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Techno-economic comparison of a solar absorption chiller and photovoltaic compression chiller

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Abstract:

Cooling systems are becoming increasingly important around the world. While centralized heating systems have been around for decades, cooling systems tend to be something that is only kept for large buildings, and decentralized cooling has flourished and is becoming the first choice when it comes to comfort needs, disregarding the efficiency of larger systems.

In this work, TRNSYS was used taking advantage of the Wedistrict methodology to compare two different alternatives and analyze which technology fits better in a cold district solution. On one side, single-stage absorption chillers combined with solar thermal technologies (Fresnel) as its heat source, and on the other, compression chillers with high energy efficiency ratios combined with photovoltaic technologies were used.

The paper shows that the current technological state singles out the compression chiller as a more appropriate selection for variable demand systems, while leaving absorption chillers as a viable option for constant cooling demand systems where a high temperature heat source is available.

Keywords:

TRNSYS; District Cooling; Solar energy; Absorption chiller.

1. Introduction

The increasing temperatures throughout the world are leading to an expansion in cooling degree days (CDD), which leads to an increasing need for cooling systems worldwide. This trend is also visible in Europe, where the significance of CDD was previously overlooked while devising a cooling strategy. At present, CDD values are becoming difficult to ignore (Figure 1)[1].

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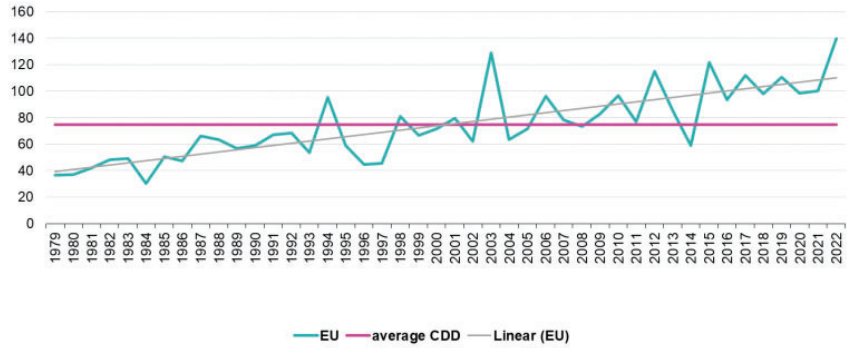

Source: Eurostat (nrg_chdd_a)

eurostat

Figure 1. Cooling degree days statistics EU, 1979-2022.[1]

Two main cases have been analysed, the first one, photovoltaic panels have been used, and have been sized to be able to fully supply the compression chiller annually (Figure 2). In the other case, solar Fresnel panels have been sized to theoretically provide the energy needed for the conventional single stage absorption chiller, along with a natural gas boiler to ensure the correct inlet temperature for the chiller heat input (Figure 3).

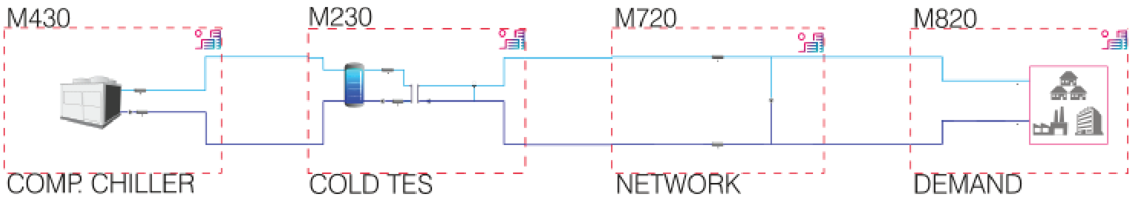

Figure 2. TRNSYS arrangement with tank.

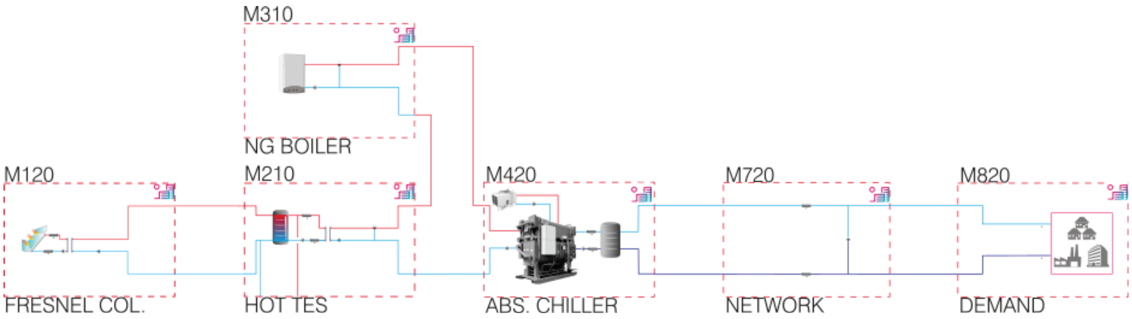

Figure 3. TRNSYS arrangement with absorption chiller with heat supply from solar energy plus boiler backup.

