A novel method for assessing the techno-economical compatibility of solar thermal integrations

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Abstract

In this work we present a method to evaluate the compatibility of a solar thermal integration in an industrial process. We introduce two indicators to quantify in a comprehensive way all the financial and technical boundaries influence on the design choices and on the costs of a solar thermal integration.

Both the indicators are measures of the divergence of an integration from a fictive (yet technically possible) ideal case and from a “do-nothing” case. In this way, the incompatibilities of the integration are associated to the consequences that the non-ideal factors have on both costs and performances. Moreover, the value of the indicators is normalized between a minimum and a maximum being the “do-nothing” and the ideal cases respectively.

We then used these indicators on a real case scenario to compare the pros and cons of two different solar thermal integration approaches (hot water vs steam) to a beer brewery in southern Europe.

The results show that retrofitting part of the existing appliance to be fed with hot water rather than steam enhances the compatibility of solar thermal with the brewery. Nevertheless, we measured no relevant improvement to the compatibility of solar thermal when designing a brewery from scratch with the same characteristics but were the solar thermal system could have been integrated “ad-hoc” rather than retrofitted.

Keywords: solar thermal integration, compatibility, low pressure industries, brewery

Introduction

The challenges of integrating a solar thermal system into an industrial process can be overcome at a cost which will surely affect the design of the optimal solution.

These challenges can be of different nature, from purely thermodynamical to logistical, to geographical, etc. and they can also influence each other so that mitigating a problem could worsen, ease and/or create other problems. Thus, normally the optimal solution consists of those precise temperature setpoints, that specific heat-exchanger, and all those other design choices corresponding to the right trade-off between being technically ideal (best performances) and economically ideal (best price). This procedure is not different from other common designing processes, after all, it is nothing more than a quality-price evaluation, but what makes the case of solar thermal different is that the quality of an integration does not depend exclusively on deterministic factors, it also depends on the compatibility between the solar energy nature and the industrial process it will serve. The lack of understanding of this compatibility can lead to an imbalance between expectations and reality.

In this work, we show a techno-economic analysis of solar thermal integration designs that with few terms reflects the influence that the compatibility has on the optimal solution.

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Background

When comparing different potential solar thermal integrations in an industrial process we often found ourselves ranking the solutions by several parameters of different nature and magnitude such as the Levelized Cost of Energy (LCoE), the pay-back period, the energy delivered/wasted, the investment costs etc. Since different integration solutions have different pros and cons, in most of the cases, each ranking is different depending on which parameter is it based on, and even within each ranking the scoring system might not be always univocal. Unless the priorities of the integration are clearly defined, it is hard to set an unambiguous score that is comprehensive of all the other parameters and with which it is possible to draw an overall ranking of the different potential solar thermal integrations. We decided to refer to this score as “compatibility”.

The key for understanding the compatibility of the integration of a solar energy technology with a specific process is to define other reference cases first, specifically we need to define a best-case scenario (ideal case) and a worst case scenario (no-integration or “do-nothing” case). These cases would score respectively top and bottom of our overall ranking. Once that those cases are defined both in technical and economic terms, we identify the compatibility of the integration in the relative divergence between the optimal solution and the ideal one.

It is important to distinguish between the ideal and the optimal cases.

By ideal case we refer to a fictive (yet possible) scenario where we assume that all the process specific needs can be fulfilled by solar energy without the need for complementary components and without any unnecessary energy loss and/or extra costs.

That implies, for example, that in the ideal case the solar energy production always matches exactly the energy needs, therefore the temporal component causing any mismatch between the energy production and utilization can be disregarded.

Moreover, the heat is always transferred at process level and at the lowest allowable temperature difference according to pinch analysis (to minimize thermal losses).

Finally, in the ideal case, no logistic constraint applies, and the space availability is virtually unlimited while the cost of the solar collectors is equal to their production cost (no profit margins or expenses due to transport etc.).

By optimal case instead, we refer to the real scenario proposed for the integration as a result of the techno-economical designing process.

Beside these two cases, we refer to the no-integration case (or worst case) as the current state of the system: without any solar thermal integration.

At this point we need to assess the divergence between the optimal solution and the ideal one.

