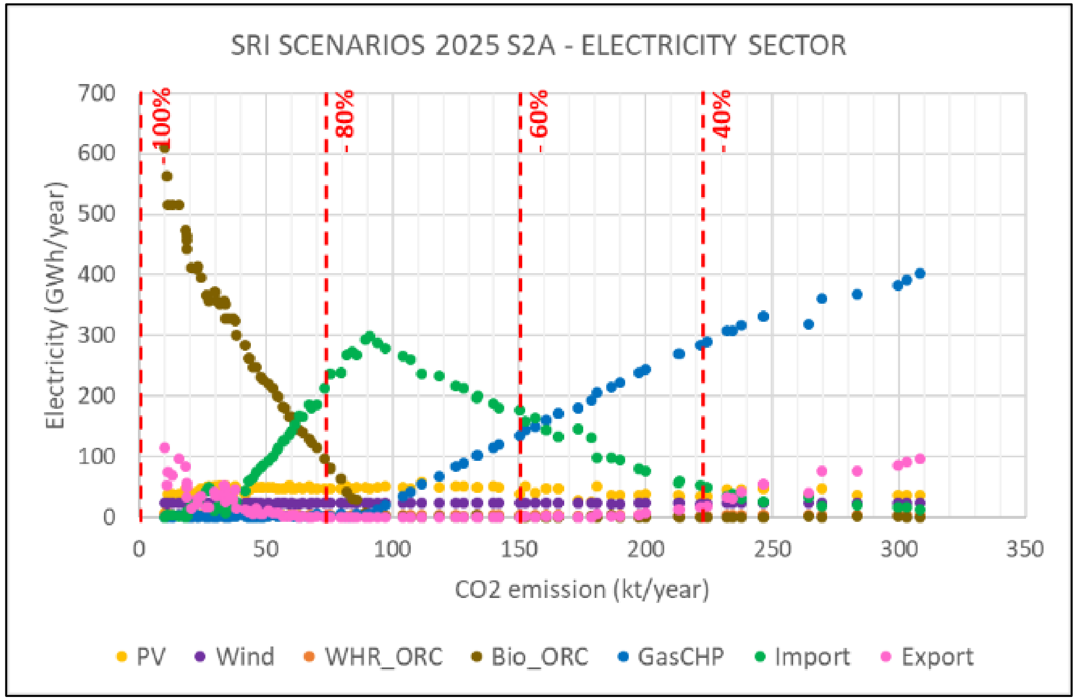
With a significant surface increase (x10), only a partial improvement (about 35%) of decarbonization potential is witnessed without biomass.

Results – Energy Sectors

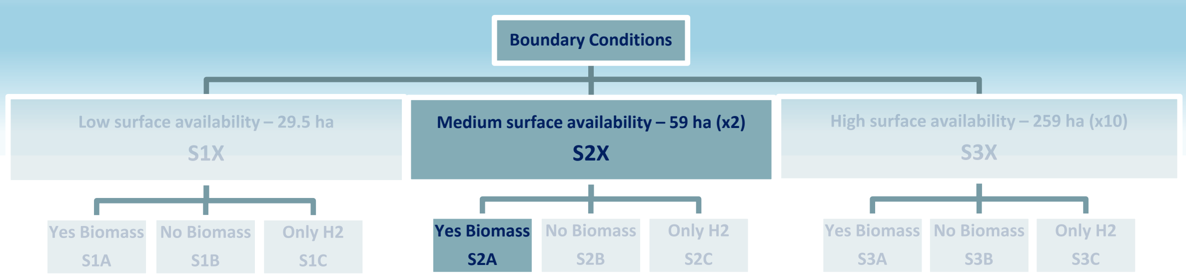


Technological breakdown: penetration of sustainable technologies in thermal and electric sectors, sector coupling (CHP), national electric grid exchange (import/export).

