SHIP4D : La chaleur solaire pour la décarbonation des processus industriels

SHIP4D : Solar heat for decarbonization of industrial processes

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Résumé - Le projet SHIP4D étudie l'intégration de la chaleur solaire pour la décarbonation industrielle entre 150 et 400°C. Un système hybride est modélisé avec photovoltaïque (PV), solaire thermique concentré (CST), stockage et chaudières auxiliaires. L'optimisation via le logiciel CAIRN minimise les coûts et l'empreinte carbone pour divers scénarios. Des études de cas à Rouen, Chambéry et Montpellier évaluent les rendements, coûts et émissions. Les résultats montrent que l'amélioration de l'efficacité de la chaudières gaz, le biogaz et la biomasse réduisent fortement les émissions. L'hybridation CST apparaît plus attractive que le PV, alors que le stockage thermique est préféré au stockage électrique.

Abstract - The SHIP4D project explores the integration of solar heat for industrial decarbonization in the 150–400°C range. A hybrid energy system is modeled with PV, CST, storage, and auxiliary boilers. Optimization with CAIRN software minimizes costs and carbon footprint for multiple scenarios. Case studies in Rouen, Chambéry, and Montpellier assess yields, costs, and emissions. Results show that gas boiler upgrades and fuel substitution reduce emissions significantly. CST hybridization proves more attractive than PV, while thermal storage is favored over electrical storage.

Nomenclature

Abbreviations
BMS Battery Management System
CAPEX Capital Expenditure
CST Concentrated Solar Thermal
EES Electrical Energy Storage
GWP Greenhouse Warming Potential, $kgCO_{2,eq}$
HEX Heat Exchanger
KPI Key Performance Indicator
LCOH Levelized Cost of Heat, cts€/kWh
MILP Mixed Integer Linear Programming
NG Natural gas
NPC Net Present Cost, M€
P2H Power to Heat
OPEX Operational Expenditure
PV Photovoltaics
TES Thermal Energy Storage
SF Solar Fraction, %
Q Heat demand, MWh

Greek symbols
Δ déviation

Indices and exponents
aux auxiliary
hybrid hybrid
load energy demand
ref reference
solar solar
waste wasted energy

1. Introduction

According to the IEA [1], the industrial sector accounts for 20% of France's final energy consumption and generates 14% of its CO_2 emissions. More than 70% of this energy is consumed in the form of heat. 50% of this heat requires a temperature below 400°C. Today, this thermal energy is mainly supplied by fossil fuels, in particular natural gas.

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Several decarbonization pathways are considered in the sectoral transition plans presented by ADEME for 2050 [2]: i) energy efficiency and conservation, ii) electrification of processes, iii) smart integration of renewable energies and energy storage. The SHIP4D project, as part of the PEPR SPLEEN program [3], studies the contribution of solar heat to the decarbonization of industrial processes, particularly in the medium temperature range (150-400°C). This paper summarizes the work described in more details in the first project task deliverable [4].

2. Methodology

2.1. Hybrid energy system architecture

A generic architecture has been defined for the optimal sizing of a hybrid energy system supplying power and heat for an industrial site, integrating various technological components: i) solar energy (photovoltaics (PV), concentrated solar thermal (CST)), ii) storage (electrical EES or thermal TES), iii) power to heat P2H (electric boiler) and iv) an auxiliary boiler (gas/biogas or biomass, e.g., pellets). This architecture is displayed in Figure 1.

