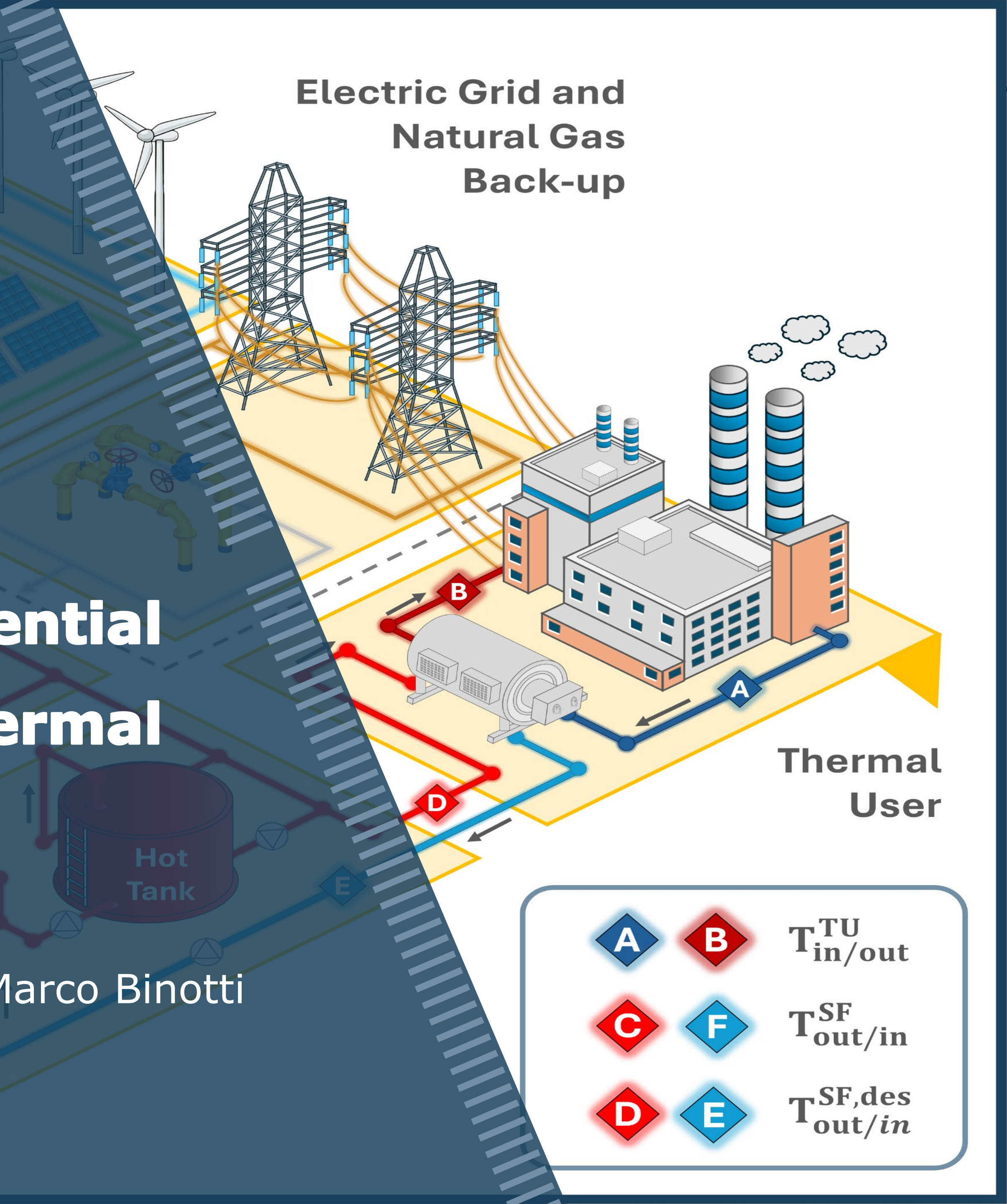
POLITECNICO MILANO 1863 | DIPARTIMENTO DI ENERGIA

Group of Energy COnversion Systems

Industrial Process Heat: The Potential of Hybrid Concentrated Solar Thermal and Electric Heating Systems

Marco Colombi, Paolo Colbertaldo, Matteo Romano, Marco Binotti

13/05/2026 – HelioCon Seminar - Online



Politecnico di Milano and the Group of Energy Conversion System

- Established in 1863,
- Largest Italian university in Engineering, Architecture and Design:
    - ~ 49,400 BSc and MSc students
    - ~ 2,240 PhD students
    - ~ 1,850 teaching staff
- QS World University Ranking by Subject, Engineering & Technology: 20^{th} in the world, 3^{rd} in the EU.
- Seven campuses located in Milan (2), Lecco, Cremona, Mantova and Piacenza.

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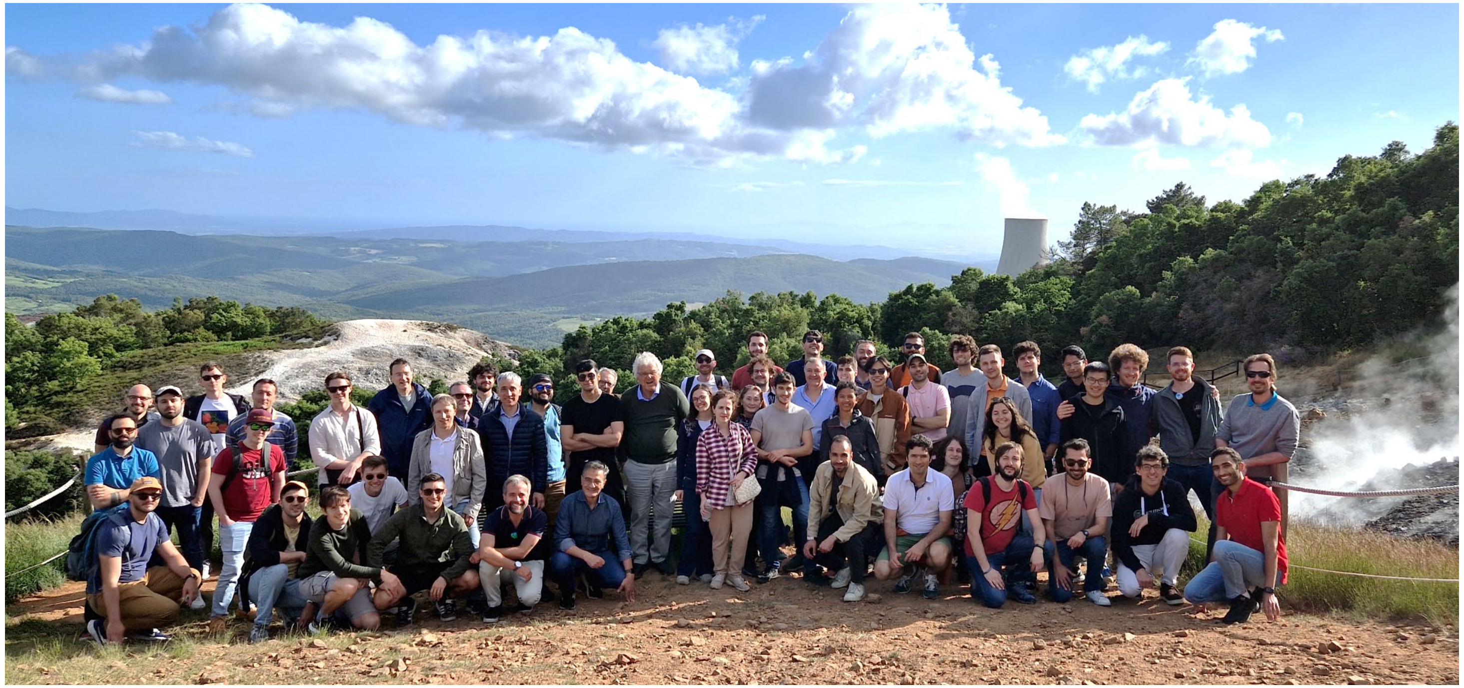

9
Full Professors

11
Associate Professors

4
Assistant professor

~50
PhD students and post-docs

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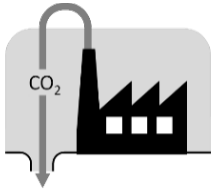
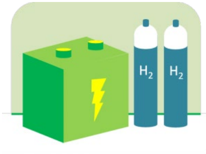
ADVANCED POWER CYCLES AND ORGANIC RANKINE CYCLES



CARBON CAPTURE TECHNOLOGIES

ENERGY SYSTEMS MODELING AND OPTIMIZATION

MICRO-GRIDS AND MULTI-ENERGY SYSTEMS



FUEL CELLS AND ELECTROCHEMICAL ENERGY SYSTEMS

RENEWABLE ENERGY SOURCES

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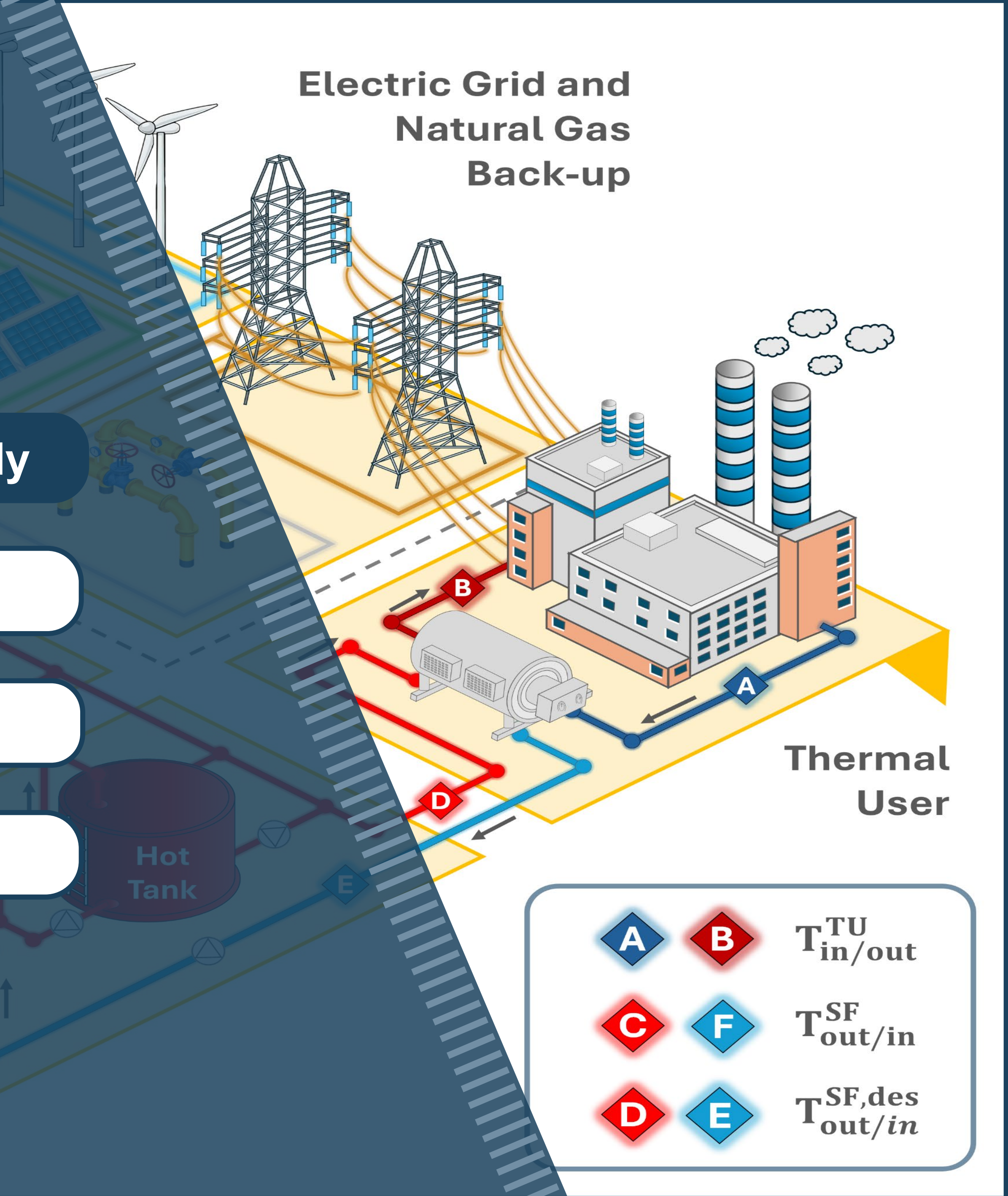
Electric Grid and
Natural Gas
Back-up
Thermal
User
A B $T^{TU}_{in/out}$
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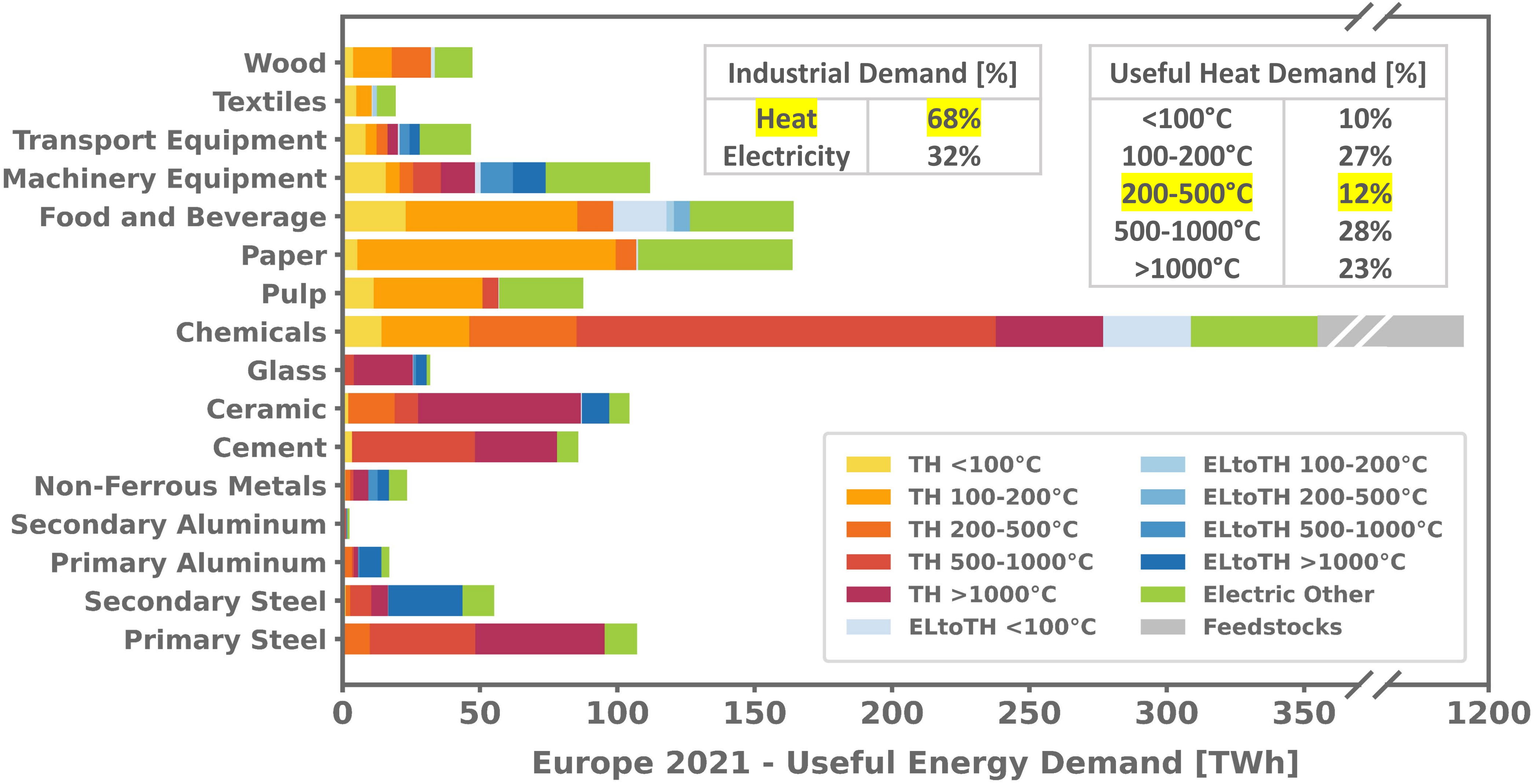
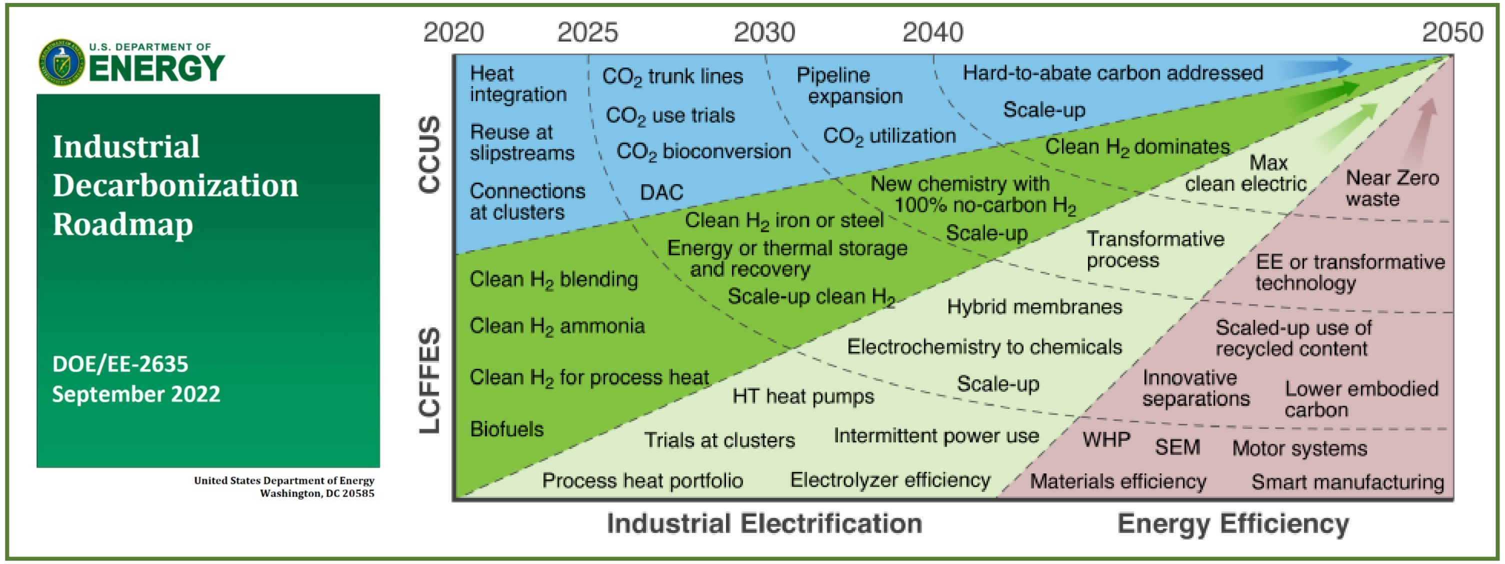
Industrial Process Heat (IPH): Stating the Problem