Different simulation approaches have been followed to arrive to correct plant sizes in order to compare technically and economically the results.

Both configurations have been simulated using TRSNYS (TRaNsient SYstems Simulation Program) following the modular methodology developed in the frame of the Wedistrict project [2]. Technical, environmental, and economic indicators have been calculated and analyzed [3].

2. Methodology

2.1. Software

TRSNYS (TRaNsient SYstems Simulation Program) software was applied in accordance with the modular methodology that was created specifically for the WEDISTRICT project.

This project studies the integration of innovative technologies for District Heating and Cooling (DHC) systems with an end goal of developing viable solutions for delivering fully renewable energy in climatization services [3].

The modular methodology is based in TRNSYS macros and decks. Macros are a series of TRNSYS types that are used together to reduce the number of connections to be done. The code to describe them has the letter "M" for "macro", followed by four numbers, the first three represent the code of the technology used, separated by the thousands in types of technologies (solar, storage, boilers, etc.), by the hundreds in different technologies between the same family, by the tenths in variations of the same technology. The unit is left in case the technology repeats itself in the same deck, due to the fact that TRNSYS, as many other software, does not allow variable name repetition.

WEDISTRICT macros have characteristics to improve the modularity and flexibility:

- Nomenclature: A standard nomenclature for macros, types, and variables
- Input and Output interfaces: Inputs and outputs variables are transmitted in and out of the macro by equation blocks. This method simplifies and reduces connections and allows replacing a macro by another more efficiently (Only a few connectors should be modified).
- Parametrization procedure: Parameters are variables that remain constant during the simulation time. A Python script has been developed to make this more fluent (from specific values calculate the majority of these parameters through correlations).
- Control strategy: Each macro has its own control strategy based on the technology represented. This method allows adding the same macro into different systems reducing the amount of control parameters to be set.
- Results: Each macro displays its own set of results and its internal calculations, such as energy and mass balance.

As an example, compression chiller macro has been taken (M4300). In this macro two different operation modes can be imposed, one in which the chiller works in series operation reaching an output temperature, and other, in which de chiller is controlled to work in parallel against a cold water storage to maintain a setpoint in the tank.

A simplified diagram is shown in Figure 4, along with its representation in TRNSYS. In the figure, heat flows are displayed in blue arrows (QCHI01 regarding the heat dissipated by the chiller, and QLsPI01 as the pipe losses), work flows are displayed in purple (WCHI01 as the power consumed by the electrical chiller and WPU01 for the pump), and mass flows with their corresponding temperatures are displayed in black arrows (MIn01/TIn01, MOu01/TOu01).

