White paper: Technological and policy recommendations for Solar-to-X Energy Systems

Introduction

SOLARX is a three-year research project funded under the European Commission's Horizon Europe Research and Innovation Programme (Grant Agreement No. 101084158), supported by the Swiss State Secretariat for Education, Research and Innovation (SERI). It explores the potential of Concentrated Solar-to-X (CST-to-X) technologies to enable high-penetration renewable energy systems. This White Paper synthesises results from ongoing project deliverables and is intended as background material for policymakers and stakeholders attending dedicated roundtable workshops or clustering webinars in collaboration with other EU-funded projects (https://SOLARX-project.eu).

A core objective of SOLARX is to demonstrate the technical and economic feasibility of co-generating high-temperature heat, electricity, and hydrogen (H_2) from solar energy in a single integrated facility. The analysis relies on two prominent energy system simulation tools:

- energyPRO: A tool for modelling and optimisation of complex energy systems (https://www.emd-international.com/energypro)
- HyDesign: A hybrid system design platform developed by DTU (https://topfarm.pages.windenergy.dtu.dk/hydesign).

In SOLARX a wide range of multi-vector energy systems will be simulated, including Carbon Capture, Utilisation and Storage (CCUS) and biogas integration, across various geographical contexts and market scenarios. The production of high temperature heat, electricity and H2 from solar resources is made in a single facility, considering energy demands and market prices for a wide range of locations and application scenarios.

In parallel, three core technological innovations are being developed at lab scale in SOLARX:

1. High-efficiency Concentrated Photovoltaic (CPV) receiver
2. Bi-energy H_2 receiver (powered by solar and electricity)
3. Smart solar resource management algorithm

In Section 1, it is shown that using the same area, a Solar Field will produce twice the amount of industrial high-temperature heat that could be generated by a PV-plant. In Section 2, examples of SOLARX multi-vector energy systems are given, which will be analysed in energyPRO and HyDesign. This leads to Section 3, where technological developments and policy recommendations will be made.

Funded by the European Union

Funded by the European Union under the Horizon Europe Framework Programme (Project name: SOLARX; grant number: 101084158). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them. The project is also supported by the Swiss State Secretariat for Education, Research and Innovation (SERI).

1 Superior Thermal Output: Solar Field vs. Photovoltaics for SHIP

Solar Heat for Industrial Processes (SHIP) remains an urgent priority in the transition from fossil-based to renewable thermal energy. Using the same surface area, CST fields in SOLARX significantly outperform PV-electric-to-heat solutions.

One of the starting points for promoting the SOLARX systems compared to using the same land area for e.g. a PV-plant, is the need for reducing fossil fuel consumption in high-temperature industrial processes. Using the same area, Solar Field will produce twice the amount of industrial high-temperature heat that could be generated by a PV-plant, where the produced electricity is converted to industrial high-temperature heat in an electrical boiler.

This is demonstrated by considering an 8000 m^2 mirror area of the Solar Field. To convert this to land area, ground coverage ratio (GCR) for a Solar Field plant is used. According to the article: https://www.sciencedirect.com/science/article/pii/S1474667016423827, the optimal GCR for a solar field, with a similar layout used in SOLARX, is 38.3%. Assuming the GCR of 38.3%, the area available for the PV installation is approximately 2.01 ha.

A PV plant covering the 2.01 ha was calculated in windPRO SolarPV (https://www.emd-international.com/windpro/windpro-modules/energy-modules/solar-pv).

The best PV plant configuration for the considered location is:

- Tilt angle of 21°
- Row spacing of 5.65 m
- Panels oriented towards south

With the above configuration the following results are found:

- Installed PV capacity: 3.25 MW
- Yearly electricity production for year 2023: 6351 MWh
- High temperature heat production (electric boiler with 95% efficiency): **6033 MWh**

For the same area (8000 m^2 mirror area), the available Solar Thermal Flux for year 2023 (incident energy on the CST receiver) from the SOLARX system is **12712 MWh**.

Conclusion: The CST Solar Field delivers twice the thermal energy output compared to a PV-based heat system for industrial use.