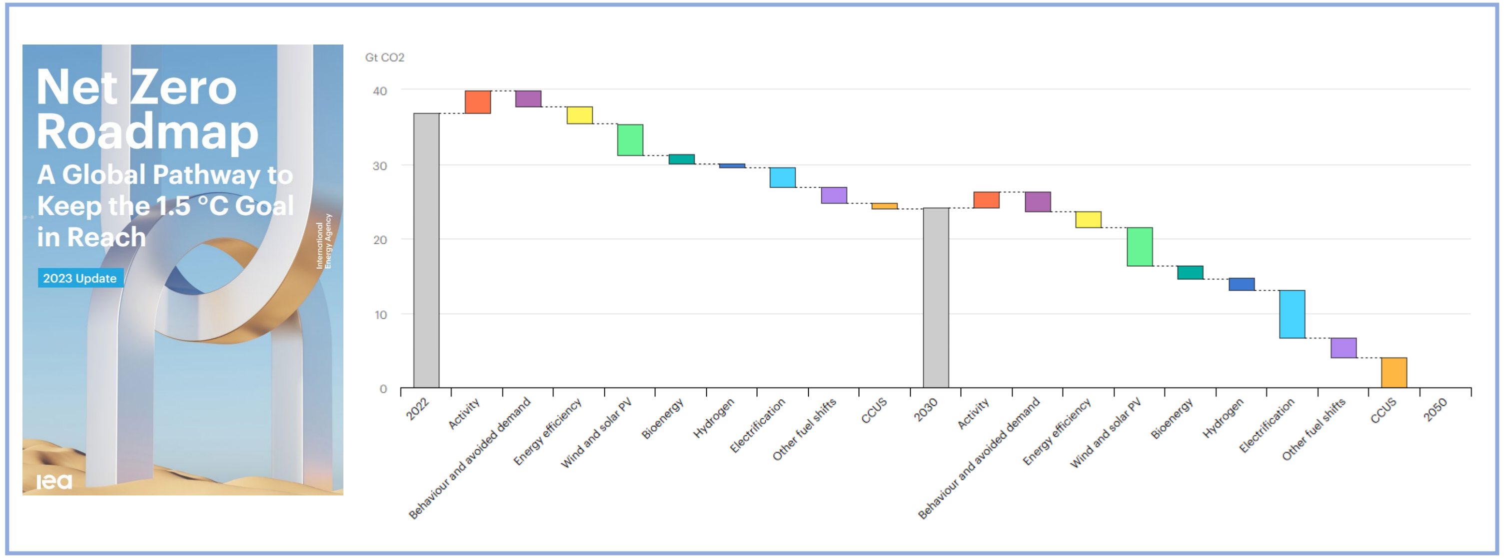


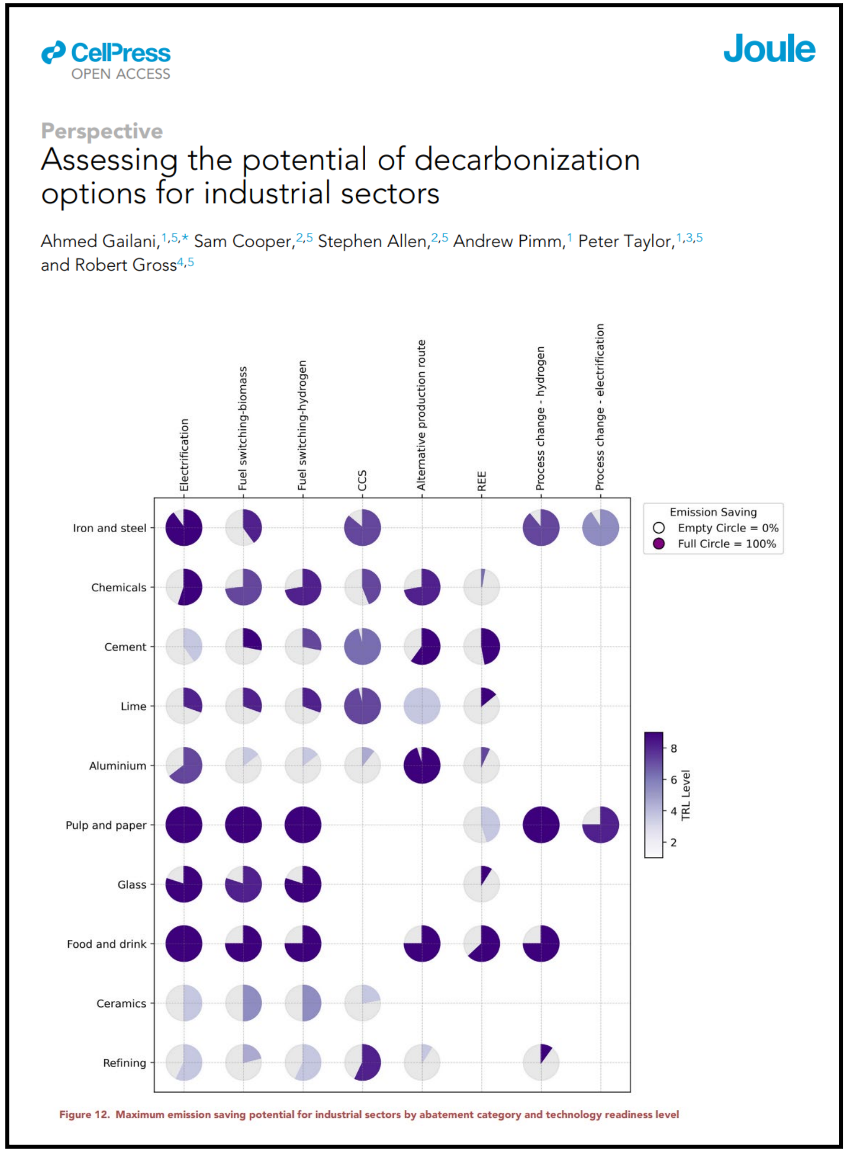
Also, the **thermal demand** can vary widely across different sectors, with **around 40% of industrial facilities requiring 0-1 MW_{TH}** and 25% between 1-10 MW_{TH}, according to a study in the US [1].

[1] G. P. Thiel and A. K. Stark, "To decarbonize industry, we must decarbonize heat," Mar. 17, 2021, Cell Press. doi: 10.1016/j.joule.2020.12.007.

Solar thermal for industrial decarbonization is often overlooked!







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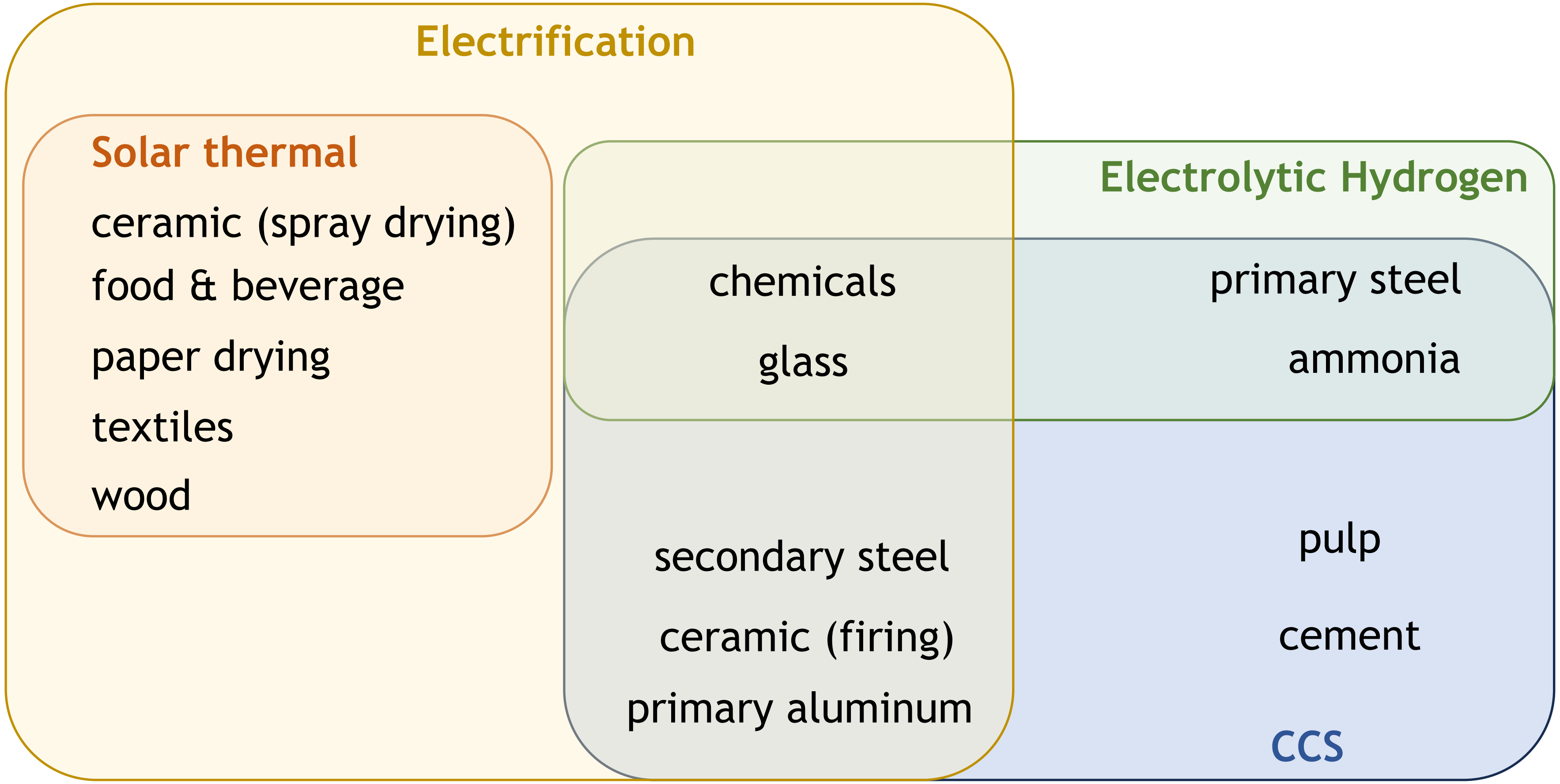
Industrial Decarbonization



Objective of the Study

- To **decarbonize** a generic medium temperature industrial process under **varying levels** of **Renewable Penetration** (RP)

- By employing **parabolic trough** collectors **hybridized** with resistive electric heating sustained by **PV** and **WT** power generation

- Focusing on the effect of:
  - i. **CST Orientation & Hybridization**
  - ii. **Heat Temperature Level** (500°C vs 300°C)
  - iii. **Location**, **Collector Cost**, **Load Profile**

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Research Paper

Industrial process heat decarbonisation with hybrid concentrated solar thermal and electric heating systems

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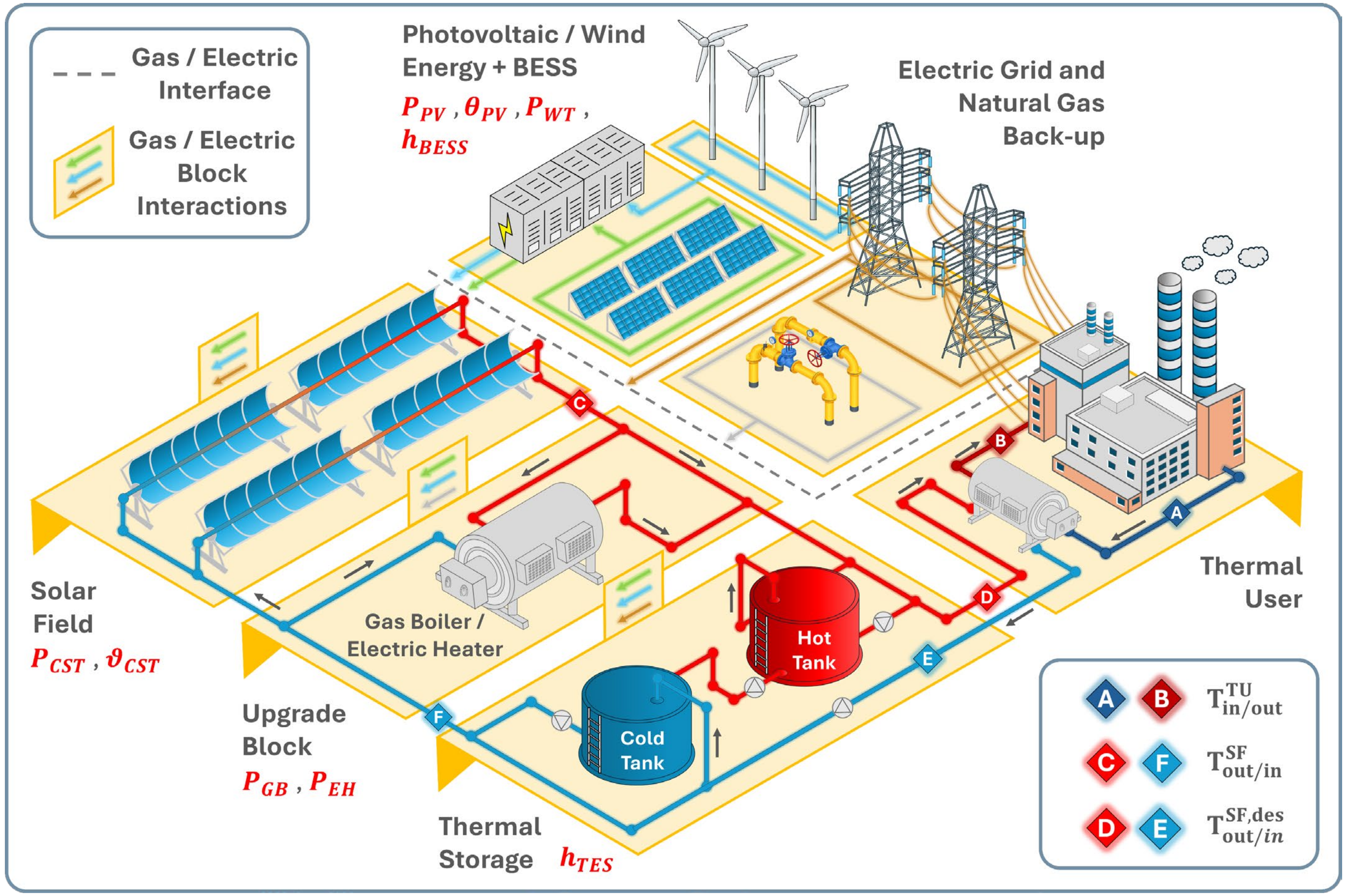
Published paper