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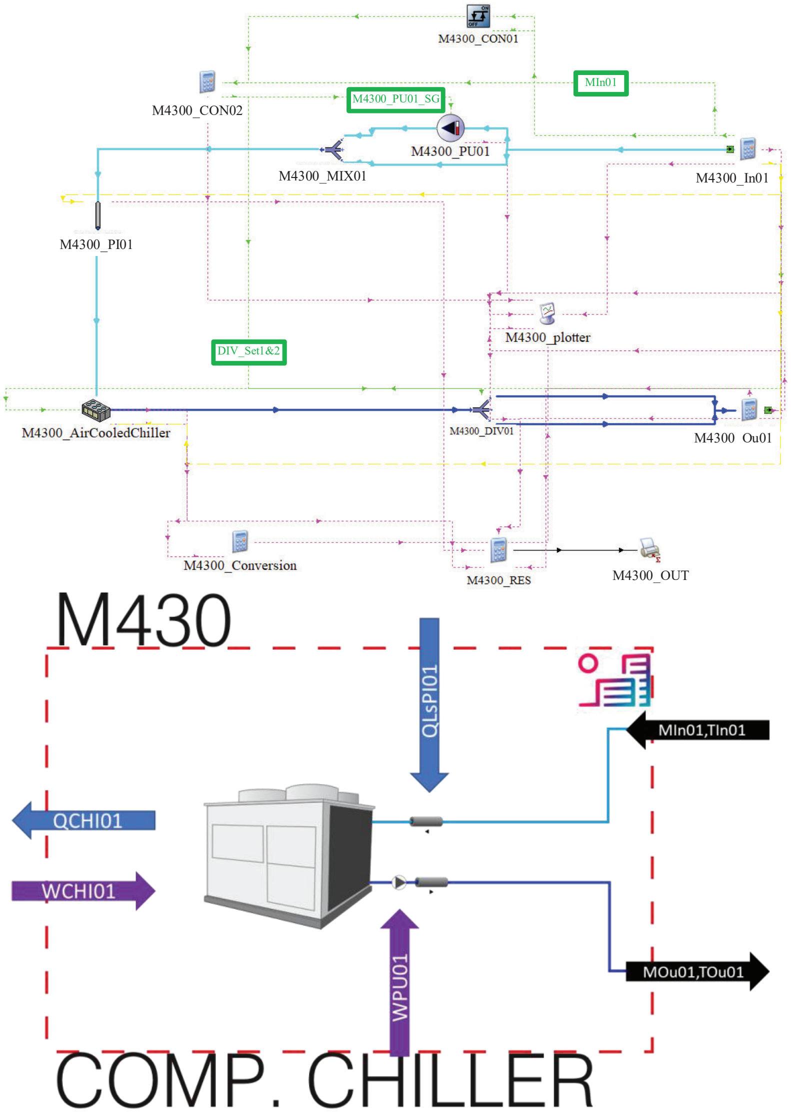

Figure 4. Compression chiller macro (M4300). Schematic diagram and TRNSYS translation.

This methodology is used to develop macros which allow a faster generation of decks to be run by TRNSYS. After running the simulations, all results are read and KPIs (Key Performance Indicators) calculated through the use of a Python script.

2.2. Location and Demand

This study has been carried out in Madrid where plenty of solar resource is available, and cooling demand is needed seasonally in summer.

Two demand profiles have been tested, a variable demand fixed by a yearly demand of approximately 733 MWh/y. And an experimental one, in which a constant value of 485 kW is considered.