In order to explain and give a measure to this divergence, a little bit of terminology is necessary, and the following graph helps visualizing better the up-coming concepts

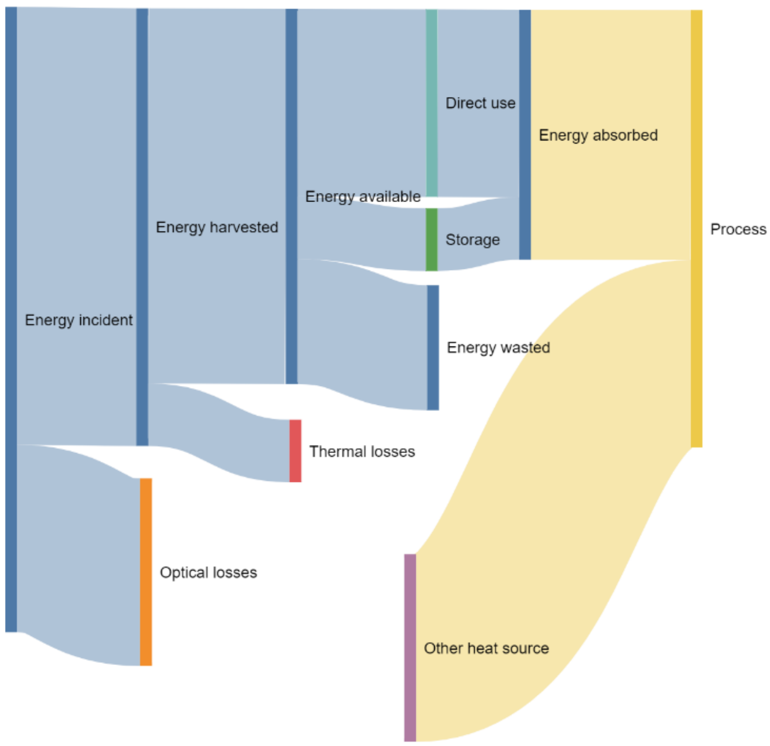

Fig.1: Solar thermal integration energy Sankey diagram

Fig. 1 shows the solar energy flows [in MWh/year] of a generic solar field to the target user. We define as:

- Energy incident, the amount of solar radiation reaching the solar thermal collectors
- Optical losses, the amount of energy incident not transferred to the heat carrier of the solar system. These losses are inevitable, so they compare also in the ideal case. Nevertheless, external factors (such as shading from surrounding structures or ground tilt) influence these losses. In the ideal case, the environment does not affect these losses.
- Energy harvested, the difference between energy incident and optical losses
- Thermal losses, the amount of energy harvested lost to the environment by heat transfer. These losses are also inevitable, but they can be mitigated to a certain extent. In the ideal case these losses are reduced to their physical possible minimum.
- Energy available (Q_A), the difference between energy harvested and thermal losses
- Energy absorbed (Q_S), the amount of energy available that is used by the process either directly or via a thermal storage. In the ideal case the energy absorbed equals the energy available and it only consists of direct use (no storage).
- Energy wasted (Q_D), the amount of energy available that was never used by the process because of a mismatch between heat production and demand.
- Heat load (Q_0), the total energy needed by the process.

Furthermore, we define the following adimensional parameters:

- Solar fraction (S_F), the ratio between the energy absorbed and the heat load. Obviously, this parameter ranges between 0 and 1 and in the ideal case is 1 while is 0 for the no-integration case.
- Capacity reserve (C_R), the ratio between energy wasted and energy available. This parameter also ranges between 0 and 1, but it is 0 for both the ideal and the no-integration case.

Finally, we define the following financial parameters:

- Levelized cost of energy ($LCoE$) measured in €/MWh, by the following formula [2]:

$$\text{LCoE} = \frac{sum\ of\ costs\ over\ project\ lifetime}{sum\ of\ energy\ load\ over\ project\ lifetime} = \frac{\sum_{t=1}^{n}\frac{I_t+O_t}{(1+\alpha)^t}}{\sum_{t=1}^{n}\frac{Q_t}{(1+\alpha)^t}} \quad \text{(eq.1)}$$

where:

- I_t are investment expenditures in the year t
- O_t are operational costs (fuel and maintenance) in the year t
- Q_t is the heat load in the year t
- n is the lifetime of the project in years
- α is the discount rate

n and α must be equal in the ideal, optimal and no-integration cases for the comparison to make sense. Moreover, the LCoE must consider the effects associated with the energy production and demand mismatch and thus, in the formula, we must use the value of the solar energy absorbed, rather than the energy available. That also implies that in the investment expenditures we must include the cost of thermal storages and any other non-exclusively-solar related costs (such as piping, foundations etc.)