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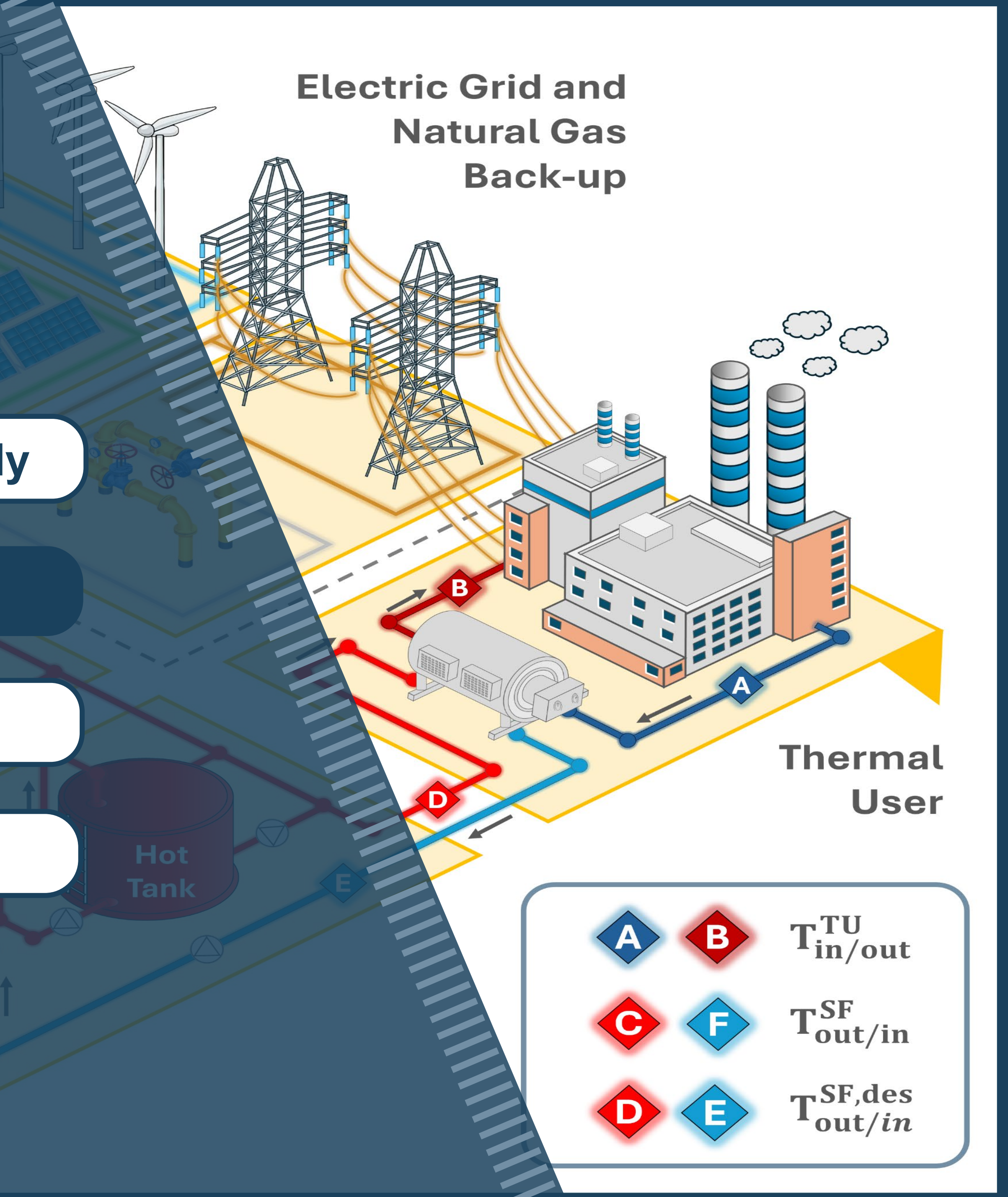

Electric Grid and
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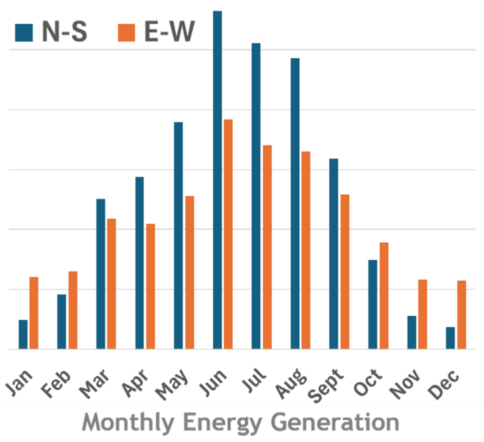
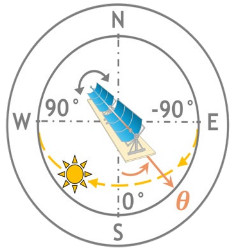
$T^{SF,des}_{out/in}$

Methodology - Analyzed Cases

Solar Collector Axis Tracking



(0°, N-S): Higher Energy Yield but Less Distributed



(90°, E-W): Lower Energy Yield but More Distributed

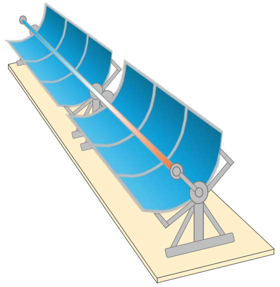
Heat Temperature Level & Thermal Load

- **510-400°C case**: molten salts
  Collector: Eurotrough ET100
  Receiver: HCEMS-11
- **310-200°C case**: mineral oil
  Collector: Eurotrough ET100
  Receiver: Schott PTR70

Both as HTF and storage media (double-tank)

- **Load Demand and Profile**:
  10 MW_{TH} (Constant, 6-22, 6-22 No Weekend)

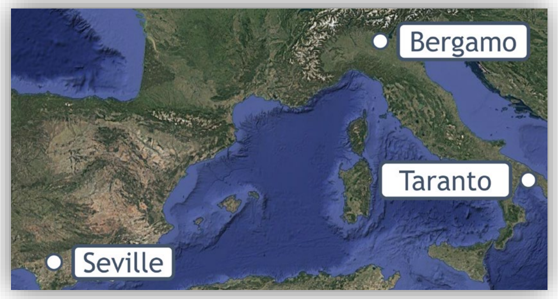
Solar Collector Cost



[1] System Advisor Model 2025. https://sam.nrel.gov/
[2] Shokrnia M, Cagnoli M, Grena R, D'Angelo A, Lanchi M, Zanino R. Comparative Techno-Economic Analysis of Parabolic Trough and Linear Fresnel Collectors with Evacuated and Non-Evacuated Receiver Tubes in Different Geographical Regions. Processes 2024;12. https://doi.org/10.3390/pr12112376.

Scenario	Cost [1], [2]
Worst case	350 €/m²
Reference case[1],[2]	250 €/m²
Best case	150 €/m²

Geographical Location



City	Solar	Wind	Industrial
Seville (ES)			
Taranto (IT)			
Bergamo (IT)			

Methodology - Optimization Algorithm

Location Weather Data (TMY)

European Commission PVGIS

Reference Normalized Generations

- CST & PV Models — System Advisor Model
- Wind Turbine Model

Techno-Economic and LCA Assumptions

One-shot MILP Optimizer

Renewable Penetration & Thermal User Load Profile

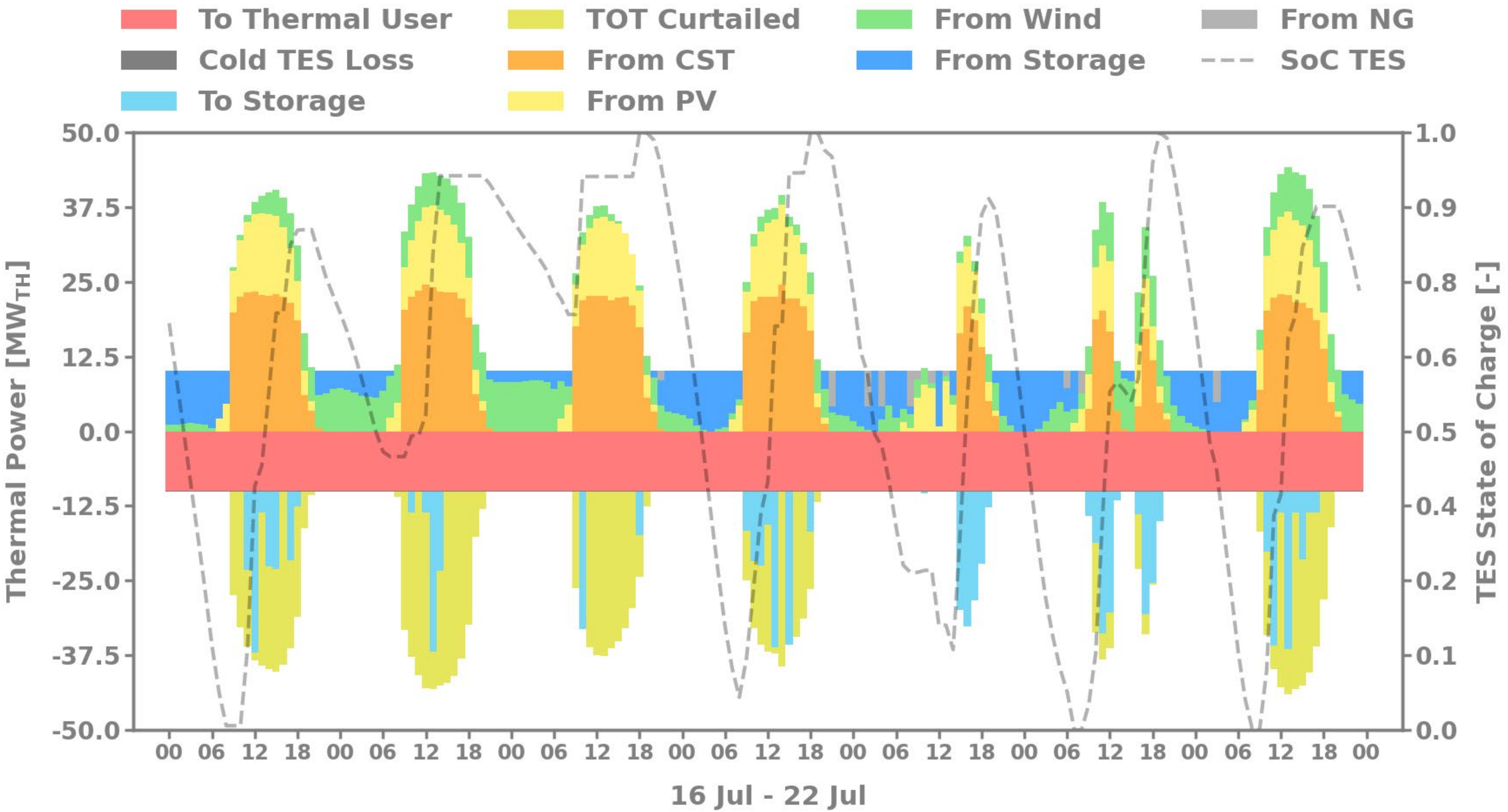
Optimal Design & Hourly Annual Operation (MIP Gap < 1%)

- Objective Function: ***LCOH*** Minimization
- Optimal Storage Capacities (h_{TES}, h_{BESS})
- Optimal Renewable Capacities (P_{CST}, P_{PV}, P_{WT}) & Orientations (ϑ_{CST}, ϑ_{PV})
- Optimal Gas Boiler & Electric Heater Capacities (P_{GB}, P_{EH})

Main Economic Assumptions

Discount Factor (WACC)	8%	Natural Gas Cost [€/MWh_{LHV}]	40	Solar Field Cost [€/m^2]	250
Financial Lifetime [y]	25	Fixed PV Cost [€/kW_p]	630	On-Shore Wind PPA [€/MWh_{EL}]	70-135
OPEX for each Technology	1-3%	Tracking PV Cost [€/kW_p]	700	Thermal Energy Storage [€/kWh_{TH}]	40-50

Methodology – Example of Hourly Annual Operation



Case with fixed capacites (P_{CST} =25MW, P_{PV} =15MW, P_{WT} =10MW, h_{TES} =10h) and optimised annual operation, achieving RP = 90%.

Key Performance Indexes (KPIs)

Renewable Penetration

$$RP = \frac{Q^{ren}_{th,load} - E^{non-ren}_{grid} \cdot \eta_{el-th}}{Q_{th,load}}$$

The use of for Non-Ren Grid Electricity to compensate Solar Field and Storage Tank Thermal Losses is penalized.

Cost of CO_2 Avoided

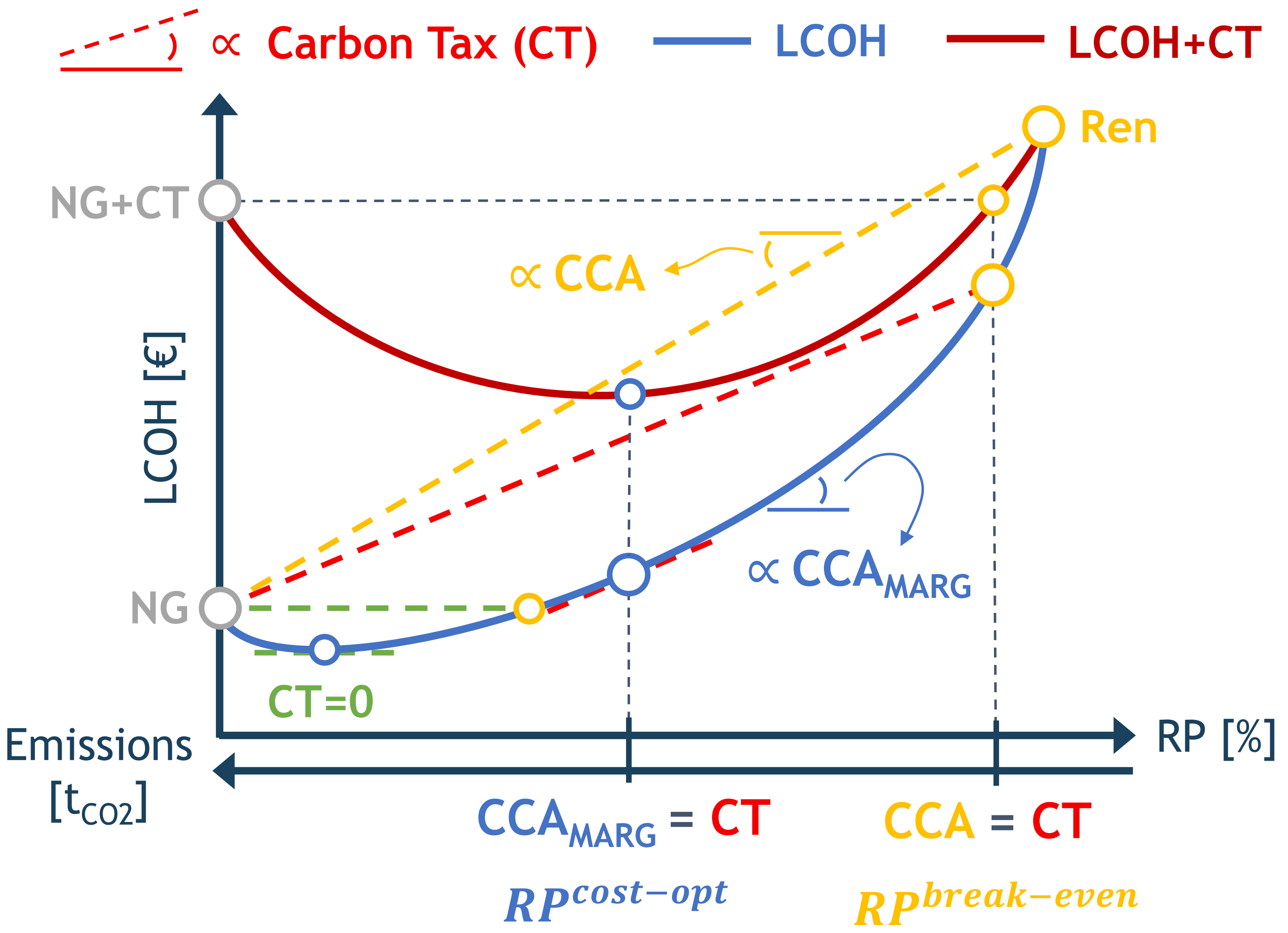
$$CCA = \frac{LCOH_{Ren} - LCOH_{NG}}{e^{NG}_{CO_2} - e^{Ren}_{CO_2}} \left[\frac{€}{t_{CO_2}}\right]$$

Marginal CCA

$$CCA_{MARG} = \frac{\Delta LCOH}{\Delta e_{CO2}} \left[\frac{€}{t_{CO_2}}\right]$$

Levelised Cost of Heat

$$LCOH = \frac{\sum_i CAPEX_i \cdot CCF_i + \sum_i f_{OPEX,i} + v_{OPEX}}{Q_{th,load}} \left[\frac{€}{MWh_{TH}}\right]$$