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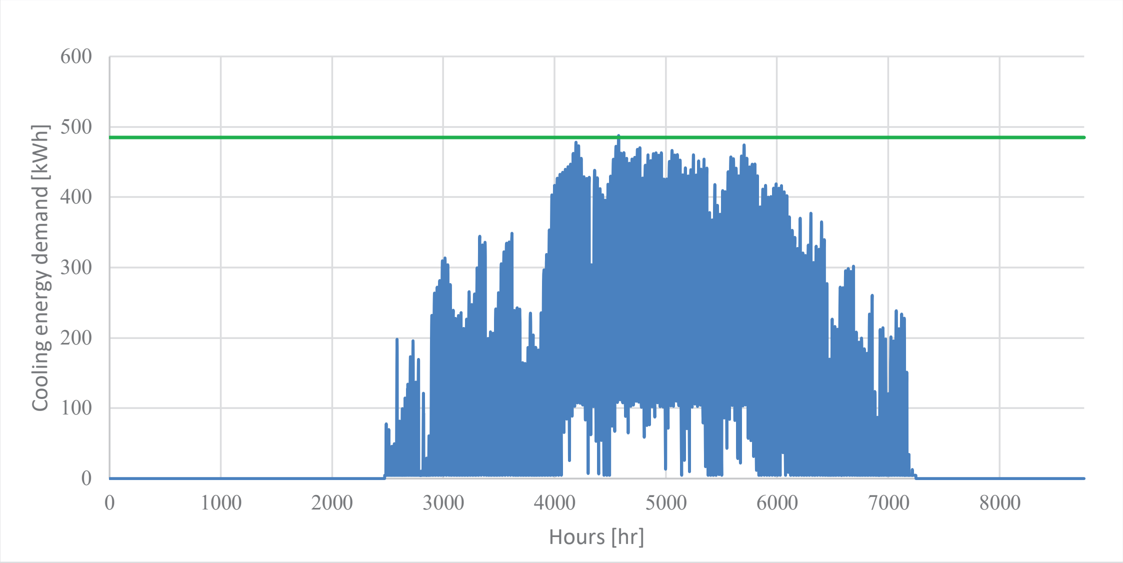
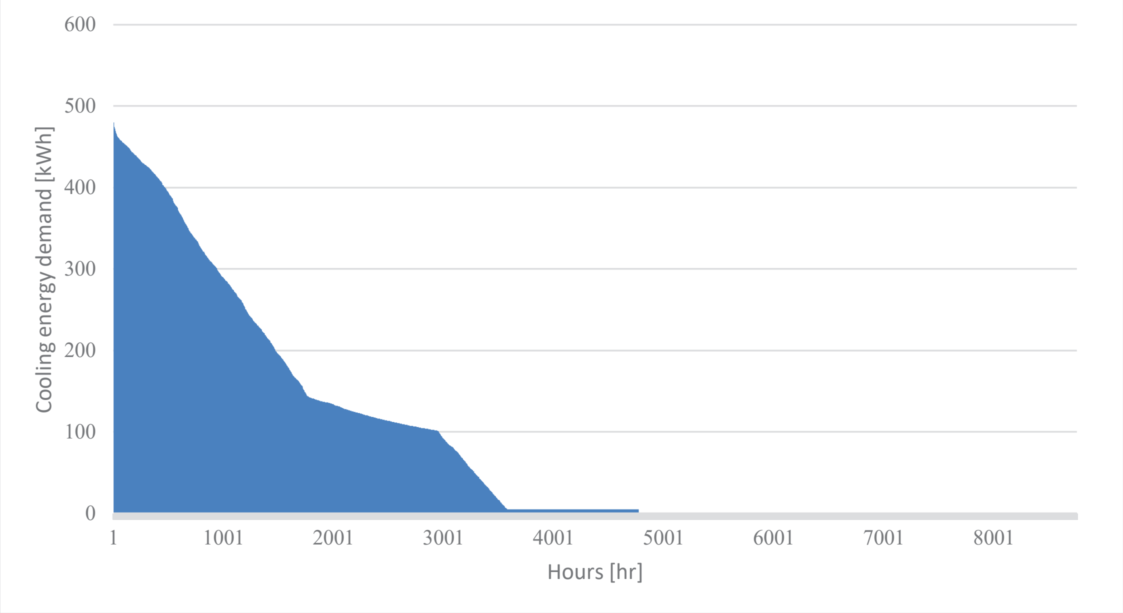


(a)



(b)

Figure 5. Hourly demand profile studied (a) and monotonic curve of thermal loads (b) [kWh].

The hourly demand distribution and the descending monotonic curve, which indicates the application of various thermal loads in the system, can be observed in Figure 5 (a and b). These graphical representations are valuable for determining the necessary capacity that must be implemented.

2.3. Technologies Considered

The discussion in this paper intends to compare two diverse options of cooling generation, in which one of the main aspects to be addressed is the coefficient of performance (COP). While absorption chillers are known not to have high COP values due to their theoretical limitations, their main advantage is that most of their energy consumption is thermal (which compared to electric energy tends to be cheaper). On the other hand, compression chillers are found, where all their energy consumption is electrical. In this regard, a single stage absorption chiller has been used for this analysis which reaches an assumed COP value of 0.75. While for the compressor chiller a value of 3 was assumed [4].

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2.4. Prices Considered

For electricity prices, the EU statistical website was used as source, and the last value available for Spain was selected (0.2298 €/kWh from S1,2022, for big consumers > 15000kWh) [5].

As not many reliable sources of pricing for technologies are available online, three different were considered [6–8], and a final value of 196€/kW was selected for the compression chiller and a 288 €/kW for the absorption chiller.

Other than that, values for Fresnel collectors were set in 190 €/m^2 and thermal energy storage (TES) were set in 260 €/m^3.

2.5. KPIs Definition

All KPIs have been calculated according to the scientific article referenced written for the Wedistrict project [2,3].

Mostly values on Levelized Cost of Energy (LCoE) and CO_2 emissions have been reviewed for comparison.

2.5.1 LCoE

The Levelized cost of energy (LCOE) evaluates the average net present value of energy expenditures during a system's lifespan. It is an important instrument for comparing various power generation technology options, particularly in situations where significant initial investments are required but operating costs decrease over time. This situation frequently occurs in systems that rely heavily on renewable sources.