- The fuel price (F) measured in €/MWh
- The cost of the investment in the ideal case (I_{ideal}) and in the optimal case $\left(I_{opt}\right)$ measured in €

For simplicity, we will assume as investment expenditures the total cost of the solar thermal integration and as operational costs no other costs but the fuel costs

The LCoE alone does not reflect all the solar thermal integration gains, indeed basing the design on the LCoE alone could results in the tendency of preferring cost-reducing installations over other factors such as energy efficiency or sustainability [4]. On the other hand, it is comprehensive of both the technical and the financial aspects of the case. In other words, the LCoE is a quite good “overall” scoring system, not for nothing it is widely acknowledged as a convenient summary measure of the competitiveness of an energy technology [4], but it should not be the only indicator to consider, and it also lacks some form of reference values in order to contextualize and give some significance to its bare figure.

Obviously, for the solar thermal integration to even make sense economically, the relation between the LCoE for the reference cases must be as follows:

$$LCoE_0 > LCoE_{opt} > LCoE_{ideal} \quad \text{(eq.2)}$$

We have in this way indirectly ranked the integration cases (no-integration as the worst, ideal as the best). This allows to measure the divergence between the optimal and the ideal cases and to normalize that value having both the best and worst cases as reference

$$\Phi = \frac{LCoE_0 - LCoE_{opt}}{LCoE_0 - LCoE_{ideal}} \quad \text{(eq.3)}$$

We introduce the financial compatibility (Φ) defined above as one of the indicators of the solar thermal technology integration compatibility with the process.

If we take the conservative assumption that the current cost of energy will not adjust for the discount rate, we can expand the terms of the financial compatibility and we can rewrite the eq.3 as:

$$\Phi = \frac{S_F - {}^{rI_{opt}}/_{Q_0 F}}{1 - {}^{rI_{ideal}}/_{Q_0 F}} \quad \text{(eq.4)}$$

where

$$r = \frac{1}{\sum_{t=1}^{n}\frac{1}{(1+\alpha)^t}} \quad \text{(eq.5)}$$

and where ${}^{rI}/_{Q_0 F}$ is another adimensional number representing the costs of the solar thermal investment as a portion of the current value of the energy costs each year of the no-integration case. We will refer to it as the relative weight of the investment with the symbol χ so that

$$\Phi = \frac{S_F - \chi_{opt}}{1 - \chi_{ideal}} \tag{eq.6}$$

Summing up, we can now observe that:

- The financial compatibility's value is bounded between 0 and 1.
- We can express it as function of two adimensional parameters being the solar fraction and the relative weight of the investment.
- It is comprehensive of both technical and financial aspects.
- It is contextualized with the current price of energy and with the best possible price achievable with solar thermal

Just like the LCoE, when comparing two possible integration solutions, Φ is very powerful to understand if it is more convenient to opt for more solar energy or for cheaper solar energy. In addition, since its value is bounded, it gives a measure of the limitations that the costs and the technical boundaries pose on the optimal solution.

At first glance, it might seem that the financial compatibility is not affected by the capacity reserve. That is because from a purely economic point of view, the capacity reserve has only significance as a theoretical limit on the economic benefits acquirable through a thermal storage.

On the other hand, in a purely energetical compatibility perspective, the capacity reserve plays a much more important role. That can be shown following the same conceptual procedure of measuring the divergence between the optimal and the ideal cases, but according to energetical aspects only.

In order to do that, we define a two-dimensional geometrical space consisting of the energy absorbed and the energy wasted (we will represent them as the x and the y respectively of a Cartesian coordinate system).