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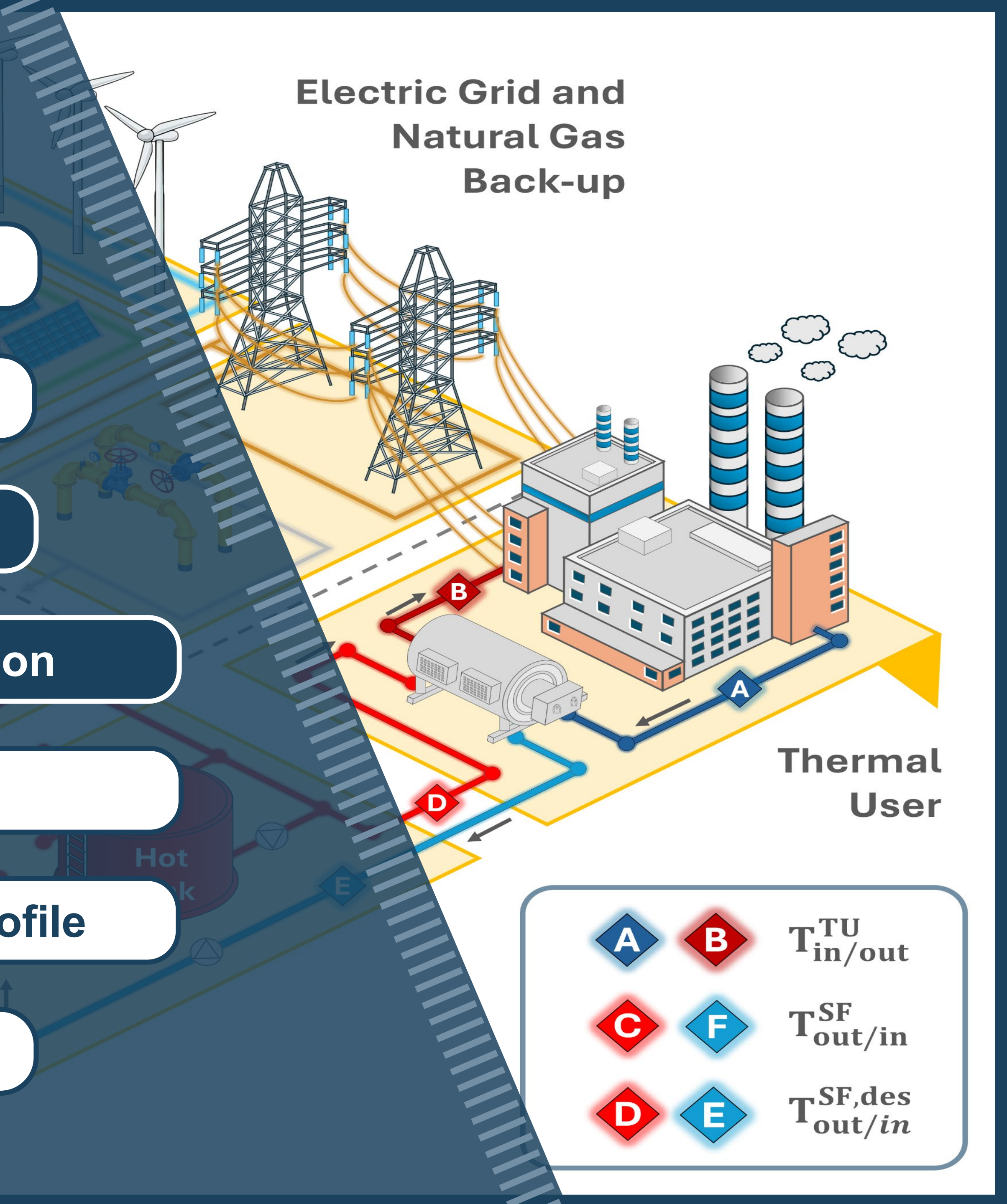

Electric Grid and Natural Gas Back-up
Thermal User
A B $T^{TU}_{in/out}$
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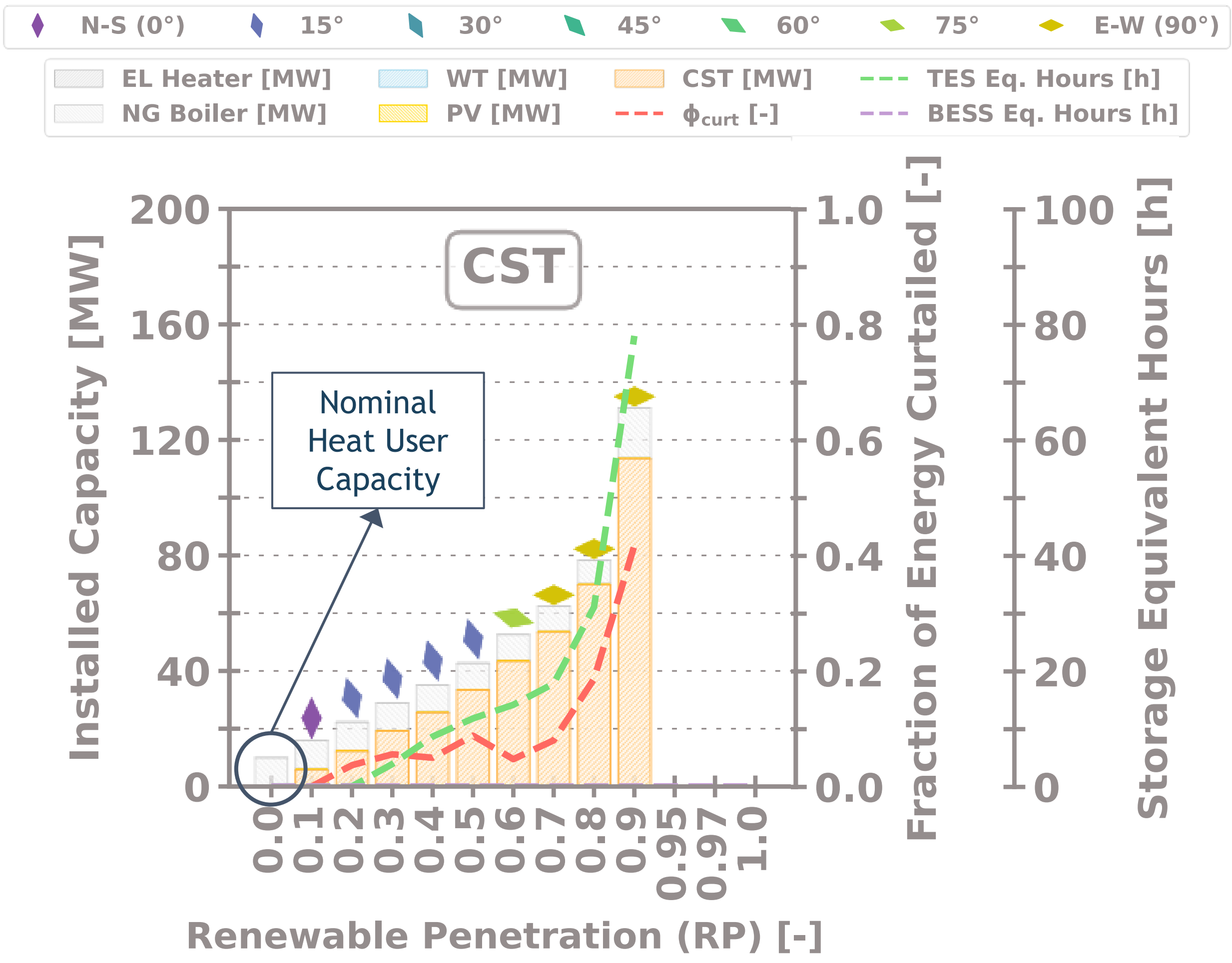
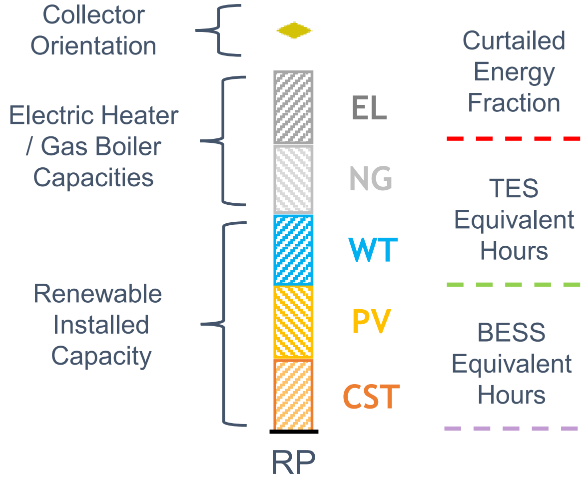
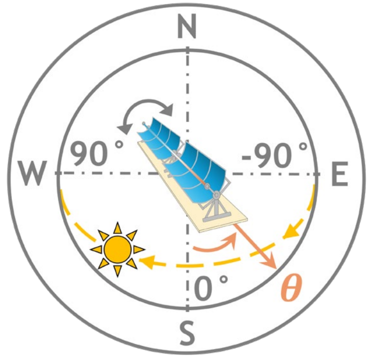
D E $T^{SF,des}_{out/in}$

Effect of Azimuth (1)

Seville, 510-400 °C, 10 MW_{TH}, CST-only case







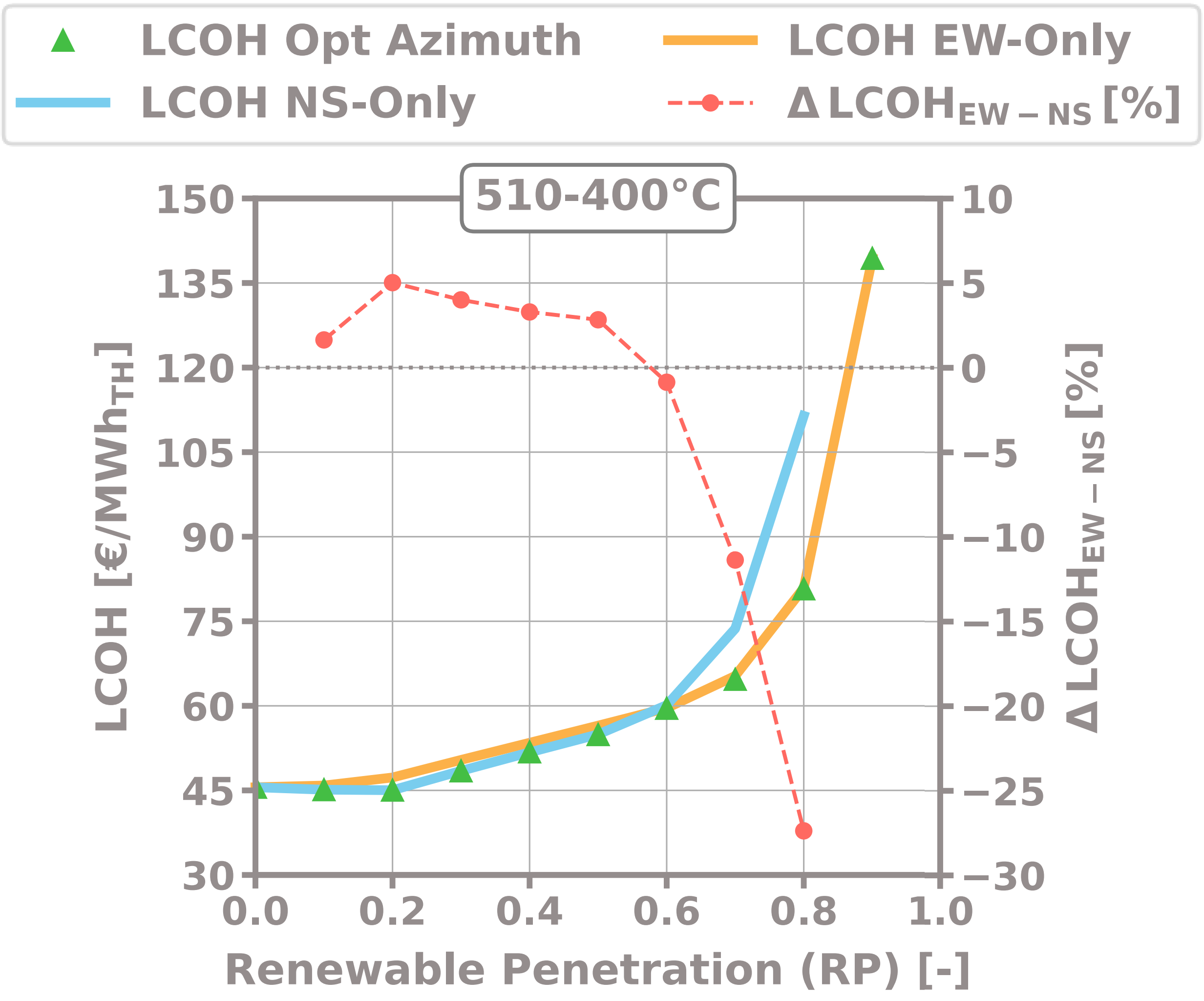
- **Exponential growth** in installed capacity **to reach high RPs**.
- **CST-only case can't reach complete decarbonization** due to parasitic solar field electric consumption (freeze protection,…).

- **N-S orientation** is preferred at **low RPs** | **E-W orientation** is preferred at **high RPs**.

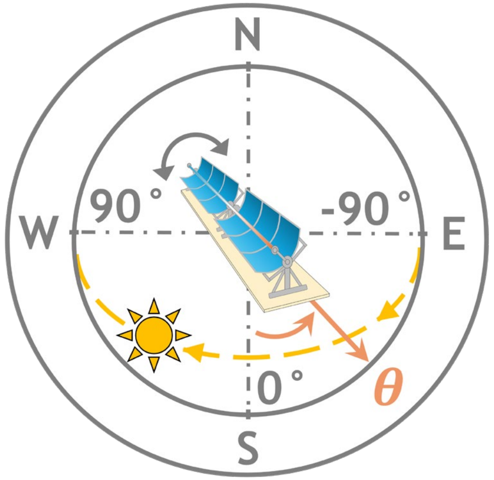
… But what's the impact on LCOH?

Effect of Azimuth (2)

Seville, 510-400 °C, 10 MW_{TH}, CST-only case

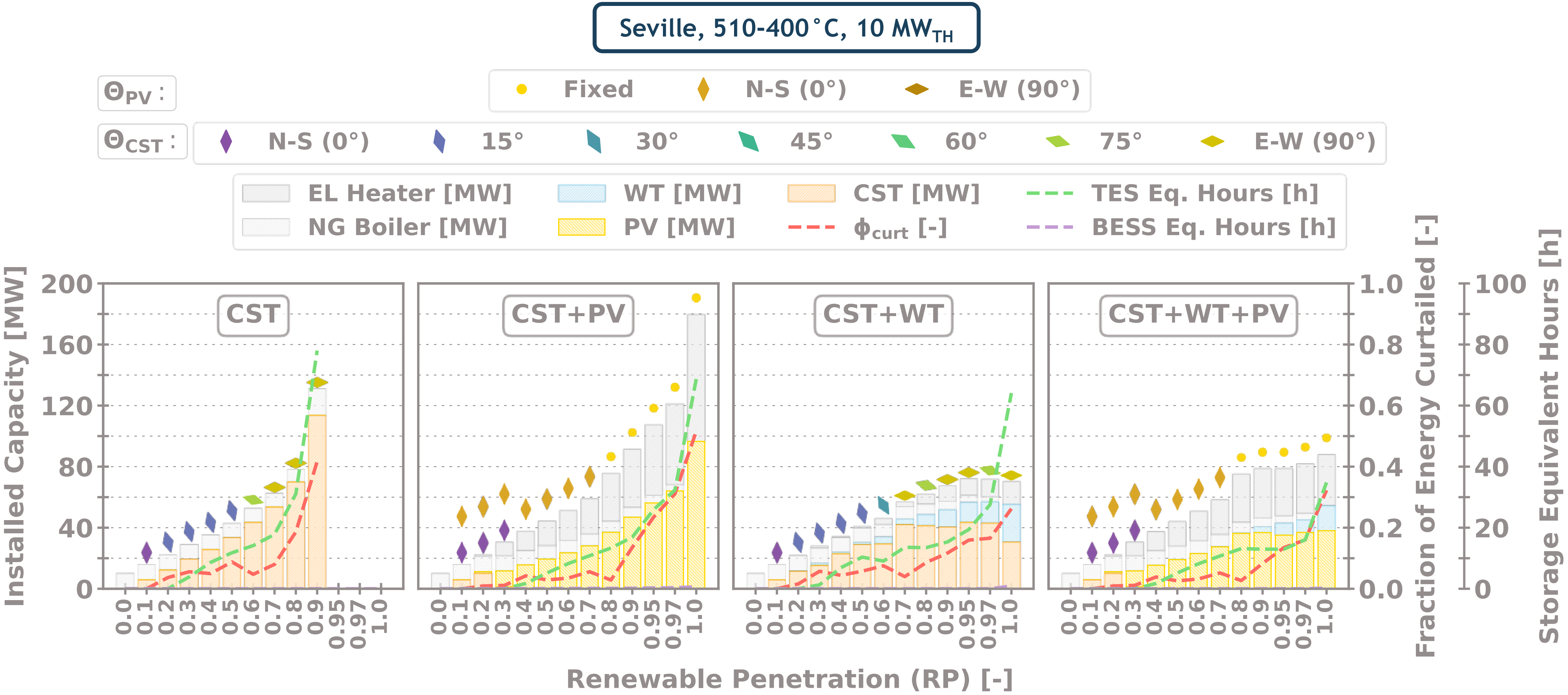


- The **choice between N-S and E-W** at low and high RPs is crucial, **generating differences of up to 20-30%** between $LCOH_{NS}$ and $LCOH_{EW}$ at high RPs.



- In the analysed framework, just **choosing either N-S or E-W is** actually **sufficient to minimize LCOH**.