The levelized cost of energy (LCOE) methodology involves the discounting of future expenditures and earnings to their current value in a designated base year, thereby enabling the determination of unit costs for generating energy. These unit costs represent the ratio between discounted lifetime expenses and projected net present value (NPV) of total energy output. In effect, they correspond to an average price that consumers would need to pay in order to cover all associated costs while yielding a rate-of-return equivalent to that defined by the chosen discount rate.

CAPEX calculations are done through the software, the value from the total system cooling capacity is also taken from the simulation results for this calculation. The rest of economic values are added in postprocessing by the script, fixing these values by the user.

$$LCOE = \frac{CAPEX \cdot CRF + OPEX_f + OPEX_v}{Q_C}$$

$$CRF = \frac{\{i \cdot (1+i)^n\}}{\{[(1+i)^n] - 1\}}$$

- $LCOE$: Levelized cost of cooling energy [€/MWh].
- $CAPEX$: Capital expenditure for the equipment [€/MWh].
- $OPEX_f$: Fix operational costs for cooling [€/year].
- $OPEX_v$: Variable operational costs for cooling [€/year].
- CRF: Capital recovery factor
- i: interest rate.
- n: project lifetime and number of annuities received.
- Qc: Cooling energy supplied per year [MWh/year].

2.5.2 CO_2 emissions

The concept of equivalent emission coefficient pertains to the quantification of non-renewable fuel-derived greenhouse gas emissions within a district heating and cooling system. It is important to note that carbon emissions generated by biofuels are not considered, while accounting for the ones related to extraction, transformation, and transportation processes. The calculation is as follows:

$$k_{CO_2} = \frac{\sum_i E_i \cdot k_i}{Q_C}$$

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Where:

- k_{CO2}: CO2 emission coefficient (kg/ MWh).
- E_i: energy supplied by energy carrier i per year [MWh/year].
- k_i: Emissions coefficient of energy carrier i [kg CO2/ MWh.
- Q_c: Cooling energy supplied per year [MWh/year].

For CO_2 emissions the following table has been taken as seen in the reference [3].

Table 1. Default primary energy factor and non-renewable emission coefficient from ISO-52000 table B-16).

Energy carrier Delivered from distant		Primary energy factor			Non-renewable CO_2 emission coefficient
		Non-renewable	Renewable	Total	g/ kWh
Fossil fuels	Solid	1.1	0	1.1	360
	Liquid	1.1	0	1.1	290
	Gaseous	1.1	0	1.1	220
Biofuels	Solid	0.2	1	1.2	40
	Liquid	0.5	1	1.5	70
	Gaseous	0.4	1	1.4	100
Electricity		2.3	0.2	2.5	420
Solar	PV-electricity	0	1	1	0
	Thermal	0	1	1	0
Exported					
Electricity	To the grid	2.3	0.2	2.5	420
	To non EPB uses	2.3	0.2	2.5	420

2.6. Cases Evaluated

A first effort has been aimed to establish what appears to be the preferred technology by the users. The definitions on LCoE and CO_2 emissions have been established for the compression chiller and studies have been held as to determine how much improvement does the system get from the use of PV solar panels to provide electricity for the system.

Then the same indicators were established for the absorption chiller case, reviewing how much power is required as heat input for the system and how different variations on the supply affect the system.

3. Results

3.1. Compression Chiller

First a calculation of the system with the compression chiller has been made.

Table 2. Results from compression chiller system

PV capacity [kW]	Battery autonomy [kWh]	TES capacity Chiller [m^3]	Comp. Chiller capacity [kW]	Deviation Cooling demand [%]	LCOE [€/MWh]	CO_2 emission coefficient [kg/MWh]
165.00	495.00	30.00	485.00	-4.05	59.97	40.14

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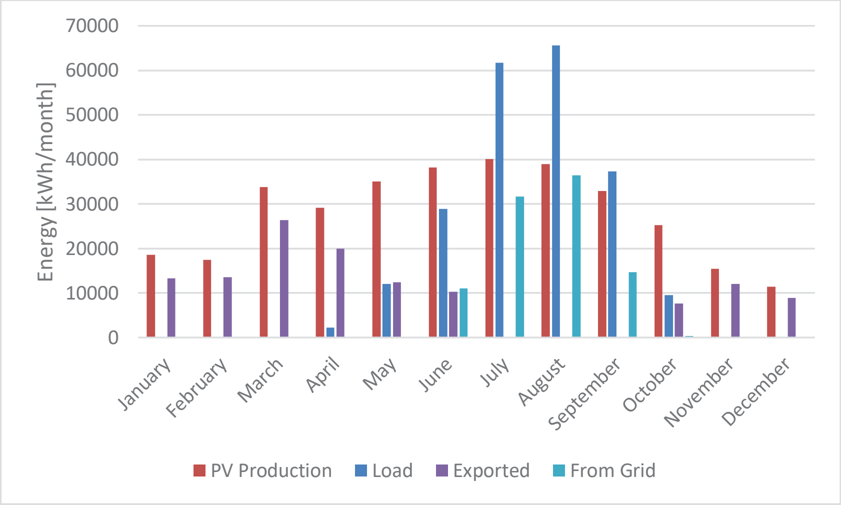