The three cases can now be represented as points in this space:

- No-integration correspond to the space origin (0;0) having neither energy wasted nor absorbed
- Ideal case is on the x-axis (Q_0; 0)
- Optimal case is the generic point (Q_S; Q_D)

We can now introduce the energy compatibility (Ψ) as the divergence between optimal and ideal cases normalized by the divergence between ideal and no-integration cases where we measured divergences as distance between points.

$$\Psi = \frac{Q_0 - \sqrt{(Q_0 - Q_S)^2 + (Q_D)^2}}{Q_0} \tag{eq.7}$$

we can rewrite this expression as

$$\Psi = 1 - \sqrt{(1 - S_F)^2 + \left(\frac{S_F C_R}{1 - C_R}\right)^2} \tag{eq.8}$$

We can observe that:

- The energy compatibility's value is < 1 but theoretically it is not inferiorly limited like the financial compatibility. This is because we have not yet imposed that that the divergence between optimal and ideal cases had to be smaller than the divergence between ideal and no-integration cases (which for the financial compatibility must happen for the integration to be economically meaningful and it is expressed by eq.2).
- Like we did for the financial compatibility, but in an energy-wise dimension only, if we had to impose a constraint to the energy compatibility's lower limit and justifying it as the minimum condition for the case to be meaningful, that would eventually translate into a relation between the solar fraction and the capacity reserve resulting in the domain of the meaningful solutions shown in Fig.2:

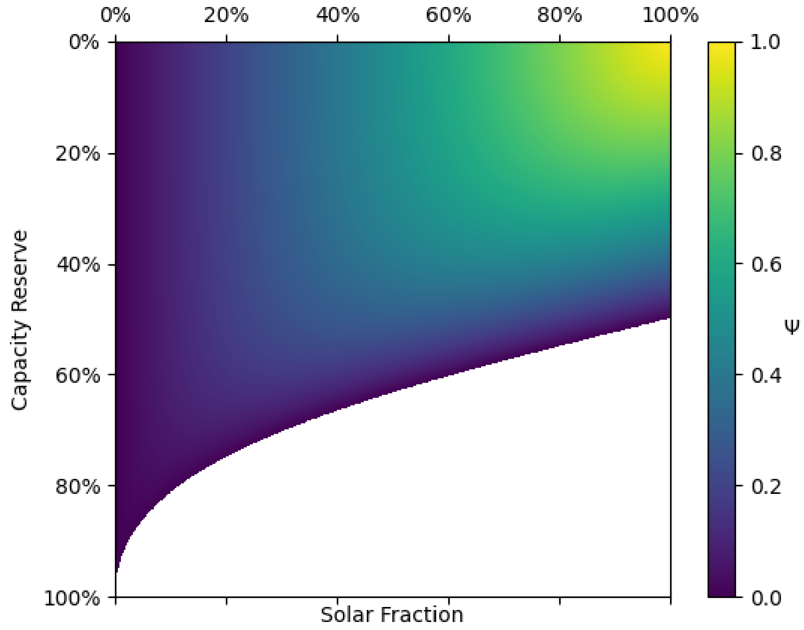

Fig.2: Values of the energy compatibility in the domain of the energy meaningful solution

- We can express it as function of two adimensional parameters being the solar fraction and the capacity reserve
- It's expressed by only energy related variables, thus it does not reflect the economics of the integration although they influence the choice of the optimal case.

Ψ becomes very useful when comparing two possible integration solutions to understand, from an energy point of view, whether is it worth to waste more to deliver more.

Methodology

We will now use the energy and financial compatibility to characterize different possible integration cases in a real scenario of a beer brewery in southern Europe. The main difference between the integration cases is the heat carrier media on the brewery side. More specifically, we want to assess through the compatibility KPIs if it is beneficial to convert the brewery, or part of its processes to use hot water instead of steam as heat carrier.

To evaluate each case, a simulation software has been developed. The software calculates all the energy flows of a solar integration corresponding to the weather condition, the heat demand, the solar thermal system layout, the current plant layout and the process physical boundaries (such as operational temperatures and pressures). Adding information about investments and current energy prices for each configuration, the software also finds the solar thermal system layout that score best in terms of financial compatibility for that specific configuration. We have chosen those layouts as the optimal cases for each scenarios and then we compared them.