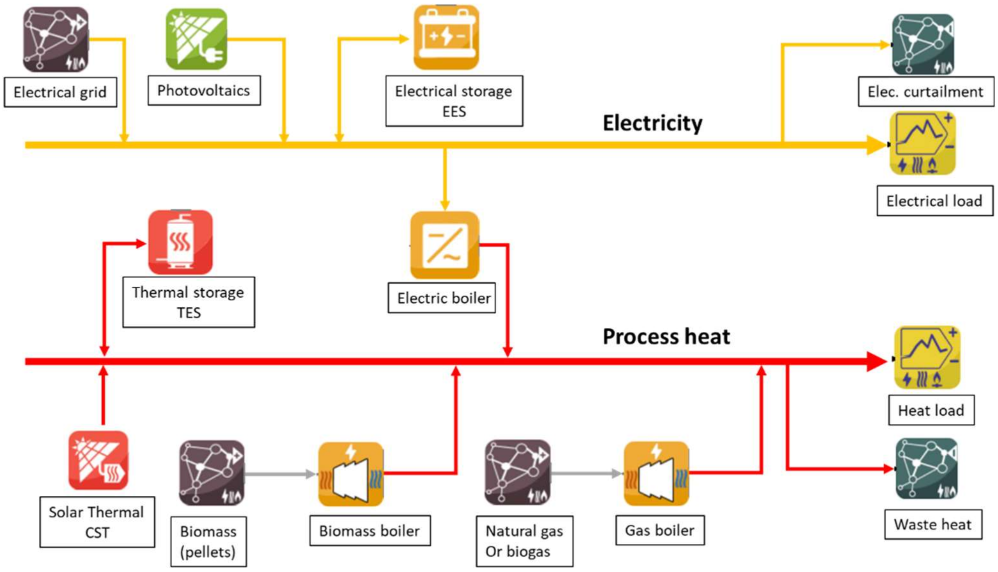

Figure 1 : *Hybrid energy system architecture.*

2.2. Optimization problem

The CAIRN open-source software, developed by CEA Liten [5,6], allows analysing this hybrid system from a techno-economic and environmental perspective. The problem of optimizing the system design and control strategy is solved by applying mixed-integer linear programming (MILP). The MILP algorithm selects relevant components and their size and balances energy flows. The cost function takes into account the Net Present Cost (NPC) of the system, expressed in M€, and can include various user-defined constraints, such as land or carbon footprint. The aim is to minimize NPC for a given system configuration.

2.3. Modelling

2.3.1. Timeseries

Meteorological data, in particular solar resource, is retrieved from Meteonorm 8 [7] with an hourly resolution. Yield estimations for solar technologies (PV, CST) are performed with U.S.

System Advisor Model open-source software [8], using meteorological data as input and selecting default configurations for PV and CST, sizing solar fields without energy storage. For PV, the reference orientation is South and the inclination is a 30° tilt (S, 30°). For CST, a parabolic trough with a North-South (N-S) tracking axis is defined. Yield estimations are then used in CAIRN software, assuming a linear relationship between field size and energy yield.

2.3.2. Assumptions

The project lifetime is set to 25 years and the discount rate is fixed at 7%. Access to energy grid infrastructures (electricity, natural gas, biomass or biogas is granted without additional CAPEX or OPEX. A greenfield installation is considered, i.e., there is no pre-installed gas boiler to retrofit. Excess energy, power or heat, cannot be exported and is thus curtailed. Land acquisition costs are not included in the techno-economic analysis.

The environmental analysis focuses on the Greenhouse Warming Potential (GWP), e.g. the carbon footprint expressed in $kgCO_{2,eq}$. A cradle-to-gate approach is adopted, using available literature. Direct emissions are taken into account for energy consumption supplied by the grid, assuming a constant footprint over the project lifetime. Grey emissions are available for PV, CST and EES technologies. This data is not yet available for TES and boiler technologies.

Technology specific parameter inputs, i.e., CAPEX, OPEX, lifetime, efficiency and carbon footprint, are aggregated from different references [9-11]. Relevant values are listed in Table 1 for a project start in 2025. OPEX costs are given as a percentage of CAPEX.

Degradation of components is not yet implemented in CAIRN. The inertia of boilers (minimum load, warm and cold start-up time) is not taken into account due to the hourly time resolution. For energy storage (EES and TES), the initial State of Charge (SOC) is set by default to 0% (empty storage on January 1st).