Figure 6. Photovoltaic production in analysed system and segregation [kWh/month].

From this first result we then took a step further to establish the same scenario without the PV panels, as to see the impact of these in the CO_2 emissions, and in the LCoE of the assumed network.

Table 3. Results from compression chiller system without PV panels.

TES capacity Chiller [m^3]	Comp. Chiller capacity [kW]	Deviation Cooling demand [%]	LCOE [€/MWh]	CO_2 emission coefficient [kg/MWh]
30.00	485.00	-4.05	87.98	129.84

These results show how LCoE values are improved by the installation of solar panels (31.8%), and how this investment reduces also the CO_2 emissions considerably (69.1%). This can be explained by the economic gain of exporting electricity throughout the year by the panels, and the reduction of the consumption from the grid, which has its assumed associated emissions (grid not completely green, Table 1).

3.2. Absorption Chiller

As for the compression chiller a first calculation has been made with the complete assumed system.

Table 4. Results from absorption chiller system.

Fresnel Collector area [m^2]	Hot TES capacity [m^3]	Boiler capacity [kW]	Abs Chiller capacity [kW]	Chiller Tank Vol [m^3]	Deviation Cooling demand [%]	LCOE [€/MWh]	CO_2 emission coefficient [kg/MWh]
1000.00	50.00	647.00	485.00	30.00	-5.94	205.67	604.75

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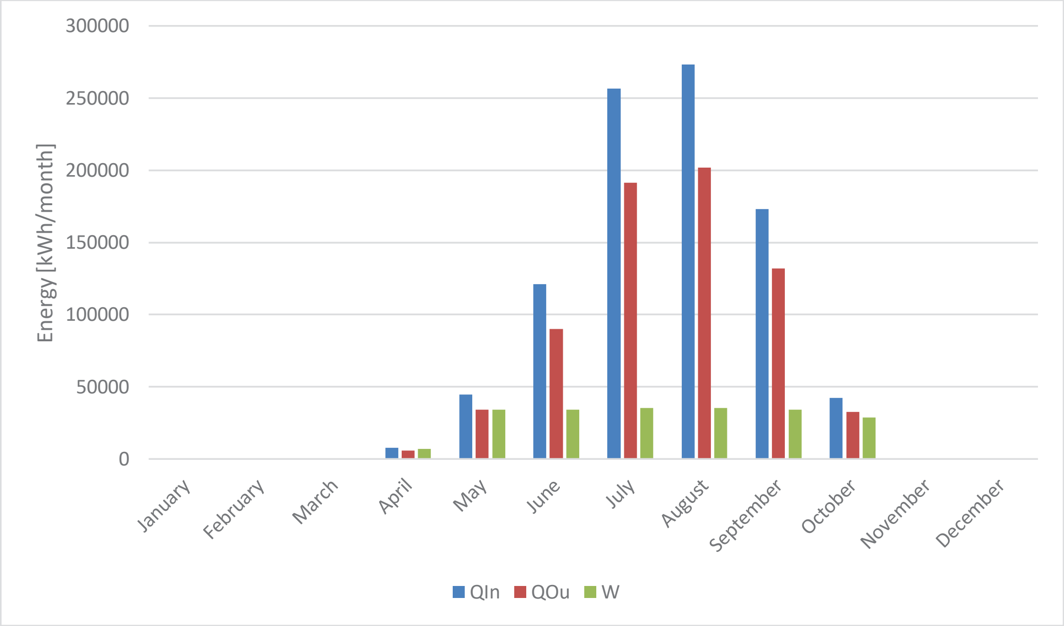

Figure 7. Absorption chiller energy flows [kWh/month].

From this first result we can see a gross difference from many different levels on the two principal KPIs compared:

To reduce the impact of the boiler production and its associated natural gas impact on the emissions we have assumed a scenario where this heat is provided by an existent net-zero emissions' source.