The first step is to define some boundary conditions and general data inputs. Two indispensable inputs are the typical meteorological year profile and the brewery heat load profile. Without them it is impossible to assess the mismatch between production and demand of solar energy. Our source of typical meteorological year profile for this case is Meteonorm [5], while for the brewery heat load profile we used the steam consumption data from the brewery's SCADA system.

The solar collectors used for the simulation are "Absolicon T160" solar parabolic trough concentrators [6]. The bare minimum price of the collectors for the ideal case is 200 €/$m^2_{aperture}$ while we will consider an actual price for the chosen location of 350 €/ $m^2_{aperture}$. Regarding the thermal energy storages, we will consider 2000 €/m^3 for pressurized storages and 400 €/m^3 for atmospheric pressure storages.

The plant currently uses heavy fuel oil (HFO) to fire the boilers. They have a taxation on their carbon emissions and their boiler efficiency is circa 85%. All in all, the cost for MWh turns to be approximately 110 €/MWh.

Considering that the total yearly load amounts to 36700 MWh/year the current annual energy cost (which is nonetheless than the no-integration case reference) is 4.037 M€/year.

We will consider a discount rate of 7% and project's lifetime of 20 years.

The boilers at the facility are fed with de-aerated water at 103°C and they produce saturated steam at 160°C (slightly above 6 bar), but all the processes occur at temperatures under 103°C. By definition, in the ideal case the heat is always transferred at process level and at the lowest allowable temperature difference according to pinch analysis. Given the heat loads and temperatures of each process in the brewery and assuming a pinch temperature difference of 5°C the pinch analysis shows that the input and output temperatures of the solar field heat carrier for the ideal case will be respectively 50°C and 110°C.

Technically, all the heat loads could be fed at process level, however mashing and wort boiling are very sensitive processes that the brewery did not want to retrofit for the fear of altering the beer taste. Therefore, although in the ideal case we include all the processes, for the hot water case we will then only consider the load fraction of the targetable processes.

Even though some of the processes are operated in batch mode, for the pinch analysis we considered them to be simultaneous with a time averaging approach by calculating each process energy consumption and dividing it by its operation time [1][3].

To integrate solar thermal energy at boiler level, the collectors field operates parallelly to the boilers: it receives a part (or all) of the boilers' feedwater in input and it outputs steam to be sent back to the plant steam distribution system (via the manifold right after the boilers). The steam produced by the solar field has properties similar to the boilers steam: it has just slightly higher pressure (to have flow priority into the system), but almost identical in temperature (since the solar steam is at saturation conditions while the boiler steam is slightly overheated to reduce condensation along the steam distribution system).

During the designing phase, the process engineers have decided to produce solar steam with a parallel flow heat exchanger. That is for enhancing a thermos-syphon effect replacing a circulation pump on the cold side of the heat exchanger. The drawback of this decision is that the pinch point temperature is now higher than the steam saturation temperature forcing the solar collectors to also operate at higher temperatures and causing higher heat losses.

Furthermore, the process engineers have also estimated that the appropriate temperature difference between input and output of the solar field should be of 20°C. The trade-off is that higher input-output temperature difference increases the heat losses but reduces the flow and therefore the cost of piping and other equipment (such as the circulation pump).

Concerning the hot water case, the pinch analysis suggest that the optimal case should have as inlet and outlet temperatures on the collector side respectively 30°C and 120°C. That results in an average mean temperature (and thus thermal losses) of the collector even lower than the ideal case, but this advantage is only a small side-effect of a major drawback for this case which is the impossibility of targeting the entire brewery heat load since the processes of mashing and worth boiling had to be excluded. That implies that the solar fraction of this case cannot exceed the value of 52%.

To avoid this problem, a third hybrid case (steam + hot water) was also investigated. This case is similar to the hot water one, but in addition, it can provide steam to the brewery. The steam is generated only with excess solar energy that would otherwise be wasted. The steam cannot be generated with energy coming from the thermal storage and cannot be stored in turn (energy to make steam can only be absorbed as direct use energy).

The hot water case requires a bigger initial investment than the steam case since it requires additional retrofitting measures, and the hybrid case requires an even bigger initial investment for the same reason.

All in all, Tab 1. summarizes the characteristics of each case.