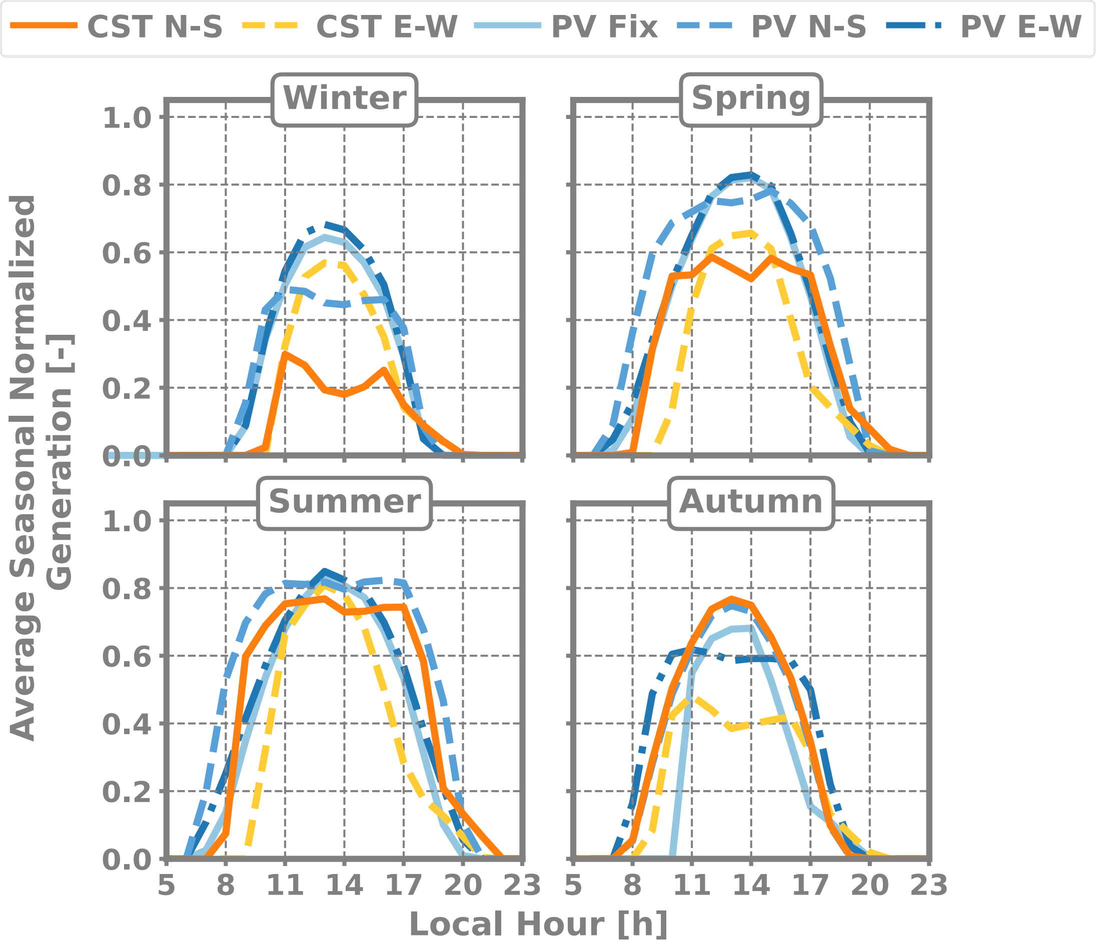
Effect of Hybridization (1)

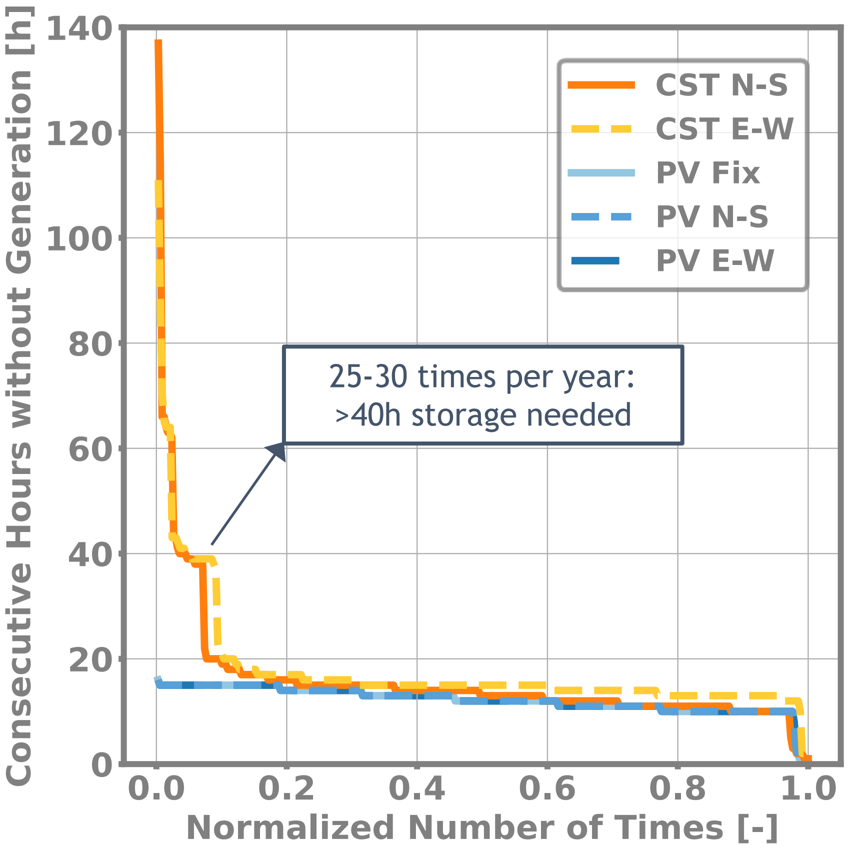


- **When coupled with PV** at **500°C**, **CST** is badly **outperformed** despite its lower specific cost (425 vs 700 €/kW$_p$).
- **Why?** Four key factors to determine the optimal mix: **technology cost**, **technology availability** (in terms of both equivalent operating hours and annual energy distribution), **storage cost**, and **desired level of renewable penetration**.

Effect of Hybridization (2)

Seville, 510-400°C, 10 MW_{TH}



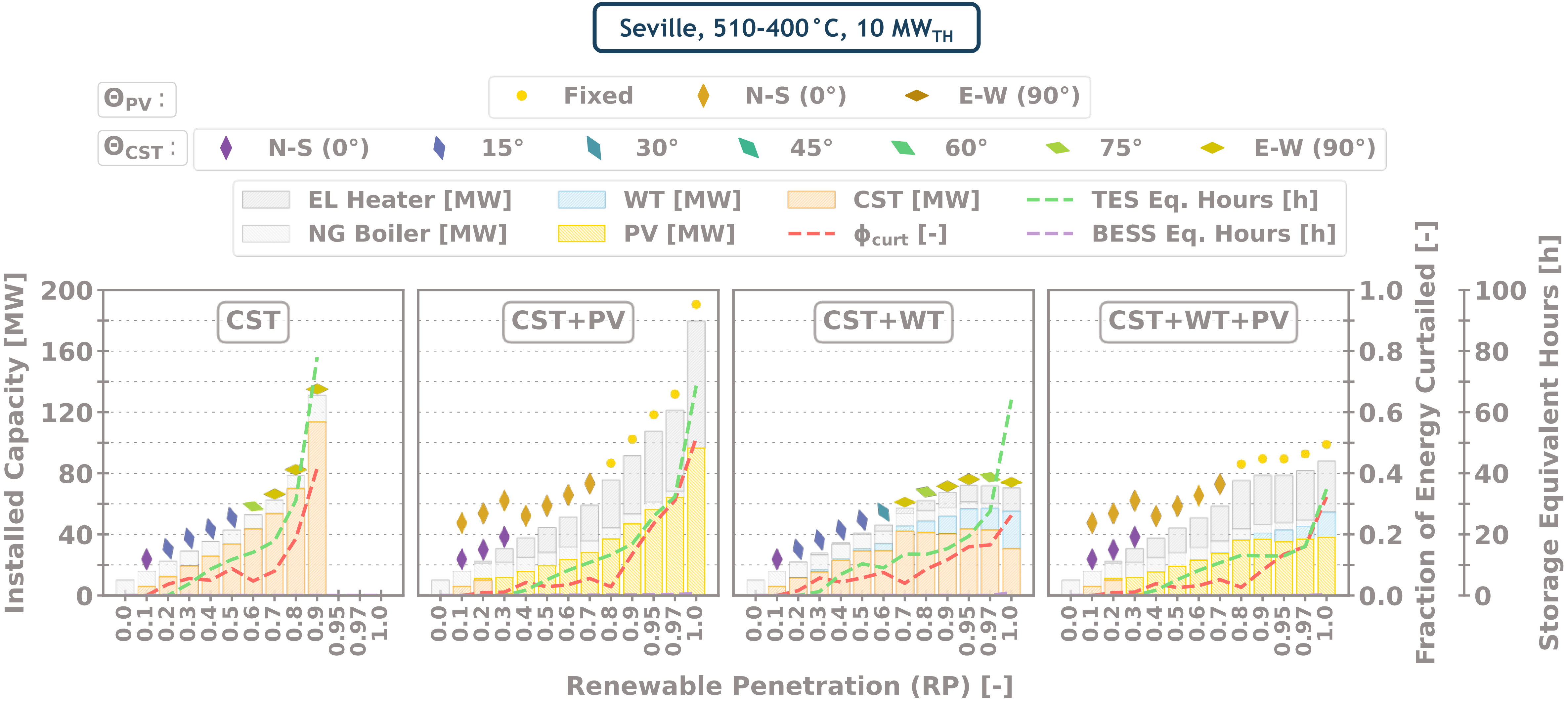


lower winter and spring **availability**

longer and more frequent **periods without generation**

- Drastical **increase** of the renewable **overcapacity** to be installed **to reach the same RP.**

Effect of Hybridization (3)



➢ **Hybridization** allows to greatly **reduce the storage and renewable overcapacity** (consequently the **LCOH**) at high RPs thanks to the wind energy decorrelated hourly generation compared to solar energy sources.

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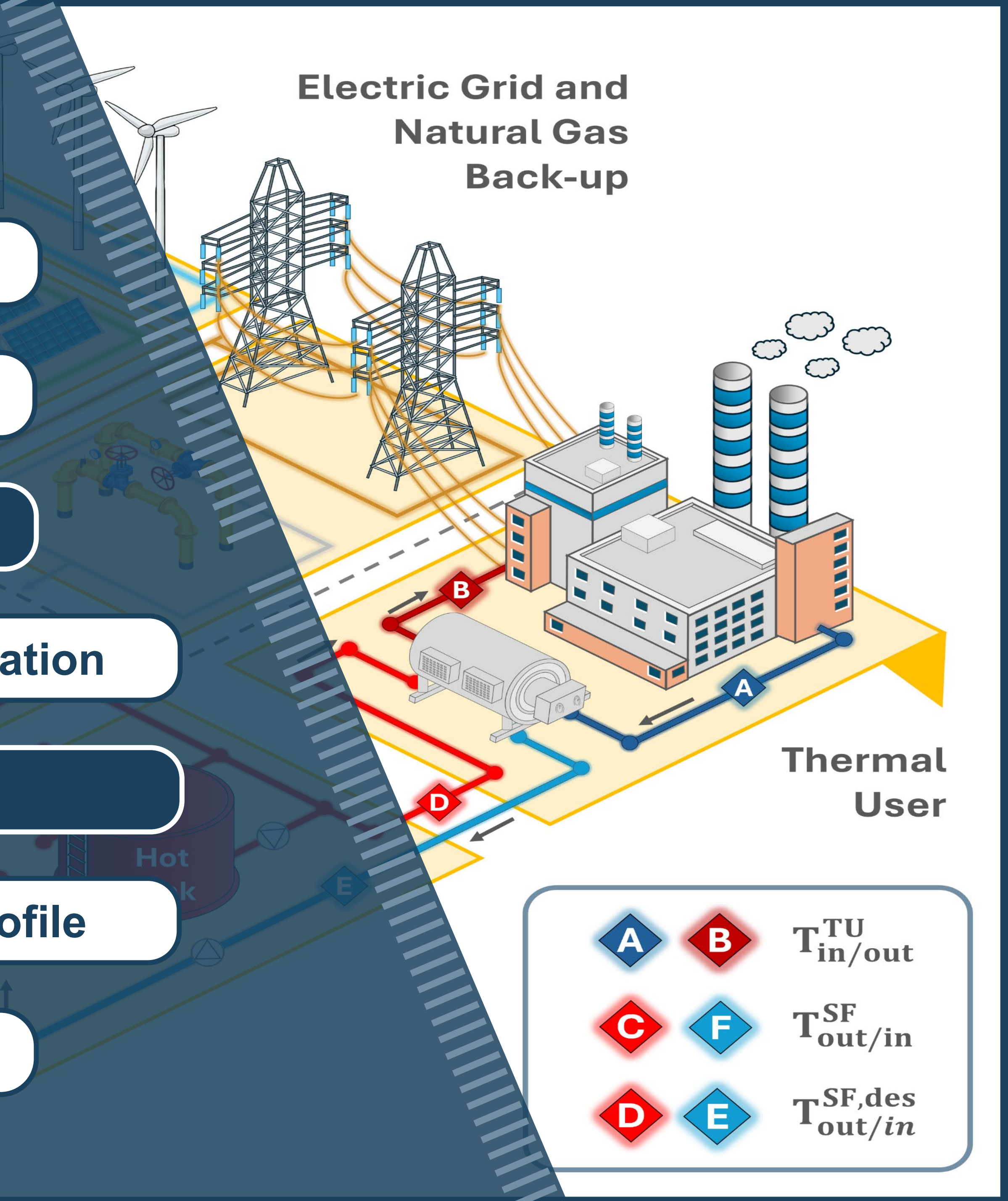

Electric Grid and
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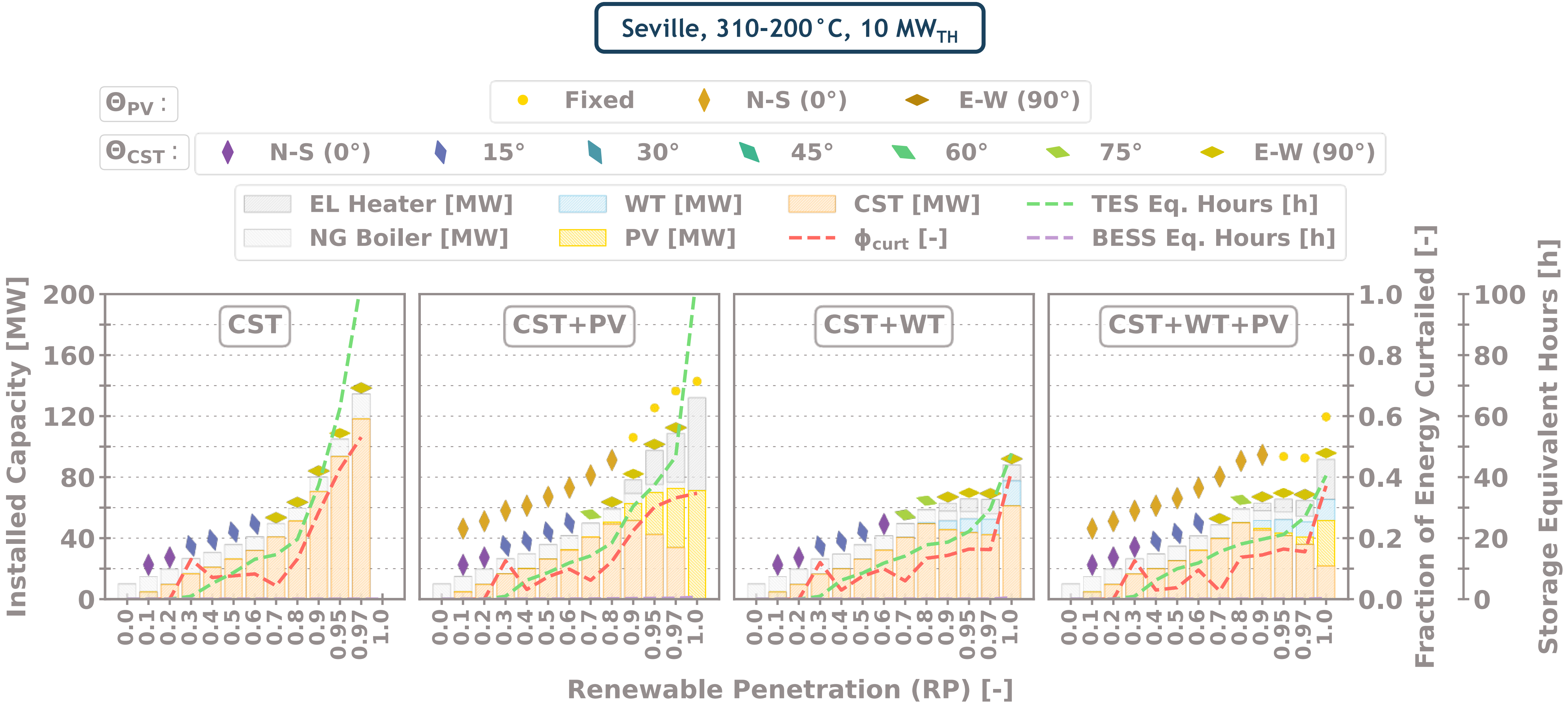
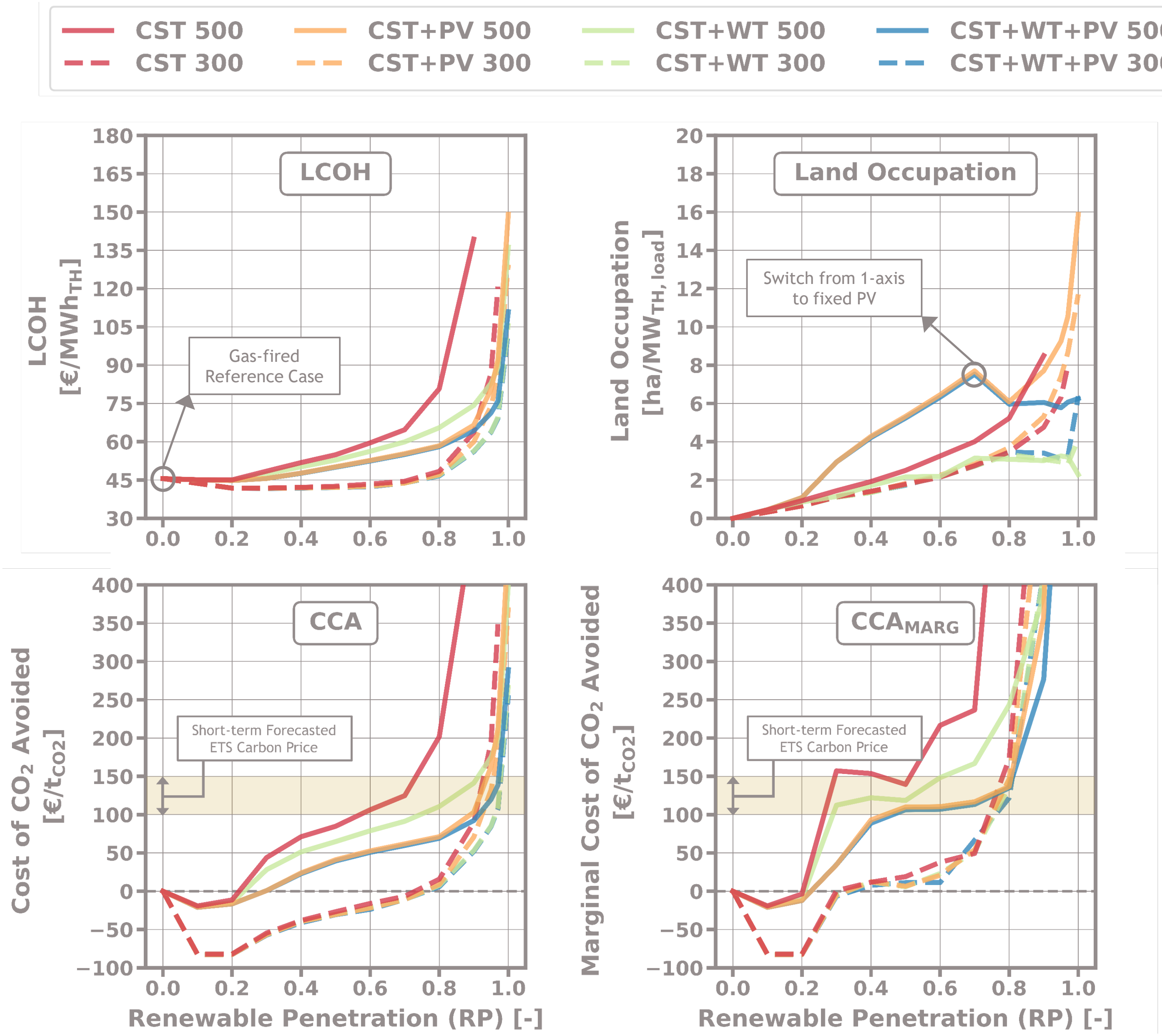
Effect of Temperature