Table 1: Summary of technology specific techno-economic and environmental parameter inputs. (*) Estimated value, considering the mirror field and excluding the power block.

Technology	CAPEX	OPEX	Lifetime	Efficiency	Carbon footprint
PV (C&I)	900 €/kW_p (incl. inverter)	3.3%	25 years	Timeseries (SAM) No degradation	1050 kg $CO_{2,eq}/kW_p$ installed
CST	300…1200 €/kW_t	1%	25 years	Timeseries (SAM) No degradation	~5 g $CO_{2,eq}$/kWh (*)
EES	300 €/kWh (incl. BMS)	2.5%	15 years	85% (round trip)	300 $kCO_{2,eq}$/kWh capacity
TES	150 €/kWh (incl. HEX)	2.5%	25 years	80%	N.A.
Electric boiler	90 €/kWe	1.2%	25 years	99%	N.A.
Gas boiler	50 €/kW_t	3.9%	25 years	80%	N.A.
Biomass boiler	605 €/kW_t	5.75%	25 years	86.7%	N.A.

2.4. Key performance indicators

A set of key performance indicators (KPI) is defined to analyze each system configuration. The Levelized Cost of Heat (LCOH), expressed in cts€/kWh, is derived by dividing the system NPC by the amount of useful energy produced. As reported by Fraunhofer ISE [12], a distinction is made between $LCOH_{hybrid}$ and $LCOH_{solar}$. Both indicators respectively correspond to the LCOH of the hybrid and the solar energy systems, including energy storage.

Assuming the reference energy system exclusively works with NG, one can derive NPC and LCOH deviations of a system configuration X with respect to the reference (Eq.1). If the deviations are negative, then the system configuration is profitable.

$$\begin{cases} \Delta NPC = NPC_X - NPC_{NG,ref} \\ \Delta LCOH = LCOH_X - LCOH_{NG,ref} \end{cases} \tag{1}$$

Furthermore, one can derive the CO_2 marginal abatement cost, factoring in the emission reduction achieved by a given system configuration with respect to the reference system (Eq.2) :

$$Marginal\ abatement\ cost = \frac{\Delta NPC}{\sum_{t=0}^{n} \Delta CO_2} \tag{2}$$

Further indicators are considered to assess the energy system performance (Eq. 3-5):

$$Waste\ heat\ fraction\ [\%] = \frac{Q_{waste}\ [MWh]}{Q_{load}\ [MWh]} \tag{3}$$

$$Auxiliary\ energy\ saving\ [\%] = 1 - \frac{Q_{aux}\ [MWh]}{Q_{load}\ [MWh]} \tag{4}$$

$$Energy\ storage\ ratio\ [-] = \frac{Energy\ storage\ capacity\ [MWh]}{Q_{load}\ [MWh]} \tag{5}$$

2.5. System configurations

A set of four reference scenarios is defined, including a single auxiliary energy carrier: NG, biogas, biomass and grid electricity. These scenarios do not include solar energy or energy storage. Two gas boiler efficiencies are considered in the benchmark, i.e., low (80%) and high (93%). For the remainder of the analysis gas boiler efficiency is set at 80%.

A set of scenarios is defined to screen the best combinations of technologies and orientation of solar fields in terms of NPC, without constraints. This analysis helped discarding electrical storage and favored default solar orientations (PV : S, 30° ; CST : Parabolic Trough, N-S axis).

For each of the four reference scenarios, the hybridization of one auxiliary energy carrier is respectively analysed with PV or CST, with and without TES. For each system configuration, the optimal auxiliary energy saving is derived, equivalent to the useful solar fraction.

A sensitivity analysis is performed with respect to the CST CAPEX, gradually varied from 300 to 1200 €/kW$_t$. In total, 502 scenarios are analysed and screened for each site, with some potential redundancy in outcomes, allowing to double-check the MILP solver consistency.