2 Examples of multi-vector energy systems analysed in SOLARX

This section provides examples of multi-vector energy systems, which will be analysed and simulated in SOLARX.

The examples are selected as parts of a more generalised setup, as shown below.

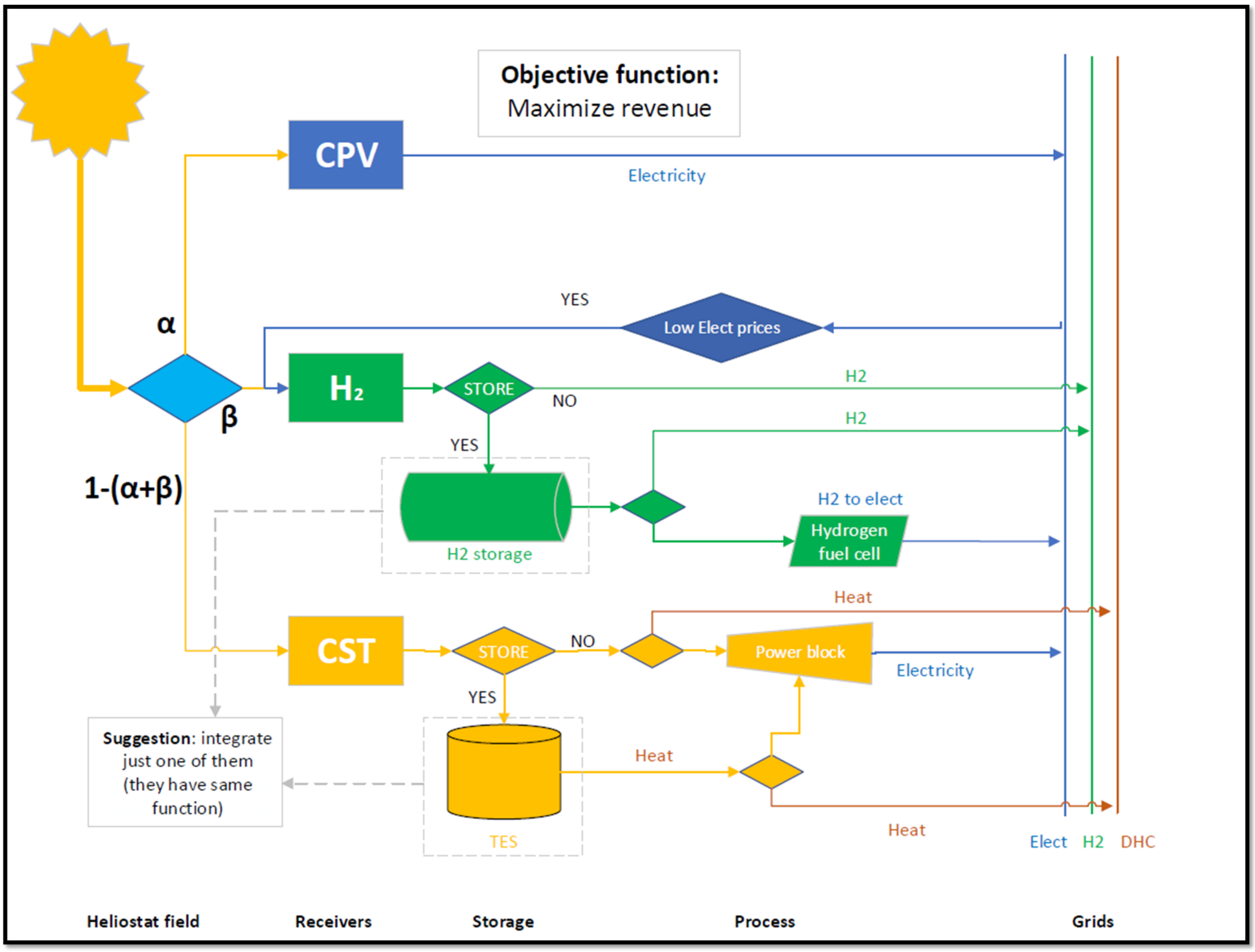

Figure 1 Examples of multi-vector energy systems analysed in SOLARX.