Table 5. Results from absorption chiller system reducing scope and emissions.

Fresnel Collector area [m^2]	Hot TES capacity [m^3]	Boiler capacity [kW]	Abs Chiller capacity [kW]	Chiller Tank Vol [m^3]	Deviation Cooling demand [%]	LCOE [€/MWh]	CO_2 emission coefficient [kg/MWh]
0.00	0.00	0.00	485.00	30	-5.94	122.51	181.00

The installation of the absorption chiller alone assumes a greater impact on the LCoE even without installing a full system to supply the heat. Given all these considerations further analysis seems inconsequential at this maturity stage of the technology.

The moment that this technology seems to flourish is when it works closer to its nominal operation point. It is interesting to compare the possibility of supplying a constant base value of cooling demand and see how this impacts the electrical consumption of both equipment.

3.3. Constant Case

A comparison of operations has been made for a constant demand equal to both equipment's nominal points. Considering that the energy supplied by the system to the absorption chiller still comes from an existent free net zero emissions source, while electrical consumptions have been taken into account.

Table 6. Results from absorption chiller with constant demand reducing scope and emissions.

Fresnel Collector area	Hot TES capacity [m^3]	Boiler capacity [kW]	Abs Chiller capacity [kW]	Chiller Tank Vol [m^3]	Deviation Cooling	LCOE [€/MWh]	CO_2 emission

[m^2]					demand [%]		coefficient [kg/MWh]
0.00	0.00	0.00	485.00	30	-11.17	35.49	57.03

Having considered nominal operation of the system and disregarded the price of installing solar Fresnel and the Boiler needed to supply the thermal demand (only considering electrical supply), absorption chiller shows a better cost and CO_2 emissions coefficient. But having made all these assumptions these results could be tied to too many considerations.

Table 7. Results from compression chiller constant demand, without PV panels.

TES capacity Chiller [m^3]	Comp. Chiller capacity [kW]	Deviation Cooling demand [%]	LCOE [€/MWh]	CO_2 emission coefficient [kg/MWh]
30.00	485.00	-4.05	86.70	129.84

On Table 7, it is visible that the electrical consumption of the chiller for this scenario yields a higher CO_2 emissions coefficient due to its electrical consumption throughout the year.

Table 8. Results from compression chiller constant demand, with PV panels.

PV capacity [kW]	Battery autonomy [kWh]	TES capacity Chiller [m^3]	Comp. Chiller capacity [kW]	Deviation Cooling demand [%]	LCOE [€/MWh]	CO_2 emission coefficient [kg/MWh]
165.00	495.00	30.00	485.00	-4.05	64.28	105.06

On Table 8, the improvement in LCoE found before due to the addition of PV panels in the variable case does not show the same impact, because panels do not generate the same amount of power throughout the year.

3.4. Discussion

From an economic standpoint, this system proves to be costlier for multiple reasons. Primarily, the implementation of absorption chillers is more financially burdensome when compared with compression chillers of equal capacity in terms of CAPEX (Figure 8). Additionally, since solar panels must be installed along with a natural gas boiler ensure diversity and generate heat input necessary for the absorption chiller's generator operation, these inputs punish severely, not only the LCoE due to these equipment CAPEX and operational expenditure (OPEX), but also, the CO2 emission coefficients linked to the production of said required heat input.

Although the absorption chiller operates efficiently during the peak months of July and August, utilizing only around 7% of its cooling capacity in electrical consumption, its lower coefficient of performance (0.75) compared to the compression counterpart (3) is significant enough to sway preference toward the compressor chiller option.

The aforementioned inclination is not upheld in situations where a consistent cooling necessity is obligatory for the system, as solar photovoltaic mechanisms do not yield an unchanging amount of electricity throughout every season (as shown in Figure 9). Therefore, absorption chillers show auspicious outcomes when considering that their energy supply originates from an already existent source.