2.6. Case study

The case study considers three French locations, i.e., Rouen, Chambéry and Montpellier. The heat demand is a baseload of 1 MW$_t$, 24/7, or 8760 MWh per year. The industrial process operates from 150 to 250°C. Table 2 summarizes solar energy yields and pre-sizing for different PV and CST configurations. Table 3 summarizes energy unit costs [13,14] and their respective carbon footprint. Unit costs are assumed to remain constant over the project lifetime, thus not taking into account any volatility (e.g. intra-day, seasonal) or inflation over the project lifetime.

Table 2: Summary of solar energy yields and pre-sizing for different PV and CST configurations, supplying 100% of the annual heat demand, without considering excess heat.

	PV [MWh/MWp] Yield		**PV [MWp] Presizing**		**CST, PT [MWh/MWt] Yield**		**CST-PT [MWt] Presizing**	
Site	*South, tilt 30°*	*E-W, tilt 15°*	*South, 30° tilt*	*E-W, 15° tilt*	*N-S axis*	*E-W axis*	*N-S axis*	*E-W axis*
Montpellier	1401	1173	6.3	7.5	1340	1190	6.5	7.4
Chambéry	1152	989	7.6	8.9	1018	865	8.6	10.1
Rouen	1022	873	8.6	10.0	741	637	11.8	13.8

Table 3: Energy unit costs and carbon footprint.
(*) The carbon footprint of NG combustion assumes a boiler efficiency of 100%.

Energy carrier (EC)	Unit cost	Carbon footprint
Unit	[cts€/kWh]	[$gCO_{2,eq}$/kWh]
Electricity	17.95	33
NG	6.98	243
Biogas	8.98	42
Biomass (pellets)	7.57	27

3. Results and discussion

The results are summarized in this section for Montpellier. Further detailed results are available in the corresponding project deliverable [4] for Montpellier and other locations.

3.1. Auxiliary energy systems

The results for reference auxiliary energy systems are summarized in Table 4. The ranking by LCOH is: 1) NG, 2) solid biomass, 3) biogas, 4) grid electricity with electric boiler. For all scenarios, except biomass, OPEX represents at least 99% of the NPC.

Upgrading the gas boiler (1b, 2b) has a major impact on the LCOH, with a reduction of 14%. Direct electrification using an electric boiler is about twice more expensive than using a gas boiler. As for the carbon footprint, upgrading the gas boiler (1b, 2b) also has a major impact, with a reduction of 14%. All alternatives to NG offer a significant reduction in CO_2 emissions, between 80 and 90%.

Scenario 1a is used as a reference to compute the CO_2 marginal abatement cost. Keeping NG and upgrading to a more efficient gas boiler (1b) is an obvious decarbonization pathway, which is profitable right away. Switching to biogas (2b) or biomass is still attractive, as the marginal abatement cost is about half of the current carbon pricing level (75€/$tCO_{2,eq}$). In contrast, direct electrification with a boiler is not attractive for this KPI, despite electricity low carbon content (Table 3). Further incentives are required to lower the unit cost per kWh, for instance through contract negotiation.

Table 4: Results for reference auxiliary energy systems.

ID	Scenario label	$LCOH_{ref}$	ΔLCOH	Carbon footprint	ΔCO_2	Marginal abatement cost
	Unit	[cts€/kWh]	vs. 1a [%]	[$gCO_{2,eq}$/kWh]	vs. 1a [%]	[€/$tCO_{2,eq}$]
1a	NG, low efficiency	8.81	0%	304	0%	0
1b	NG, high efficiency	7.58	-14%	261	-14%	-290
2a	Biogas, low efficiency	11.31	28%	52	-83%	99
2b	Biogas, high efficiency	9.73	10%	45	-85%	35
3	Biomass	9.83	12%	31	-90%	37
4	Grid electricity	18.32	108%	34	-89%	352

3.2. Solar hybridization

3.2.1. Solar PV and TES

The results of hybridization with solar PV and TES are summarized in Table 5 for Montpellier. Electricity is supplied to an electric boiler for P2H conversion.