2.1 CPV & CST

This multi-vector SOLARX energy system consists of Solar field aiming at a CPV receiver or CST receiver that heats molten salt which eventually, when prices are higher is used in a steam turbine to produce electricity.

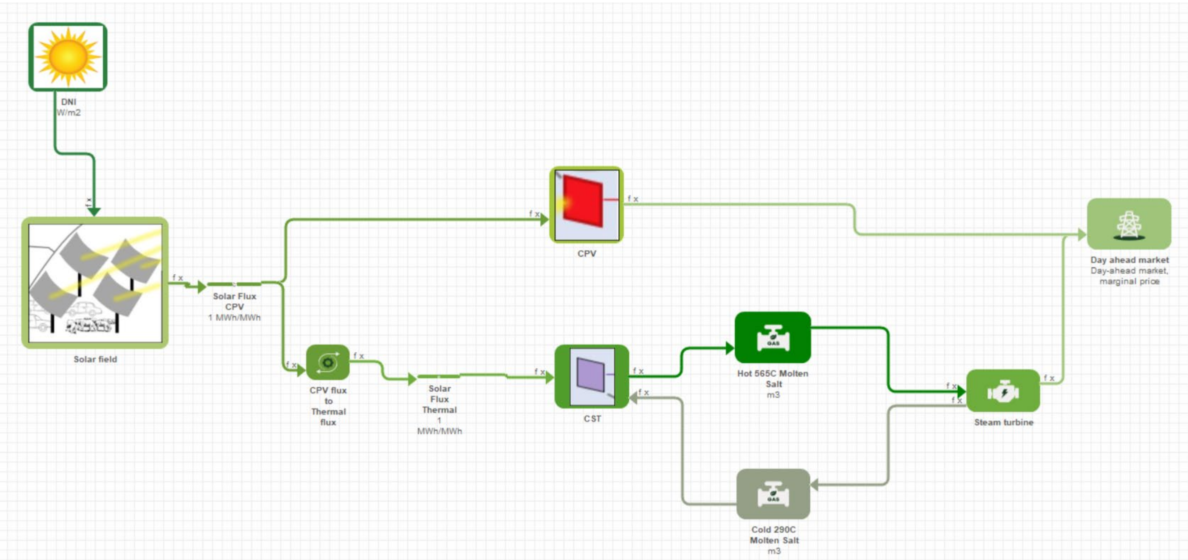

Figure 2. Solar field heats molten salt for later electricity generation via a steam turbine.

A typical operation of this plant is seen Friday 23-06-2023. The hot molten salt tank is filled when Day-ahead prices are low, and in the evening, when prices are higher the steam turbine produces electricity, the hot molten salt tank is emptied, and the cold molten salt tank is thus filled.

Figure 3 . Example: On 23 June 2023, salt storage (red curve at the bottom) charges during low day-ahead electricity prices (dark green curve); electricity is generated in the evening during peak prices.

2.2 CPV & CST receiver on both solar field and Electricity

This multi-vector SOLARX energy system is based on the one in section 2.1. Here an additional component is added that can heat the molten salt with electricity (CST on El).