Tab. 1: Summary of simulation results and economical choices of each considered integration case

Case	*No-Integration*	*Ideal*	*Steam*	*Hot Water*	*Hybrid*
Integration type	None	Process level	Boilers level	Process level	Process and Boilers level
Targeting load	Total load	Total load	Total load	Partial load	Total load for direct heat. Partial load for storage
Type of storage	No storage	No storage	Pressurized	Non-pressurized	Non-pressurized
Collectors' inlet temperature [°C]	-	50	165	30	30 or 165
Collectors' outlet temperature [°C]	-	110	185	120	120 or 185
Price of field [€/m2]	0	200	350	350	350
Price of storage [€/m3]	0	0	2000	400	400
Optimal field area [m2]	0	37437	12069	15325	18390
Optimal storage volume [m3]	0	0	190	1456	1571
Extra integration costs [M€]	0	0	0.1	1.0	1.5
Solar thermal investment [M€]	0	7.487	4.703	6.946	8.565
Energy produced [MWh/year]	0	36700	9093	15193	17684
Energy absorbed [MWh/year]	0	36700	7733	14050	15904
Energy wasted [MWh/year]	0	0	1361	1143	1780
Heat rate [kWh/m2/year]	0	0.980	0.641	0.917	0.865
LCoE [€/MWh]	110	18.00	98.13	84.59	82.92
Payback period [years]	-	2	11	7	9
Solar fraction	0%	100%	21%	38%	43%
Capacity reserve	0%	0%	15%	8%	10%

In addition, we also investigated a case of a hybrid steam-water greenfield scenario. For this case the investment cost must also account for the cost of the boilers. The boiler size is dimensioned after the solar field performances to be complementary to it. The boiler size of each case is obtained as the maximum value of the power not delivered by solar energy. The boiler prices are estimated from a linear regression of commercially available boilers prices vs their nominal powers [7]. The relation obtained is shown in eq.9

$$B = 0.2782P_w + 29.849 \quad \text{(eq.9)}$$

Where B is the boiler price is thousands € and P_w is the boiler's nominal power in kW.

Obviously, the non-integration case must be updated with the cost of a full-sized boiler that we will add to the extra integration costs and that will impact on the LCoEs calculation.

Despite our expectations, the boiler size of the optimal case was not reduced a lot showing that the peak power demand hours did not match well the solar thermal production. This mismatch is a true form of incompatibility and thus will be reflected both in the financial and in the energy compatibility as we have defined.

Tab 2. summarizes the updates to the reference case and the results of the simulation for the greenfield scenario.

Tab. 2: Summary of simulation results and economical choices the greenfield integration case

Case	*No-Integration*	*Ideal*	*Greenfield (Hybrid)*
Optimal field area [m2]	0	37437	18333
Optimal storage volume [m3]	0	0	1613
Extra integration costs [M€]	3.038	0	2.924
Total investment [M€]	3.038	7.487	9.986
Energy produced [MWh/year]	0	36700	17670
Energy absorbed [MWh/year]	0	36700	15903
Energy wasted [MWh/year]	0	0	1767
Heat rate [kWh/m2/year]	0	0.980	0.867
LCoE [€/MWh]	117	18.00	86.33
Solar fraction	0%	100%	43%
Capacity reserve	0%	0%	10%

Results and conclusions

Before revealing the values of financial and energy compatibility of each case, we can make some judgments over their simulation results and economical choices.

From both an energy and an economical perspective, the water integration case is surely more compatible with solar thermal than the steam integration since it can deliver more and waste less energy by also costing less at the same time. The energy and the economical compatibility definition were still useful to measure and quantify objectively how much more compatible is the water integration respect to the steam one. Indeed, without using the energy compatibility as we defined, the answer would be subjective to the personal interpretation of the trade-off between higher solar fractions and lower capacity reserves. Similarly, it is hard to understand the scale of the economical improvements without contextualizing the LCoEs of the two cases with the current price of the energy, the increase of energy delivered and the different investment costs.

The difficulties of comparing unequivocally the compatibility of the integrations are even more evident when comparing the hot water integration case with the hybrid (steam and hot water) integration case. Indeed, the multitude of pros and cons of the two cases do not allow for an obvious interpretation and even less for a quantifiable measure of the compatibility.