➢ The **trade-off** between **CST and PV** adoption has undergone a **clear shift** due to: (i) CST **higher receiver thermal efficiency**, which results in higher availability and lower specific cost; (ii) **lower CST parasitic electric consumptions**, going from 3-5% to 0.25-0.5% [kWh_{EL}/kWh_{TH}]; (iii) **lower TES cost** (oil vs molten salts).

Effect of Temperature - 500°C vs 300°C - LCOH, CCA, CCA_{MARG}

Seville, 500°C vs 300°C, 10 MW_{TH}



- **RP 80%** marks a clear **boundary**, beyond which **decarbonization** begins to require a **significant economic effort**, especially in the 500°C case.

- **CST** may hold an **advantage over PV** whenever **land availability** is **constrained**.

- In the **CST+WT+PV**:

Break-even RP	No Carbon Tax	100-150 €/t$_{CO2}$
500°C	Up to 25-30%	Up to 85-95%
300°C	Up to 70%	Up to 95-97%

Cost-optimal RP	No Carbon Tax	100-150 €/t$_{CO2}$
500°C	Up to 20%	Up to 45-80%
300°C	Up to 30%	Up to 75-80%

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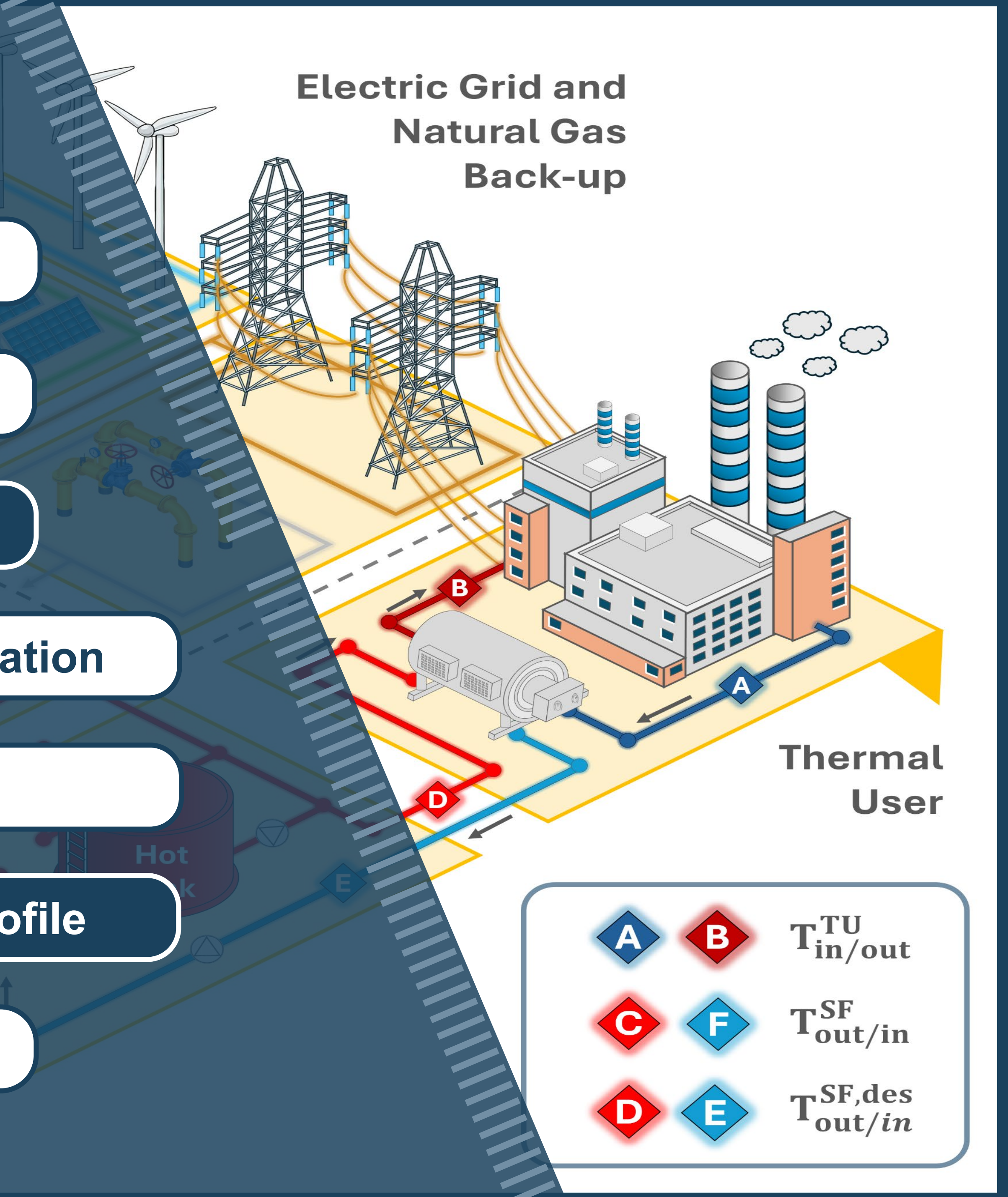
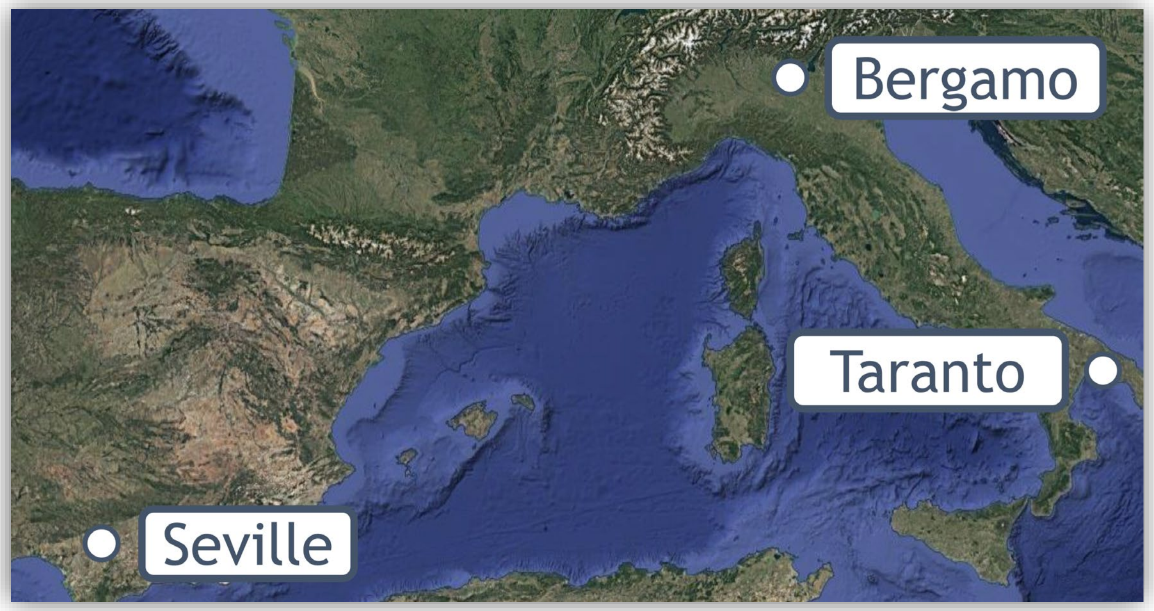
2. Methodology & KPIs
3. **Results**
   - Effect of Azimuth and Hybridization
   - Effect of Temperature
   - **Effect of Location, Cost, Load Profile**
4. Conclusion

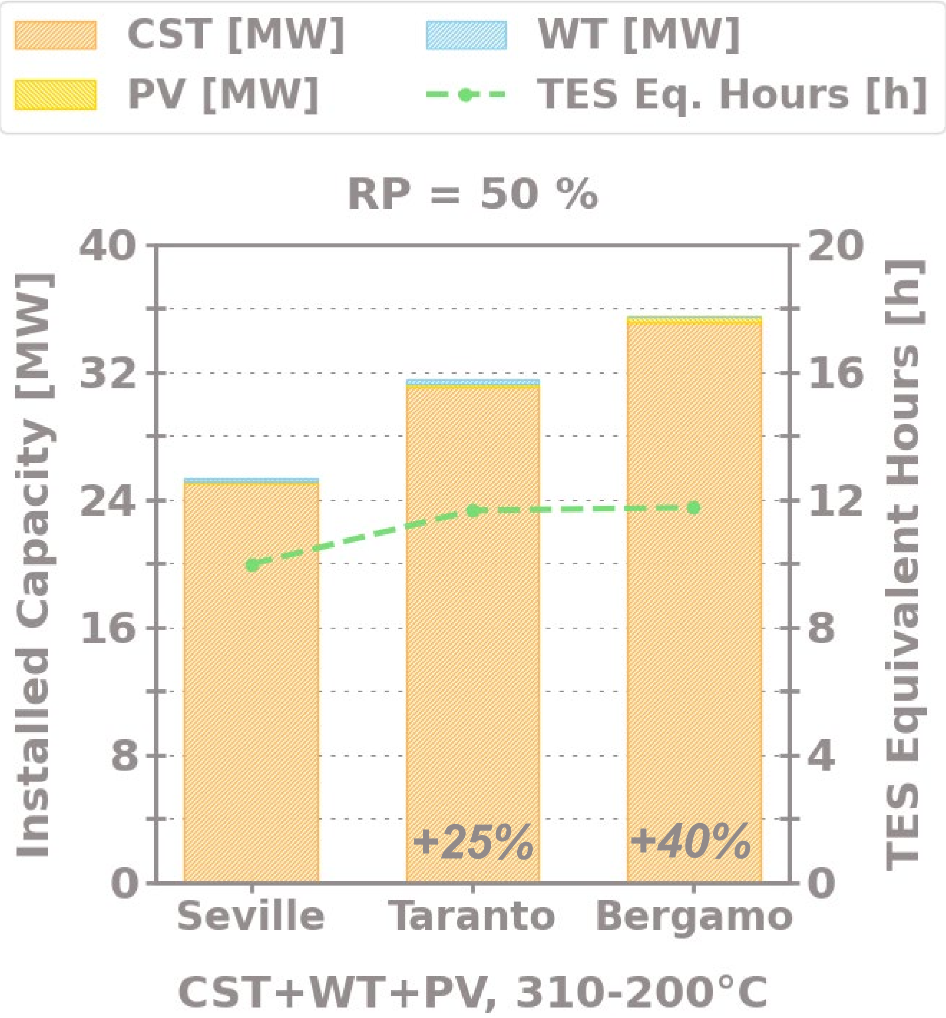


Effect of Location - Seville / Taranto / Bergamo - CST+WT+PV case

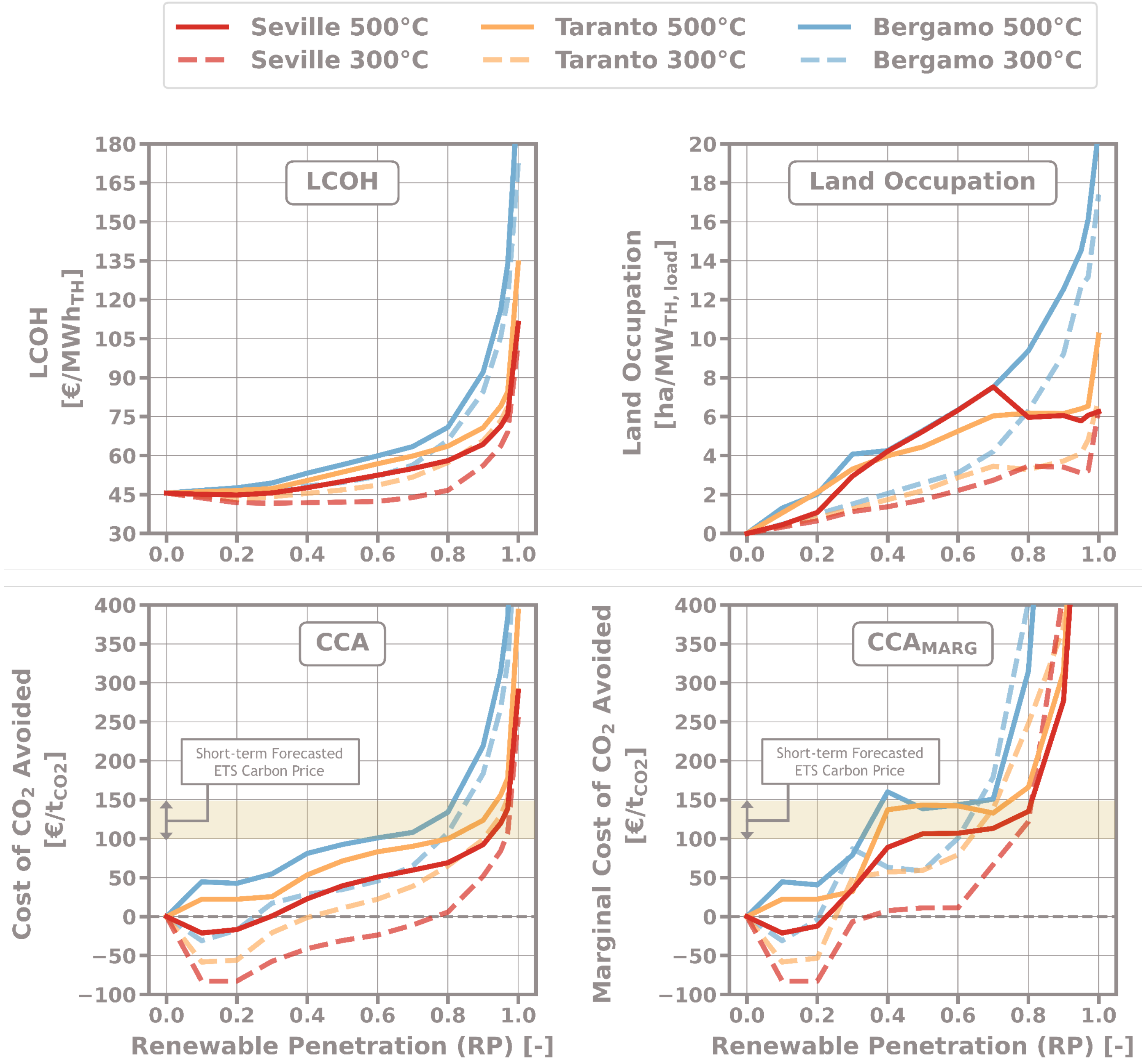


Location	Seville	Taranto	Bergamo
Direct Normal Irradiation [kWh/m²/y]	2175	1875 *(-15%)*	1733 *(-20%)*
Global Horizontal Irradiation [kWh/m²/y]	1872	1684 *(-10%)*	1502 *(-20%)*
Mean Wind Speed @ Hub [m/s]	6.80	6.65	5.13 (nearby)

- **Reduction** in **DNI**, GHI and wind speed → Industrial hubs with low solar/wind resources are disadvantaged.