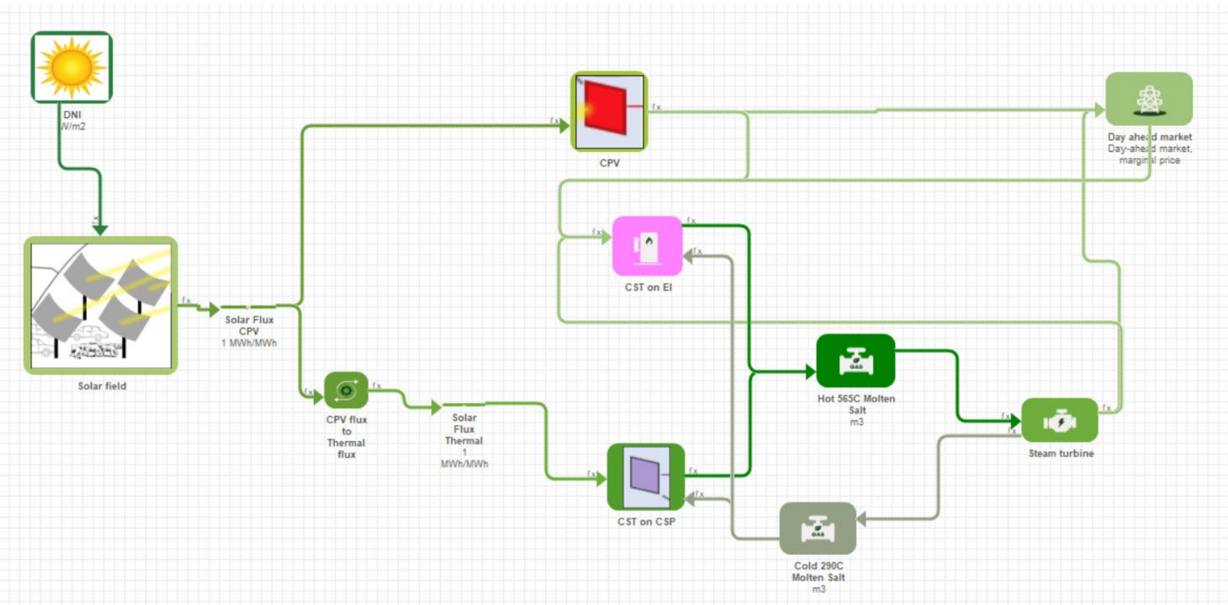

Figure 4. CST receiver (in pink) also powered by grid electricity.

A typical operation of this plant is seen Tuesday 14-03-2023. In the night hours the hot molten salt tank is filled with CST on El when Day-ahead prices are low, and in early morning, when prices are higher the steam turbine produces electricity, and the hot molten salt tank is emptied.

Figure 5. Example: On 14 March 2023, salt charging occurs at night via grid power; turbine operates in the morning.

2.3 CPV and H2 production

This multi-vector SOLARX energy system consists of Solar field aiming at H2 receiver and a CPV receiver. The methane to the H2 production is delivered from a biogas plant, equipped with a biogas storage.

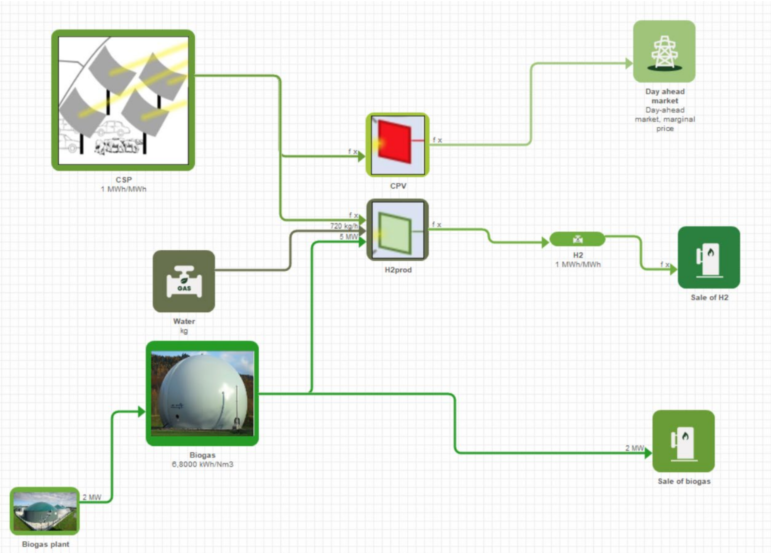

Figure 6. Solar-driven CPV for electricity and H_2 production from biogas-sourced methane.

A typical operation of this plant is seen Friday 09-06-2023. In the morning, where Day-ahead prices are high, the solar flux converted to electricity in the CPV receiver. In these hours the biogas storage is filled. Later that day – when Day-ahead prices get lower, the hydrogen production starts thus emptying the biogas storage.

