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Optimal solar district cooling harvesting scenarios

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Abstract

In the Southern European countries solar thermal energy is harvested few moths per year as heating, thus, solar cooling is a suitable option to increase the yield of solar fields that supports tri-generation power plants. In this kind of facilities solar cooling integration is achieved with the use of absorption chillers and appropriated energy generation management strategies. These strategies depend on the resource availability, primary energy price and energy storage facilities.

Sizing these generation systems or planning modifications on existing ones, requires detailed studies and deep knowledge on the particular boundary conditions of the site and the possible scenarios that the power plant can be subjected at. In this work a comparison between solar system and CHP system is carried out for different repowering scenarios of an existing power plant. Different tilt angles are tried out in order to obtain the most cost-effective solution over useful life for a solar system which is size to harvest solar for cooling purposes.

Keywords: *Solar thermal, CHP, Cooling, District heating and cooling, Absorption, Optimization*

1. Introduction

Worldwide the energy panorama is rapidly changing; the appearance of renewable energies is gaining relevance in despite of conventional technologies based on fossil fuels. Nevertheless energy consumption is increasing in amount and in forms such as heating, cooling and electricity. This three forms of energy are considered the threefold of energy consumption in residential, public and commercial buildings (Sivak, 2009). Furthermore, in warm environments, the demand of cooling as form of energy is exponentially increasing, especially in developed countries where as the life standards improve the demand increases. In such places it is common to find heating demand for domestic hot water (DHW) coexisting with cooling demand for space cooling.

In warm environments solar thermal energy can be harvested few moths per year as heating, therefore solar cooling is a suitable option to increase the yield of solar fields as heating and cooling demands are complementary along the year. Such fields are usually connected to a hybrid generation plant to soften its generation variability and uncertainty.

In hybrid power plants, solar cooling integration is achieved with the use of absorption chillers, thus, enduring the power plant with poly generation. These hybrid poly generation power plants require an appropriated energy generation management strategies to maximize energy generation.

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Given a complex generation system, the plant manager bases management strategies on appropriated tools to support optimal decisions. Such tool shall include information regarding non-dispatchable thermal energy forecast, prices for primary energy and power plant efficiency on the different performance points.

Once the generation is sorted out, the demands can be aggregated and centralized by means of a distribution network, in those cases a District Heating and Cooling (DHC) network fulfils the transportation requirements of a centralized generation point supplying energy consumers located in various locations.

This paper present two repowering options and their possible working scenarios and it is organized as follows: next section provides an overview of the problem description. Section 3 describes the methodology used to approach the problem. Section 4 presents the result obtained and the conclusions from those are given in Section 5.

2. Problem description

The hybrid poly generation plant under study in this work is located in Majorca, Spain and constructed in 2000. The generated energy is provided to the Balearic Islands University and the Innovation centre of Balearic Islands "Parc Bit" through a DHC. The customers are the university facilities, including the student house and the sports centre and office buildings from the innovation park; in total the system provides heating and/or cooling to 25 different customers with different load profiles. The DHC network is detailed explained in (Perez-Mora et al., 2016b).

The actual cooling generation system comprises two absorption chillers of almost 2.0MW$_c$, two electric chillers summing 2.5MW$_c$, plus cooling towers and dry coolers for condensing purposes.

In the other hand, the heating generation system comprises an existing solar thermal installation with 864m^2 of solar collectors, two Combined Heat and Power (CHP) engines of 1360kW$_e$, biomass burner and a diesel burner as auxiliary summing 3.0MW$_t$. The system includes, as well, energy storages for heating and cooling; there are four tanks of 100m^3, two for cooling and two for heating. The system schematic can be seen in Fig. 1 and the generators figures and technologies can be seen in Tab. 1.

Currently the solar collector field generation is quite decreased due strong deterioration and the proper ageing of a 16 years old solar collector (Fan et al., 2009).