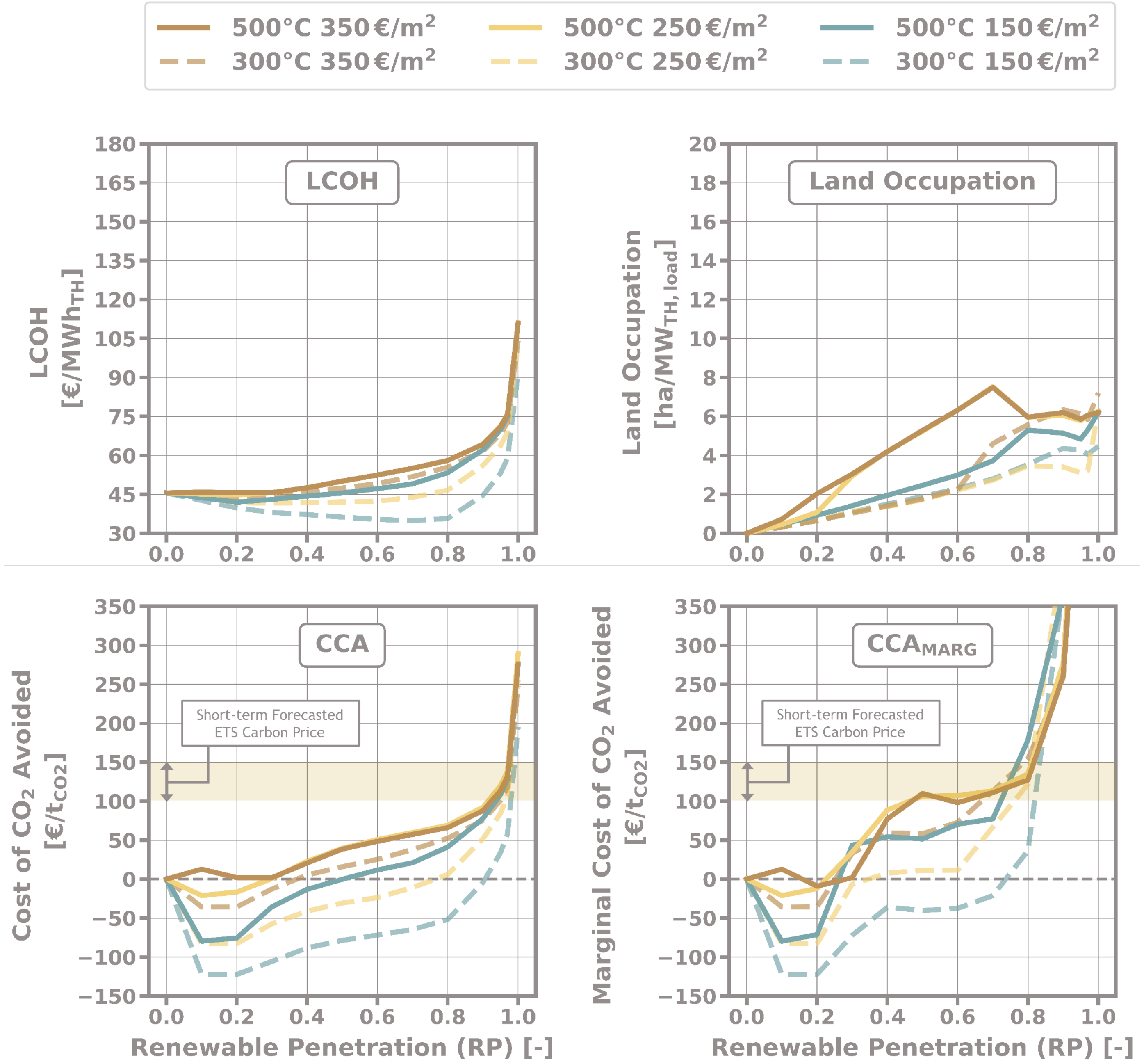
Effect of Location - Seville / Taranto / Bergamo - CST+WT+PV case



- Going **from Seville to Bergamo** → **Investment economic viability drop** to lower RP levels.

No Carbon Tax	Break-even RP	Cost-optimal RP
Seville	30% @500°C	20% @500°C
	75% @300°C	30% @300°C
Taranto	-	-
	40% @300°C	25% @300°C
Bergamo	-	-
	25% @300°C	20% @300°C

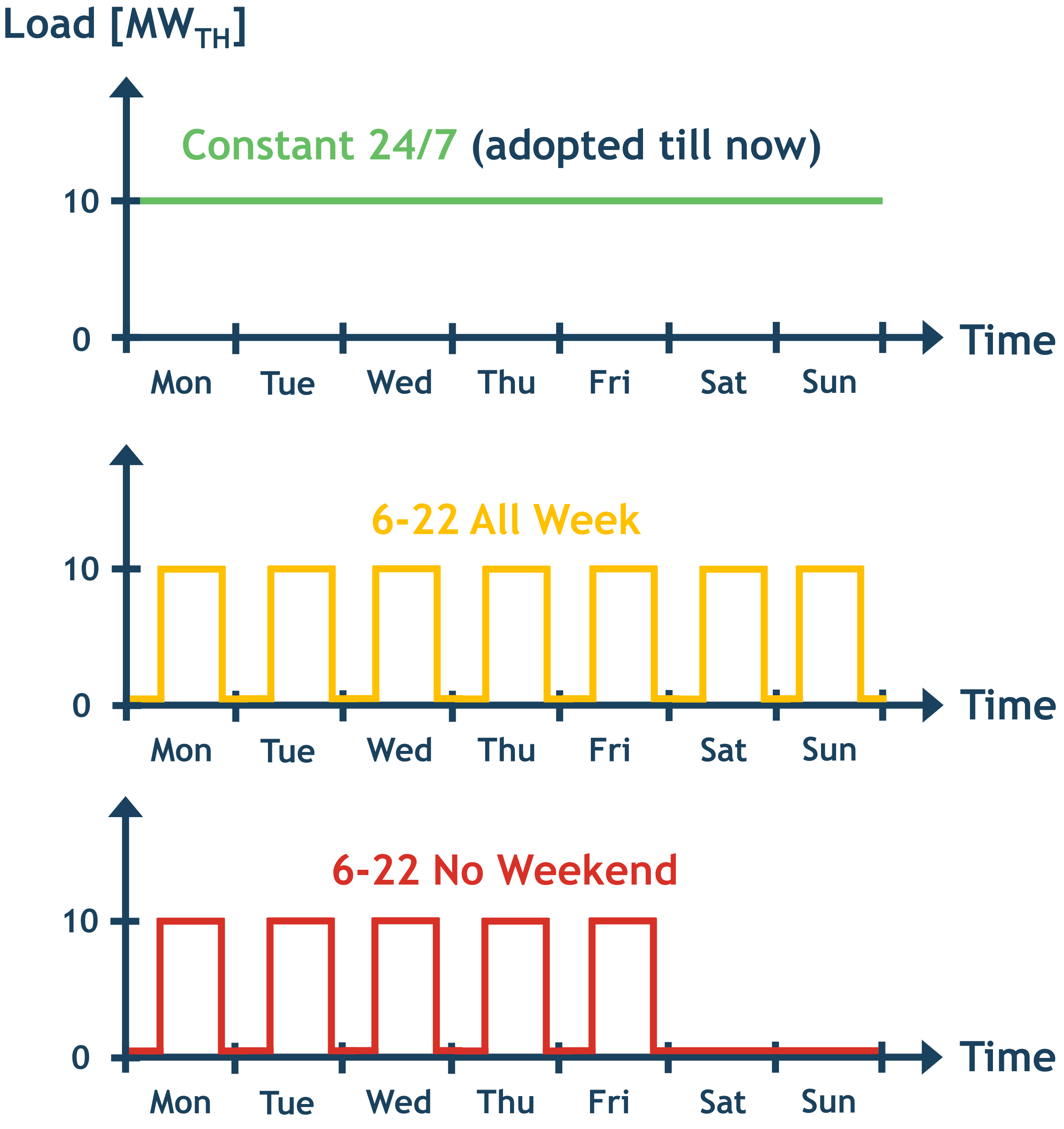
Effect of Collector Cost - CST+WT+PV case - Seville



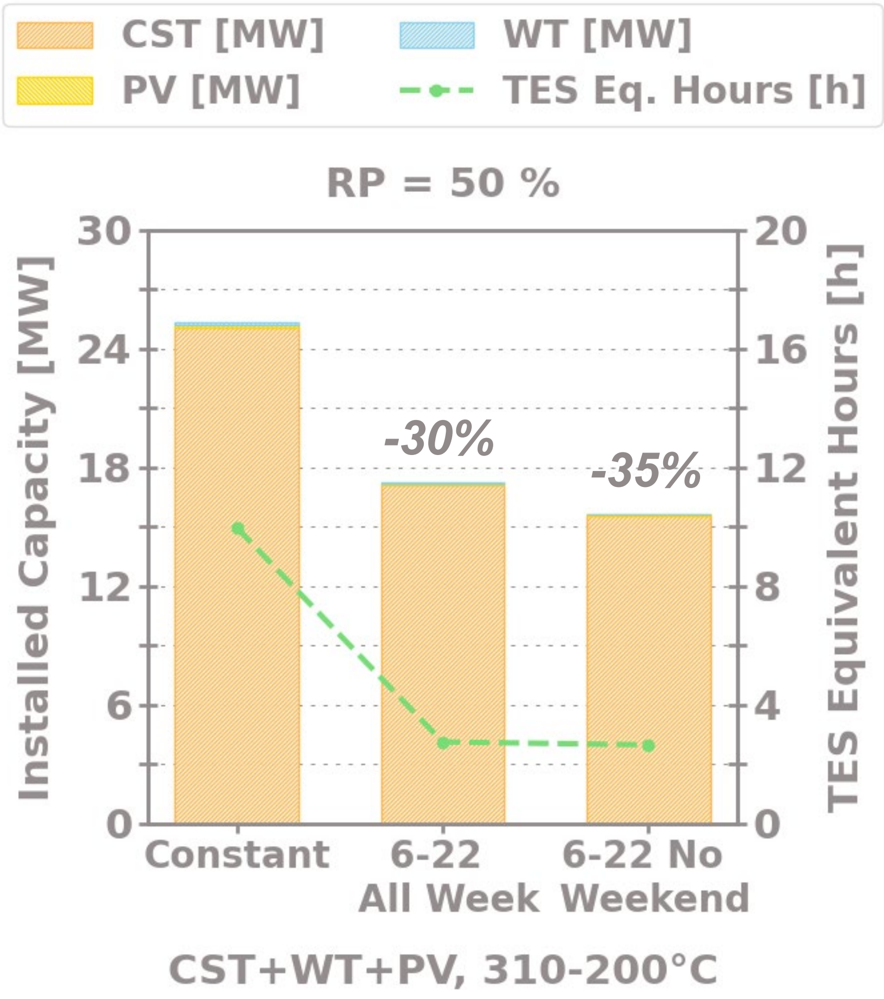
- **Collector cost reduction** → Higher share of installed CST & **Investment economic viability increase** to higher RP levels.
- **Development of supply-chain to achieve economies of scale is paramount**.

No Carbon Tax	Break-even RP	Cost-optimal RP
350 €/m²	-	-
	35% @300°C	25% @300°C
250 €/m²	30% @500°C	20% @500°C
	75% @300°C	30% @300°C
150 €/m²	50% @500°C	25% @500°C
	90% @300°C	75% @300°C

Effect of Thermal Load Profile - CST+WT+PV case - Seville



➢ **No nighttime load** → significantly **lower renewable and storage capacity** needed to achieve the **target RP**.



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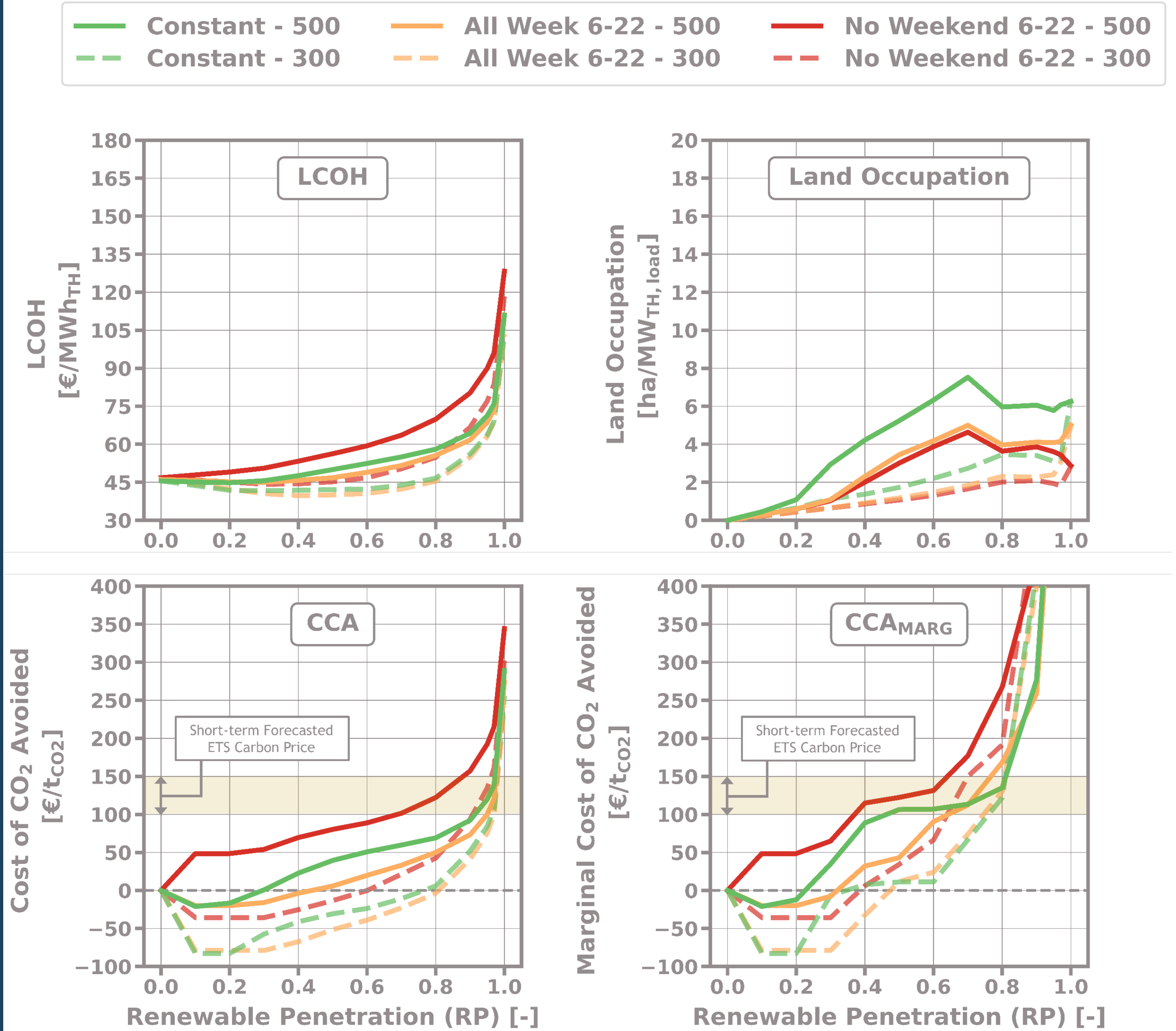
Effect of Thermal Load Profile - CST+WT+PV case - Seville



- Trade-off: **lower renewable/storage capacity** vs **lower operating hours** (CAPEX amortization).