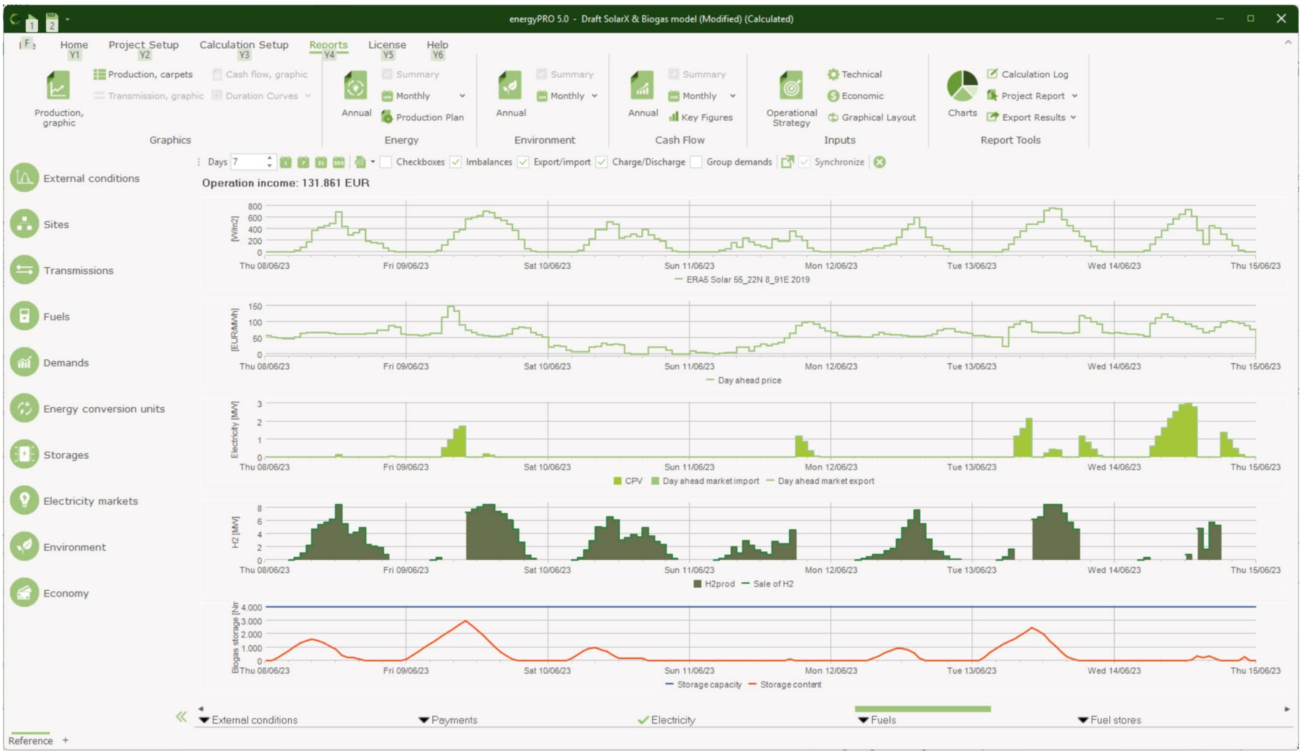

Figure 7. Example: On 9 June 2023, CPV output is used to charge biogas storage early in the day; H_2 production begins later as electricity prices fall.

2.4 CPV and H2 production on both Solar Field and El

This multi-vector SOLARX energy system is based on the one in section 2.3. Here an additional H2 production component is added, that can produce H2 electrically heated.