The optimal auxiliary energy saving is slightly above 20% if NG, biogas or biomass are selected. There is no waste heat in these cases and TES is not integrated into the optimal configuration. $LCOH_{hybrid}$ is about 9.5±1 cts€/kWh while $LCOH_{solar}$ is about 7.6 cts€/kWh. If grid electricity is selected, then solar PV allows achieving higher savings, up to 48% including a TES capacity of 6 hours. As for the CO_2 marginal abatement cost, NG+PV is a profitable option, while biogas+PV or biomass+PV remain under the defined threshold for carbon pricing (75€/$tCO_{2,eq}$). A coupling with grid electricity is not attractive for this KPI.

Table 5: Optimization results for hybrid energy systems coupling one auxiliary energy carrier with solar PV and TES. Site: Montpellier.

Scenario label	Aux. energy saving	Waste heat fraction	$LCOH_{hybrid}$	$LCOH_{solar}$	TES capacity	CO_2 marginal abatement cost
Unit	[%]	[%]	[cts€/kWh]	[cts€/kWh]	[MWh, hours]	[€/$tCO_{2,eq}$]
NG, PV, w/o TES	23%	0.0%	8.61	7.46	0.0	-28
NG, PV, TES	23%	0.0%	8.61	7.46	0.0	-28
Biogas, PV, w/o TES	25%	0.0%	10.51	7.69	0.0	64
Biogas, PV, TES	25%	0.0%	10.51	7.69	0.0	64
Biomass, PV, w/o TES	23%	0.0%	9.63	7.46	0.0	29
Biomass, PV, TES	23%	0.0%	9.63	7.46	0.0	29
Grid electricity, PV, w/o TES	29%	0.0%	15.49	8.59	0.0	238
Grid electricity, PV, TES	48%	1.6%	15.13	11.29	6.2	221

3.2.2. CST and TES

The results of hybridization with CST and TES are summarized in Table 6 for Montpellier. The CST CAPEX is here set at 900 €/kW_t.

The optimal auxiliary energy saving is about 20% if NG, biogas or biomass are selected. There is less than 2% waste heat in these cases and TES is also not integrated into the optimal configuration. $LCOH_{hybrid}$ is 9.4±1 cts€/kWh while $LCOH_{solar}$ is about 6.4 cts€/kWh. If grid electricity is selected as a reference, then CST allows achieving slightly higher savings, up to 25% including a TES capacity of 1.5 hours. As for the CO_2 marginal abatement cost, NG+CST is profitable, while biogas+CST or biomass+CST remain under the defined threshold for carbon pricing (75€/$tCO_{2,eq}$). A coupling with grid electricity remains unattractive.

Table 6: Optimization results for hybrid energy systems coupling one auxiliary energy carrier with CST and TES, CST CAPEX 900€/kW_t. Site: Montpellier.

Scenario label	Aux. energy saving	Waste heat fraction	$LCOH_{hybrid}$	$LCOH_{solar}$	TES capacity	CO_2 marginal abatement cost
Unit	[%]	[%]	[cts€/kWh]	[cts€/kWh]	[MWh, hours]	[€/$tCO_{2,eq}$]
NG, CST, w/o TES	18%	0.6%	8.36	6.25	0.0	-82
NG, CST, TES	18%	0.6%	8.36	6.25	0.0	-82
Biogas, CST, w/o TES	20%	1.5%	10.39	6.52	0.0	60
Biogas, CST, TES	20%	1.5%	10.39	6.52	0.0	60
Biomass, CST, w/o TES	18%	0.6%	9.38	6.25	0.0	20
Biomass, CST, TES	18%	0.6%	9.38	6.25	0.0	20
Grid electricity, CST, w/o TES	22%	4.8%	15.93	7.37	0.0	257
Grid electricity, CST, TES	25%	4.7%	15.88	8.55	1.5	254

3.3. Summary

Optimization results are summarized for Montpellier in Table 7. This summary highlights the sensitivity of selected KPIs with respect to CST CAPEX and benchmarks them versus some reference energy systems as well as PV hybridization. TES is not included in this summary as previous observations suggest it is only relevant in combination with grid electricity.