The hybrid case costs more than the hot water case, it wastes more energy (thus it has a lower heat rate) and has a longer payback period. On the other hand, the hybrid case also delivers more energy and has a slightly lower LCoE than the hot water case.

Furthermore, the optimal sizes of field and storage of the hybrid case as retrofitting and as greenfield scenarios are almost identical. The boiler costs for the no-integration and the greenfield optimal case are also very similar. This suggest that the only advantage that the solar thermal integration would have as a greenfield project rather than as a retrofitting project for this specific case are due to the increased relative cost of the no-integration case.

In the next figures are shown the simulation outputs for Φ and Ψ for the considered solar field aperture and storage volume ranges. The red star represents the optimal case for each scenario.

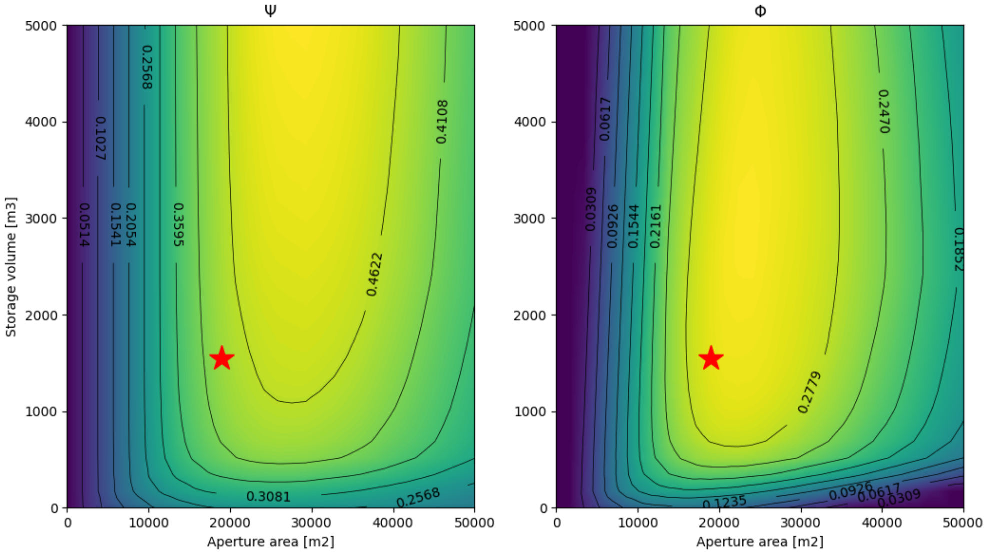

Fig.3: Parametric analysis results for energy and economic compatibility (hybrid case)

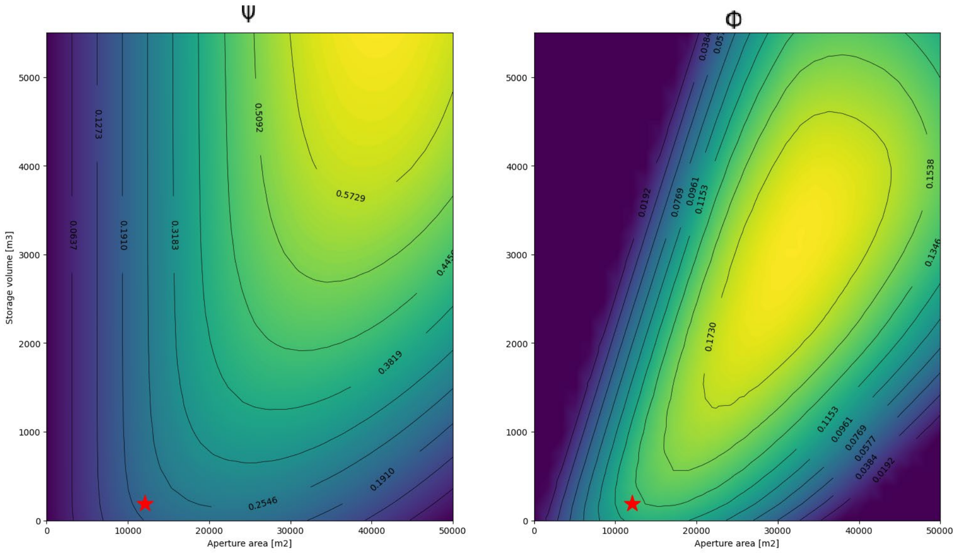

Fig.4: Parametric analysis results for energy and economic compatibility (steam case)