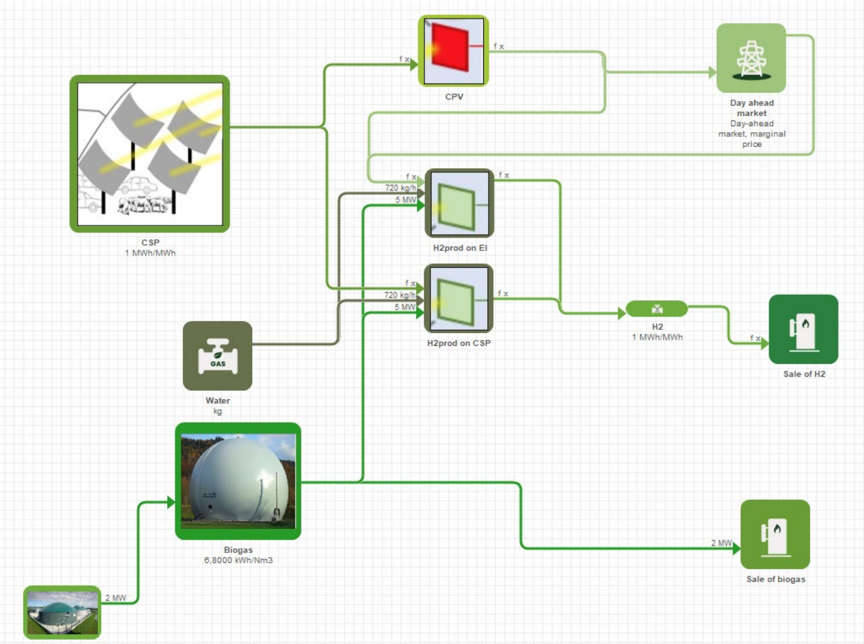

Figure 8. Adds grid-electric heating to the H_2 receiver.

A typical operation of this plant is seen Friday 09-06-2023. After midnight, where Day-ahead prices are low, electricity is purchased for H2 production on the component that can produce H2 electrically heated.

Figure 9. Example: On 9 June 2023 (after midnight), H_2 is produced from low-cost grid electricity.

2.5 Methanol production on syngases

One of the most advanced multi-vector SOLARX energy systems analysed in the SOLARX project involves the production of syngases, which are subsequently converted into methanol. The mole balances as well as the model of the energy system is shown below.

H_2 Receiver Reactor

Making synthesis gas

	Reaction		Inlet	Outlet
- Dry reforming:	$CH_4 + CO_2$	-> $2CO + 2H_2$	CO_2/CH_4=1	H_2/CO=1
- Steam reforming:	$2CH_4 + 2H_2O$	-> $2CO + 6H_2$	CO_2/CH_4=0	H_2/CO=3
- Combined	$3CH_4 + CO_2$ + 2H2O	-> $4CO + 8H_2$	CO_2/CH_4=1/3	**H_2/CO=2**

Converting synthesis gas

- Pure H2	$CH_4 + 2H_2O$	-> $CO_2 + 4H_2$	$H_2/CO=\infty$
- Methanol	$CO + 2H_2$	-> CH_3OH	H_2/CO=2
- Kerosene	$nCO + 2nH_2$	-> $(CH_2)n + nH_2O$	H_2/CO=2