Optimal auxiliary energy savings are higher with a solar PV hybridization in comparison to a CST hybridization. These auxiliary energy savings steadily increase as the CST CAPEX drops, regardless of the auxiliary energy system. These savings are lower for a coupling with NG or biomass. They increase for a coupling with biogas or grid electricity.

At optimal LCOH, there is no waste heat if solar PV is integrated. Contrarily, the waste heat fraction sharply increases as CST CAPEX decreases. Similar waste heat fractions are observed for a coupling of CST with NG or biomass. These increase for biogas or grid electricity.

Similar trends are observed for $LCOH_{hybrid}$ and $LCOH_{solar}$. The lowest $LCOH_{hybrid}$ value is always achieved with NG. In first approximation, optimal LCOH values decrease linearly as a function of CST CAPEX. For Montpellier, CST combined with any auxiliary energy system, except grid electricity, is already more attractive than PV for a CAPEX below 1200 €/kW$_t$.

Table 7: Summary of results for hybrid energy systems in Montpellier. SF : Solar fraction.

Aux. energy saving [%]				
Auxiliary EC	NG	Biogas	Biomass	Grid electricity
PV	23%	25%	23%	29%
CST1200	16%	18%	16%	21%
CST900	18%	20%	18%	22%
CST600	20%	22%	20%	24%
CST300	23%	24%	23%	25%

Waste heat fraction [%]				
Auxiliary EC	NG	Biogas	Biomass	Grid electricity
PV	0%	0%	0%	0%
CST1200	0%	0%	0%	3%
CST900	1%	2%	1%	5%
CST600	2%	4%	2%	9%
CST300	8%	12%	8%	18%

$LCOH_{hybrid}$ [cts€/kWh]				
Auxiliary EC	NG	Biogas	Biomass	Grid electricity
reference (SF = 0%)	8.81	12.35	10.74	20.01
PV	8.61	10.51	9.63	15.49
CST1200	8.71	10.79	9.73	16.43
CST900	8.36	10.39	9.38	15.93
CST600	7.95	9.92	8.96	15.34
CST300	7.41	9.32	8.43	14.59

$LCOH_{solar}$ [cts€/kWh]				
Auxiliary EC	NG	Biogas	Biomass	Grid electricity
reference (SF = 0%)	8.81	12.35	10.74	20.01
PV	7.46	7.69	7.46	8.59
CST1200	8.12	8.29	8.12	9.10
CST900	6.25	6.52	6.25	7.37
CST600	4.50	4.81	4.50	5.56
CST300	2.74	2.99	2.74	3.48

4. Conclusion and outlook

The case study demonstrates that solar heat represents a viable decarbonization pathway for industrial processes up to 250°C, with the potential to deliver both tangible economic and environmental benefits for the French industry.

In the absence of incentives, direct electrification is not competitive due to the high cost of electricity in comparison to natural gas. Improving the efficiency of a gas boiler is a cost-effective decarbonization option. Replacing natural gas with biogas or biomass (pellets) is also attractive, despite the additional energy cost. Hybridization with Concentrated Solar Thermal seems more attractive than solar PV, while thermal storage is favored over electrical storage in order to achieve energy savings greater than 30%.

Case studies for real industrial sites located in Southern France are currently being carried out to refine the obtained generic results. These case studies combine heat and power demands.

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