No Carbon Tax	Break-even RP	Cost-optimal RP
Constant	30% @500°C	20% @500°C
	75% @300°C	30% @300°C
6-22 All Week	45% @500°C	30% @500°C
	80% @300°C	50% @300°C
6-22 No Weekend	-	-
	60% @300°C	40% @300°C

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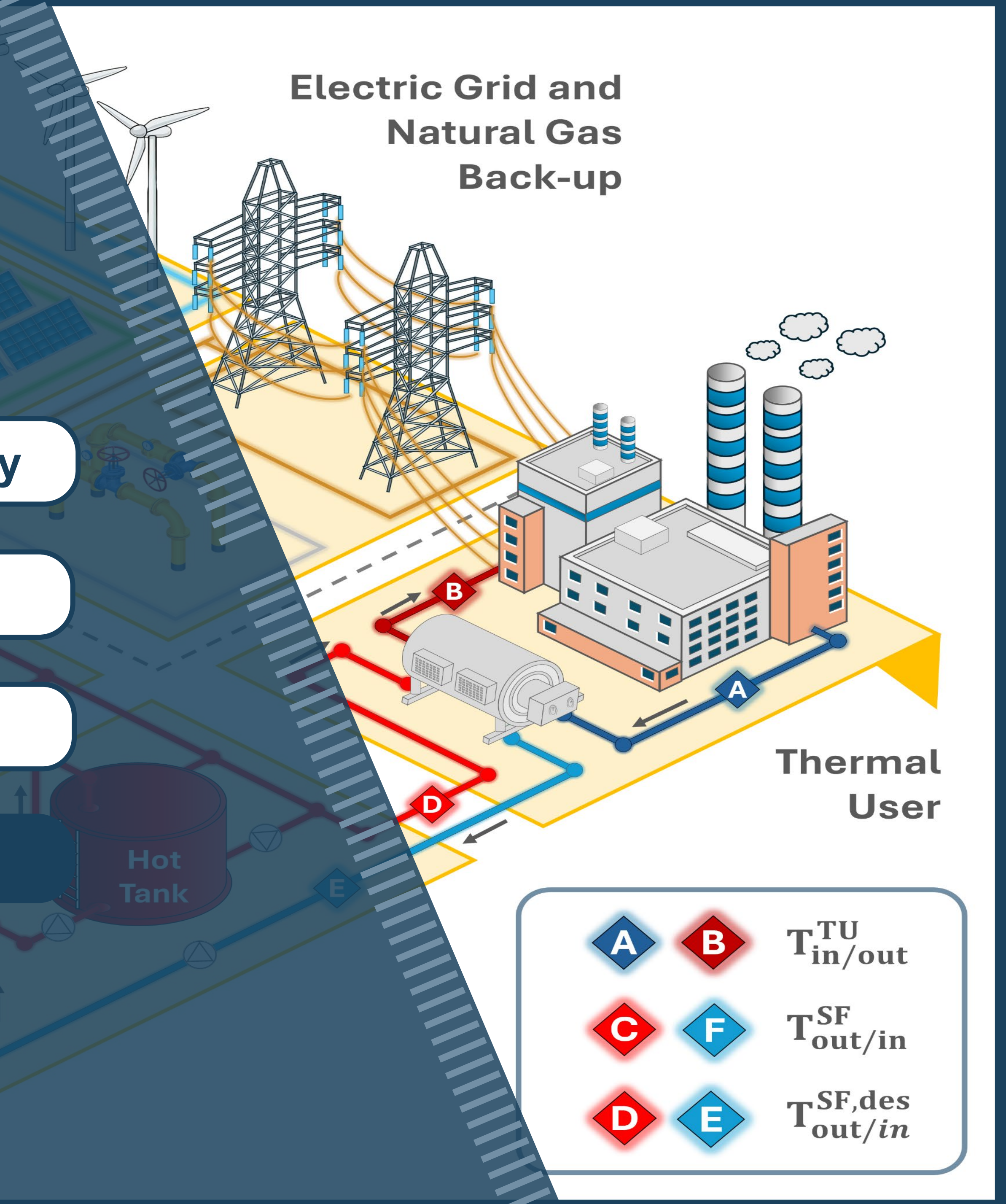

Electric Grid and Natural Gas Back-up
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Conclusions (1)

- **Optimum Renewable Mix**: Given a location and a thermal load profile, the optimum mix is a trade-off between **technology cost**, **technology availability**, **storage cost**, and **desired RP**. Important factors:

  - **Temperature** (**500°C** vs **300°C**)**:** directly impacts on technology availability and cost, marking a RP threshold beyond which Resistive Electric Heating is more competitive than CST given a certain economic framework.

  - **Collector Orientation** (N-S vs E-W): allows to modify technology availability, making it more attractive either at low or high RPs.

  - **Hybridization** (CST+WT): thanks to synergic decorrelated energy generations, combining CST/PV and Wind allows to reduce the drawbacks of each technology.

  - **Land occupation** (not accounted in the analysis): whenever land availability is constrained and there is a target RP, CST may hold an advantage compared to on-site PV thanks to its 2-4 times lower land occupation.

Conclusions (2)

- **Economic Target**: increasing the renewable penetration of a process, two RP thresholds arise, i.e. **breakeven RP** ($RP^{break-even}$) and **cost-optimal RP** ($RP^{cost-opt}$). Important factors:
  - **Temperature**: $RP^{break-even}$ shifts from 30% to 70% without carbon tax in Seville CST+WT+PV going from 500°C to 300°C.
  - **Hybridization**: massive LCOH reductions at high RPs, with up to 40% LCOH decline at 90% RP between CST and CST+WT cases at 500°C in Seville.
  - **Location**: renewable availability plays a crucial role → $RP^{break-even}$ decreases from 75% to 25% going from Seville to Bergamo without carbon tax. Similarly, $RP^{cost-opt}$ decreases from 30% to 20%.
  - **Collector Cost**: paramount to achieve developed supply chain to bring the collector cost lower than 250 €/m^2.
  - **Load Profile**: Trade-off - lower renewable/storage capacity vs lower operating hours.

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GeCoS – Group of Energy COnversion Systems

Thank you!

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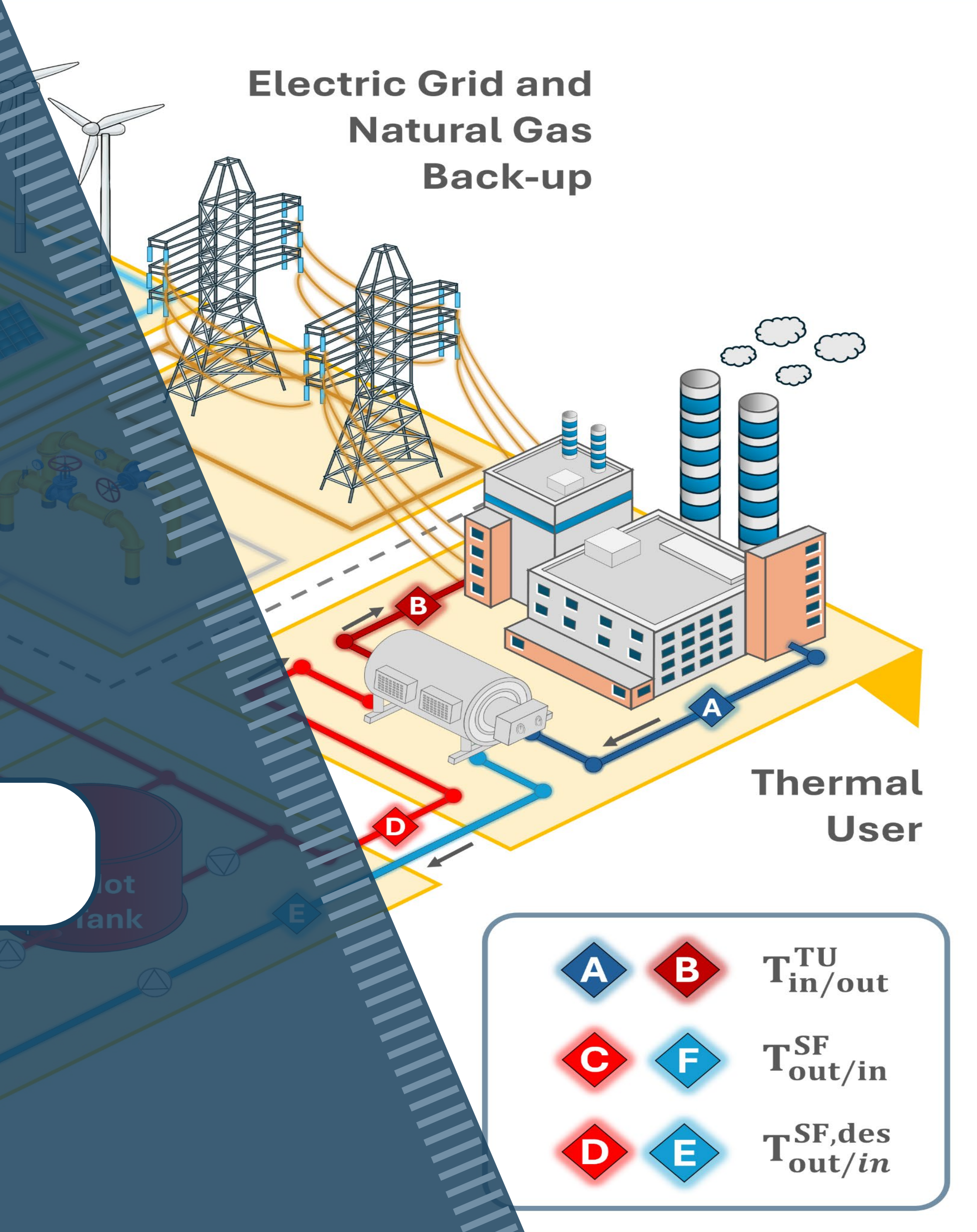
Any questions?



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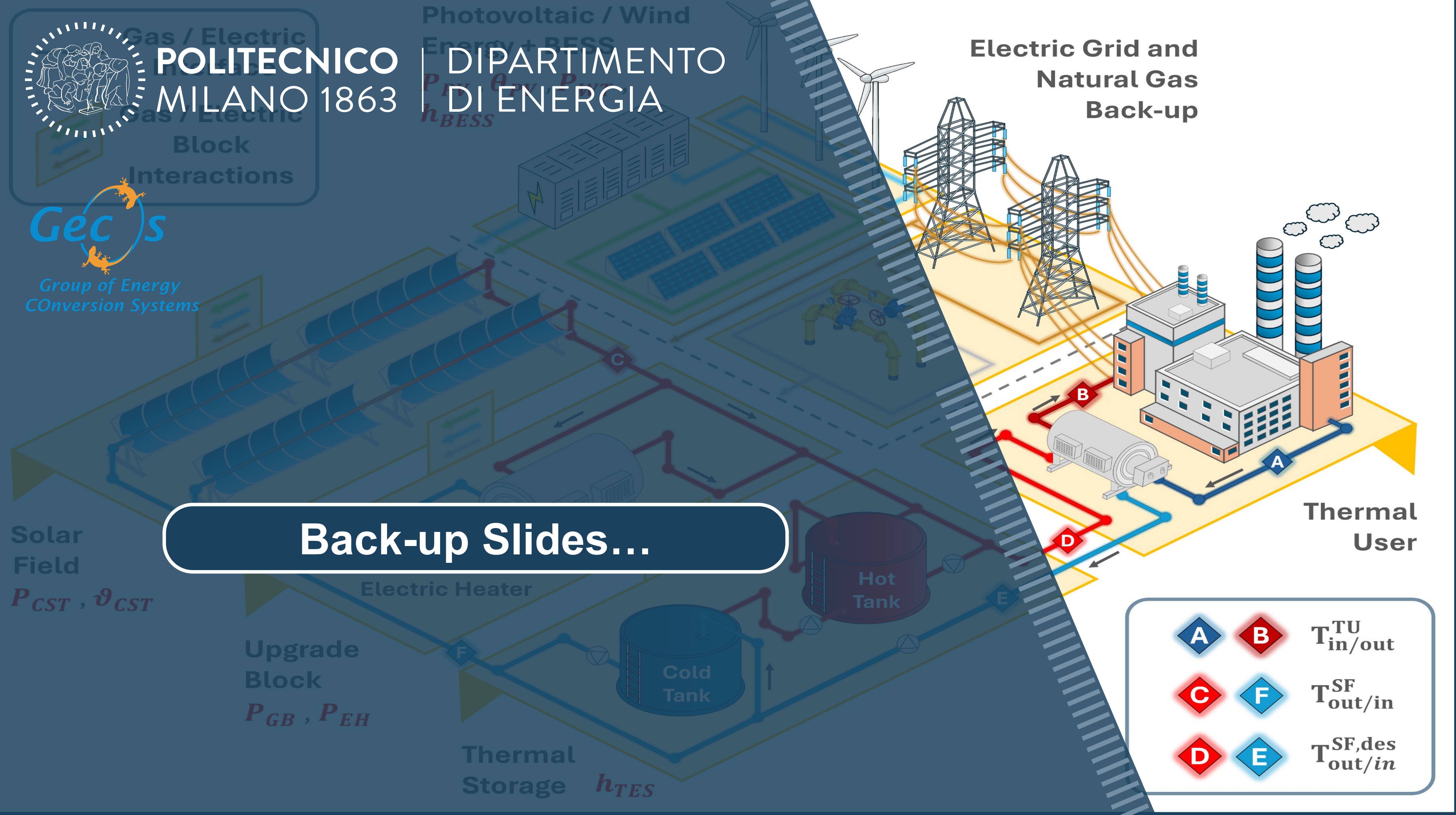
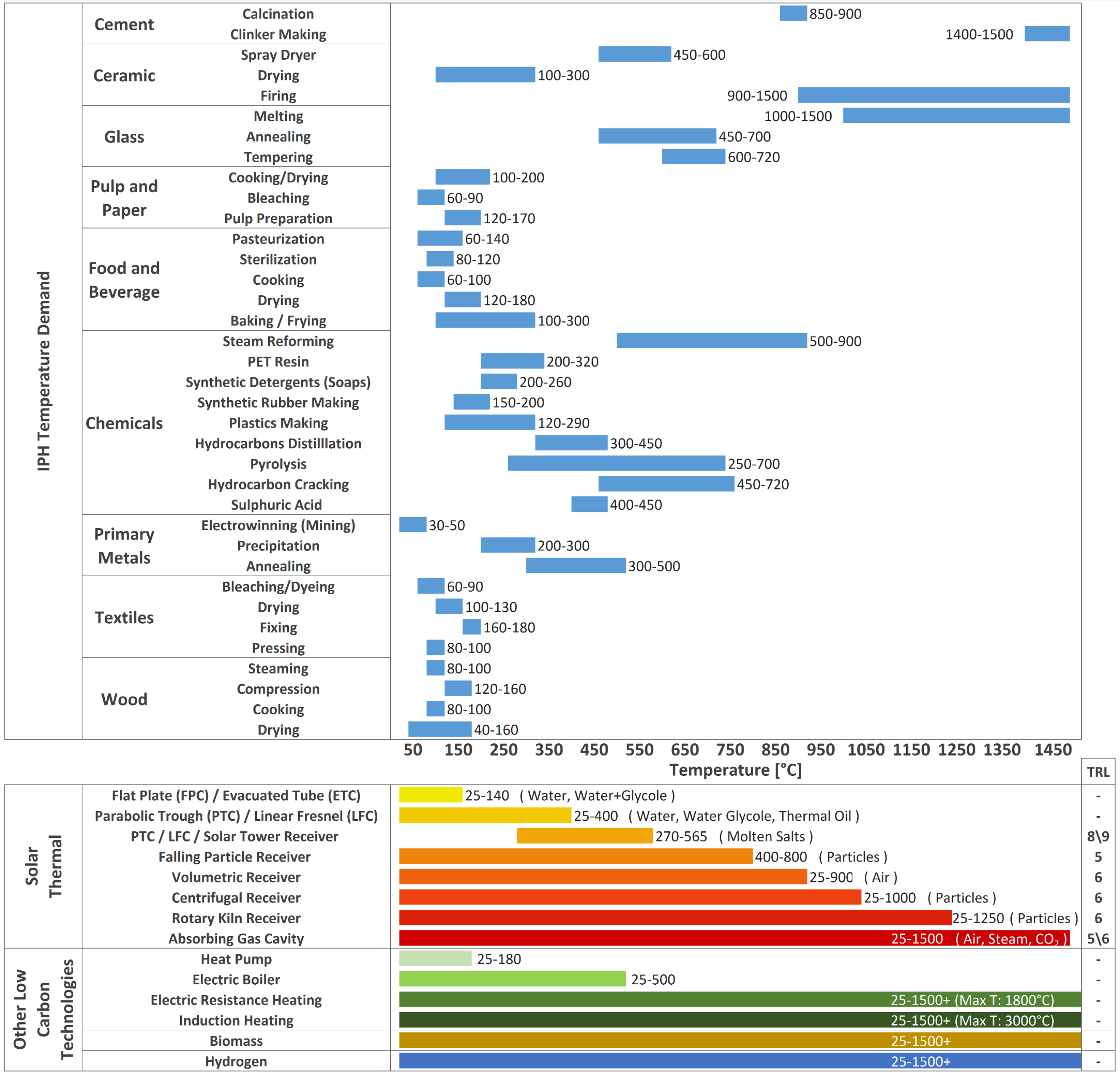
Back-up Slides…



Industrial Process Heat (IPH): Stating the Problem



- Wide Temperature Range
- On-Site Heat Generation
- Each Process requires Tailor-made Solutions

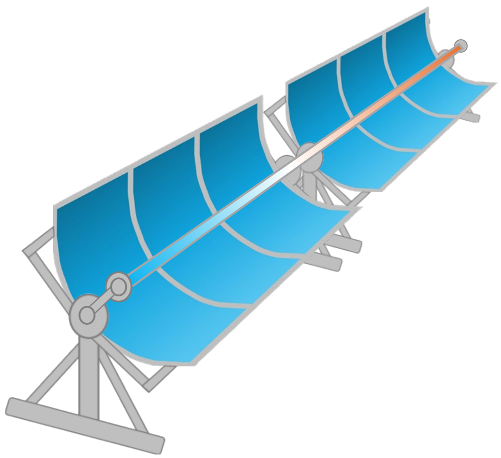
Which Technology to Adopt ?

Medium Temperature Heat (200-500 °C): CST as Possible Solution

Low reliance on **critical materials**, high recycling rates (steel, glass)

60% Cost Reduction between 2010-2023 (IRENA)

Higher solar-to-thermal efficiencies and **power densities**



Concentrated Solar Thermal (CST)

PV + Electric Resistance → 0.2-0.25 $\frac{kW_p}{m^2}$

Parabolic Trough Collectors → 0.55-0.7 $\frac{kW_p}{m^2}$

Linear Fresnel Collectors → 0.4-0.7 $\frac{kW_p}{m^2}$

Deployment is limited to low-medium temperature processes (50-250°C)

Lack of adequate **policy support**

High **upfront costs**, perceived **risks**, underdeveloped **supply chain**