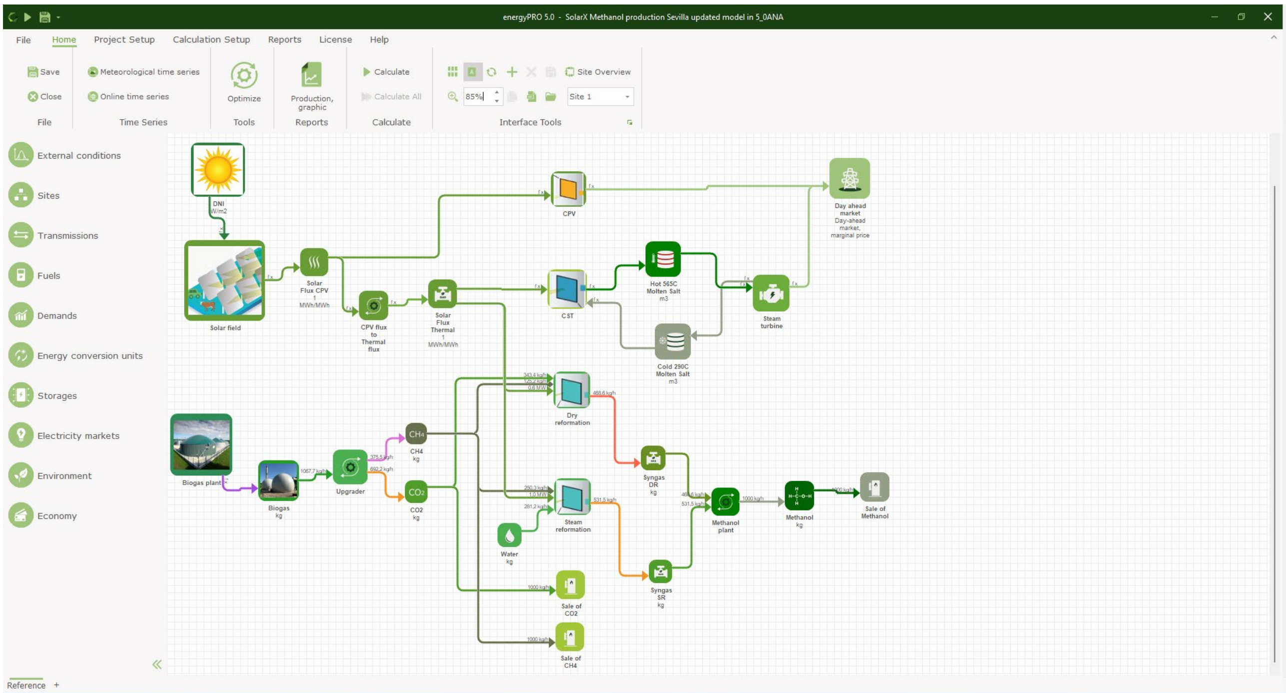

Figure 10. Advanced setup: Solar-to-syngas pathways feeding into methanol synthesis. Includes stoichiometric balances and energy integration flows.

3 Technological developments and recommendations

Based on the examples of SOLARX multi-vector energy systems presented in Section 2, this section provides an overview of the technological developments. Three key innovations have emerged:

1. Bi-energy H_2 Receiver

- Operates on both solar heat and electricity
- ***Recommendation***: Proceed to pilot-scale testing, even without a Solar Field (electrically driven mode suffices)

One of the key technological elements developed at laboratory scale in SOLARX is the bi-energy H2 receiver. In the laboratory, it is demonstrated that the developed H2 production receiver can be operated on both solar energy and electricity. It is recommended that this technological element will be tested outside laboratory in a pilot plant. It is not necessary that this pilot plant may be operated with a Solar Field supplying the H2 production receiver, since it is able to be operated also on electricity, as shown in section 2.4.

2. Advanced CPV Receiver

- High-efficiency solar-to-electric converter
- ***Recommendation:*** Develop European manufacturing capacity for CPV cells to reduce reliance on imports

In the case of the CPV receiver, we recommend establishing production capacity in Europe for advanced CPV cells.

3. Molten Salt Thermal Storage

- Enables time-shifted use of thermal energy for industrial process heat
- ***Recommendation***: Pilot demonstrations to validate scale-up potential (also operable with grid electricity)

Besides the key technological elements in the project, it is recommended that another future key technological element is the molten salt tanks storing high-temperature molten salt for later use for e.g., covering high temperature process heat for industry. It is also recommended that this technological element will be tested outside the laboratory in a pilot plant. This pilot plant doesn't need to be operated with a Solar Field supplying the CST receiver, since it can also be operated on electricity, as shown in section 2.2.

4 Policy recommendations

Based on technological findings and simulation results, a policy recommendation is that these pilot plants will be publicly cofinanced, to make the operational experience of the pilot plants available for all companies offering multi-vector energy systems. Anyhow, these pilot plants address the possibilities in concentrated Solar-to-X energy solution but will also be valuable when used for e.g., integrating wind production in Northern Europe.

Another important policy recommendation is inspired by the example of SOLARX multi-vector energy systems in section 2.2, where electricity is purchased and later sold when prices are higher from the steam turbine. It should be considered that the electricity thus stored and later returned to the grid should not pay consumption taxes, since in a way it is not consumed but later returned to the grid.

SOLARX presents the following policy priorities. These are our 3 recommendations:

1. Public co-financing of pilot plants

Support the deployment of H_2 receivers and molten salt storage systems in pilot installations. Pilot plants should be accessible to industry players to share operational insights and reduce innovation risks.

2. Tax exemptions for re-injected electricity

For systems like the one in Section 2.2, where electricity is stored and later returned to the grid via turbines, exempt this flow from electricity consumption taxes. This would acknowledge its role in grid balancing rather than consumption.

3. Strengthen European solar technology value chains

Invest in domestic production of CPV components to secure strategic autonomy and supply resilience for high-performance solar technologies.