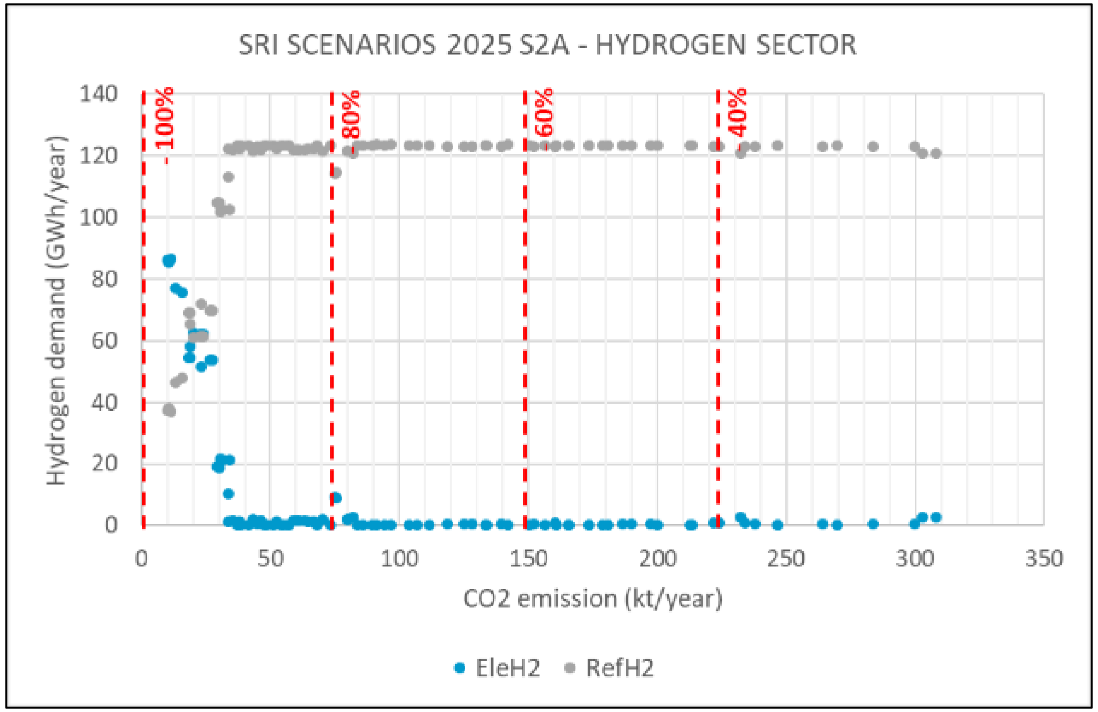


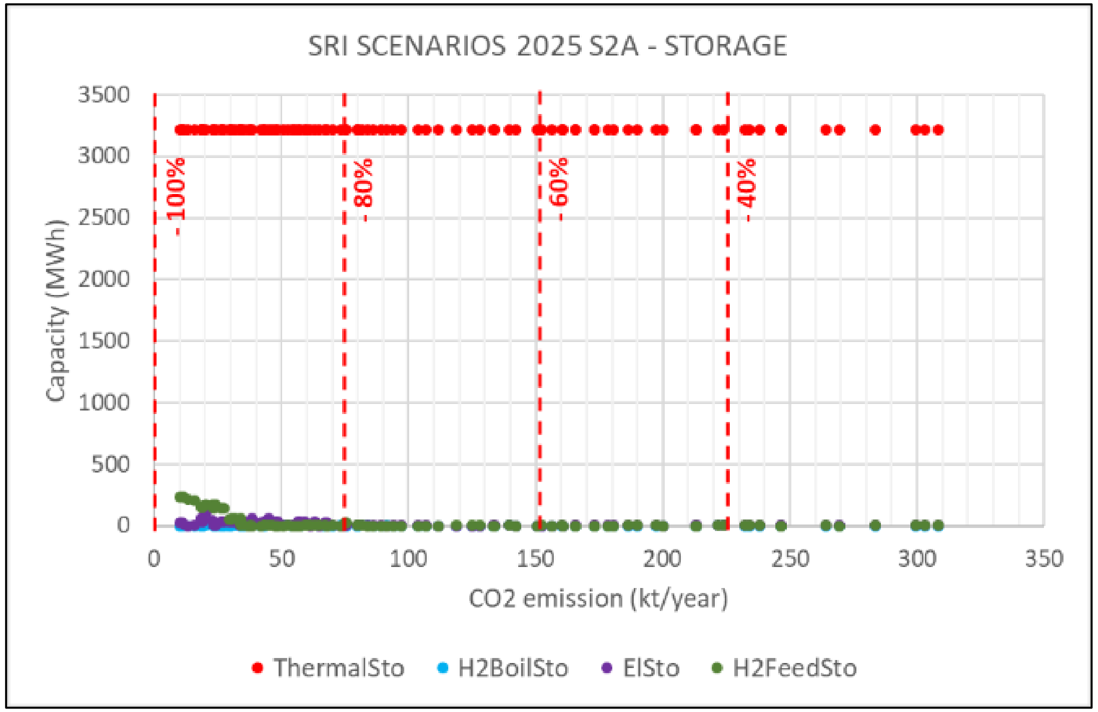


Results – Energy Sectors



Technological breakdown: penetration of sustainable technologies in hydrogen sector, sector coupling (PtH_2), role played by storage.





Conclusions

- Oil refineries are energy intensive, and their productive structures rely heavily on fossil fuels.
- Deeply decarbonized scenarios are attractive with a programmable and steady source of biomass.
- Integration of non-programmable RES (solar, wind), are economically feasible for intermediate decarbonization. To reach 100% CO_2 reduction, high terrain occupation and seasonal storage are required.
- Economically attractive scenarios see biomass fired steam generators and refinery furnaces, as opposed to the more costly biomass ORC.
- Electrolytic hydrogen is mandatory as substitution of gray feedstock hydrogen but is the most expensive technology among all energy sectors.
- In favor of electrolytic feedstock hydrogen is the ease of integration in the existing system layout and the possibility of long-term, large-scale storage.

Acknowledgments

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