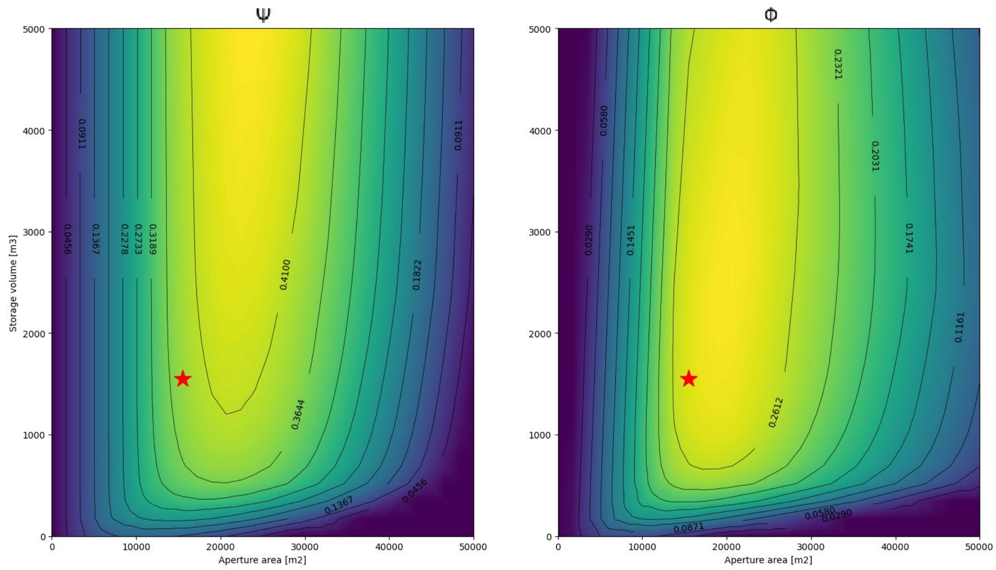

Fig.5: Parametric analysis results for energy and economic compatibility (hot water case)

Note how the trends of the contour lines for Φ and Ψ have similar shapes but different values across both the different scenarios and the two indicators themselves.

Finally, Tab. 3 shows the results for the financial and energy compatibility of all the considered optimal cases.

Tab. 3: financial and energy compatibility of each integration optimal case

Case	*Steam*	*Water*	*Hybrid*	*Greenfield (Hybrid)*
Ψ	21%	38%	43%	43%
Φ	13%	28%	29%	31%

As expected, the steam integration ranks the lowest for both financial and energy compatibility, nevertheless we had expected the energy compatibility gap between the two scenarios to be much larger since the actual gap is comparable to the solar fractions gap and we thought that the capacity reserve would have contributed to enlarge it even further. The reason of that is because the capacity reserve negative impact on the energy compatibility increases with the solar fraction too (the absolute amount of wasted energy of the two cases is quite similar).

The financial compatibility, on the other hand, is more than double as high for the water compared to the steam integration case, but almost identical to the financial compatibility of the hybrid case suggesting that the economical advantages achievable through technical improvements in the hybrid case are proportional to their costs.

As we expected, both the energy and the financial compatibility of the hybrid case does not increase much in a greenfield scenario either, since the power peaks mismatch makes impossible to reduce the boiler size.

In all the cases, the energy compatibility results higher than the financial one which means that the ideal conditions for this integration are easier to achieve from an energy point of view rather than from an economical point of view regardless the layouts.

In conclusion, according to the indicators presented in this work, there is a substantial improvement from both economic and financial perspective in choosing hot water rather than steam as heat carrier for the considered solar thermal integration. There is an additional yet less remarkable improvement in choosing a hybrid system of hot water and steam.

In the case of a greenfield project, where the solar thermal integration and the plant can be designed to meet each other needs much better than in a retrofitting project, we assessed the scale of the advantages to be relatively small.

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