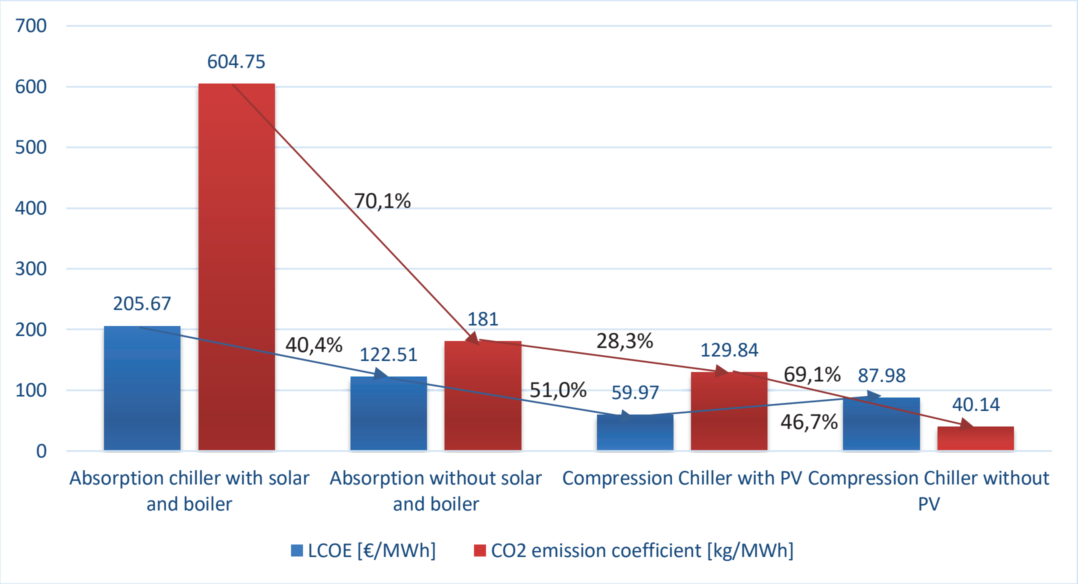

Figure 8. LCoE and CO2 emissions for variable demand cases and percentual evolution.

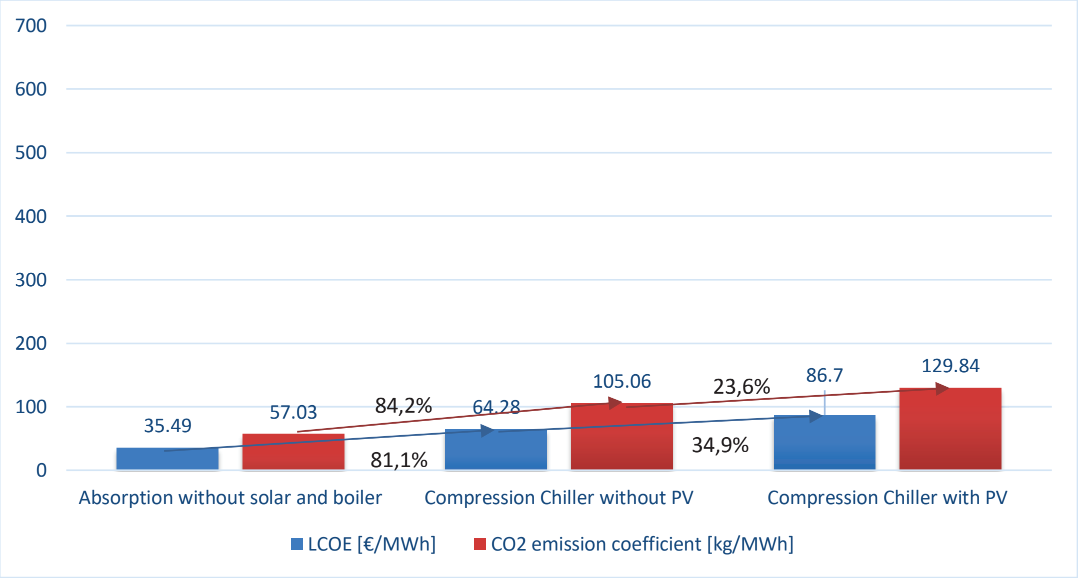

Figure 9. LCoE and CO2 emissions for constant demand cases and percentual evolution.

3. Conclusion

In terms of district cooling systems, the present circumstance limits options for technology selection. Presently, absorption chillers are viable if high-quality energy is anticipated to be wasted and their implementation can enhance system efficiency. However, when selecting a cooling system that will only supply a variable cooling demand, without any other interactions with other heating systems, the current technological state singles out the compression chiller as a more appropriate selection.

There is potential for utilizing the absorption chiller heat output as an energy source, considering that the outlet of the generator still can be rendered as a good energy source with temperatures around 85°C. This possibility presents itself as an intriguing subject of research from both financial and technical perspectives particularly when accounting for consistent cooling requirements such as those found in data centers.

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