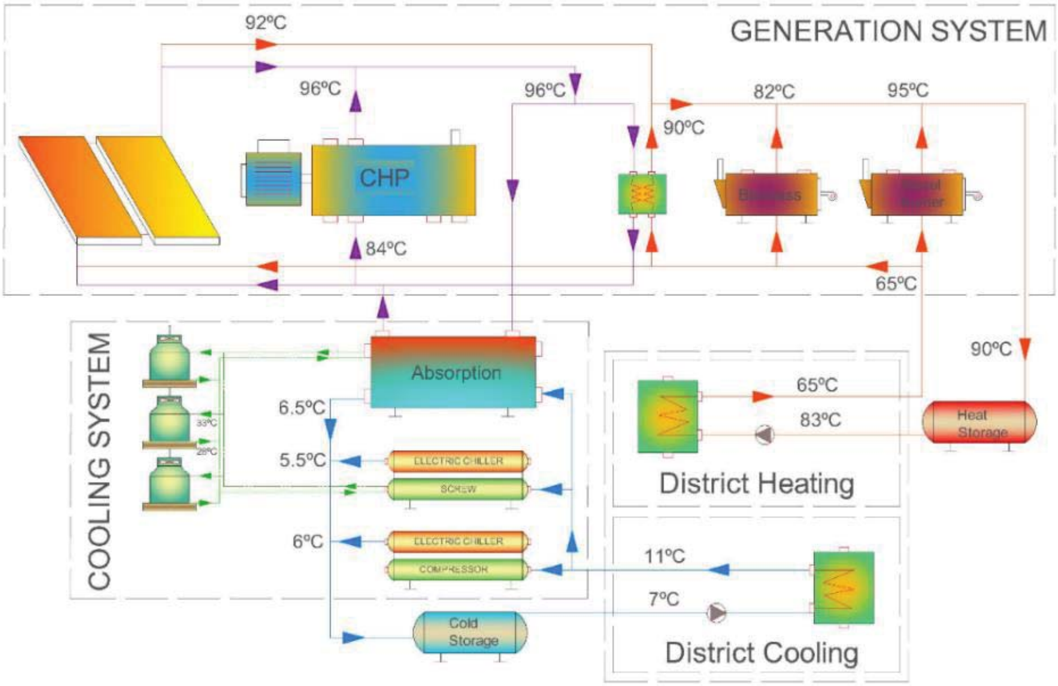

Fig. 1: Current energy generation system schematic.

Tab. 1: Current figures of installed generators at Parc Bit.

	Element	Technology	Installed Figure	Design parameters
Generation	IC Motor (2)	Diesel	2 x 1.36 MW_e	η_e=0.415; η_t=0.43
	Solar Collectors	Flat Plate	864m^2	η_0=0.76; a_1=3.5; a_2=0.002
	Biomass	Wood chip	1 MW_h	η_t=0.95
	Burner (2)	Diesel	1.2+0.8 MW_h	η_t=0.9
Cooling	Absorption (2)	Single. Li-Br	1.32 + 0.64 MW_c	η_c=0.6
	Electric Chiller	Compressor	1.2 MW_c	η_c=3.5
	Electric Chiller	Screw	1.3 MW_c	η_c=3.5
	Cooling Tower (3)	Open	3 x 4m^3	-
Storage	Heat Storage	Water	2 x 100 m^3	η_t=0.998
	Cold Storage	Water	2 x 100 m^3	η_t=0.999

2.1. Repowering scenarios

As mentioned before the hybrid poly generation power plant providing energy to the DHC was built more than 16 years ago and therefore its lifetime is coming to an end. This work studies possible scenarios that could be carried out in order to repower the existing power plant. In those scenarios only the main heating generator change is proposed, keeping the use of the auxiliary, cooling, storage and distribution systems. In the repowering scenarios the following assumptions are taken:

- Heating system is backed up by the existing auxiliary diesel boiler,
- Biomass burner, solar collector field and CHP engines are decommissioned,
- The existing installation can be used and only the generator has to be replaced,
- Only one technology is considered at once, either CHP or solar thermal system,
- Absorption and electric chillers are able to work at any load with a fixed COP,
- The cooling towers are sufficient to fulfil the condensing requirements at any time,
- Energy storages have a fixed heat loss expressed in stored energy by hour,
- The inertia of the DHC is not taken into consideration at simulation time step,
- The heating generation temperatures matches the absorption chiller requirements,
- Heating and cooling demands must be matched by all means,
- Energy demands are measured at generation point and not at customer location, therefore delay or inertia is not taken into consideration,
- Selling electricity price from CHP is equal to the market at the feed in hour,
- Purchasing electricity price for the power plant is equal to the market plus fees and taxes,
- There is not governmental incentive for green energy generation, neither electric nor thermal,
- Requested land area is considered as part of the existing power plant and there is not extra rent cost.

The proposed repowering thermal generation system is designed to harvest the required amount of energy requested by the absorption chillers during the summer simulation. Therefore it is dimensioned so its peck generation fulfils the requirements from the existing absorption chillers. This design aims to boost solar cooling as main supplier of the District Cooling (DC) and its power calculation explained in equation 1.

$$P_{sys} = \frac{P_{abs}}{COP} = \frac{2.0MW}{0.6} \approx 3.33MW \rightarrow 3.4MW \qquad \text{(eq. 1)}$$

2.2. Solar thermal system

The proposed solar thermal system is designed to harvest the required amount of energy during the summer simulation at the first year of installation, without taking into consideration any performance loss due ageing. Therefore the collector area and tilt are dimensioned so its peck generation fulfils the requirements set form the existing absorption chillers. To do so, the collector field present the following features and design data summarized as:

- Range of tilt angle used: 20º - 65º,
- Azimuth angle used: 0º South.
- Collector performance figures are η_0=0.816; a_1=2.418; a_2=0.085,
- Collector area installed depends on the tilt angle; installation land free of charge and available,
- IAM = 1, albedo = 0.2,
- Mean temperature inside collector is 75ºC, as return from the DH or absorption can be considered 60ºC and flow to either of the options is fixed in 90ºC,
- Peak generation in summer week = 3400 kW,
- Operation and Maintenance (O&M) cost is fixed in 1€/MWh generated,
- Approximated cost of installation = 248€/m^2,(Bava et al., 2015)
- Useful life: 25 years.

Accordingly, solar generation can be used either directly for heating along the year for the customers in the District Heating (DH) or for cooling being converted with absorption chillers for the users in DC. In addition to the solar generation field, the existing heating and cooling storages are kept to improve solar performance. The heating storage being used as buffer, is able to provide a constant output temperature to the DH or the absorption chiller, meanwhile, the cooling storage helps increasing system reliability and improving cooling generation performance. Moreover, the solar generation is backed up by the diesel auxiliary boiler which provides the energy shortages that may occur during operation. In the same way, electric chillers back up cooling generation in case of shortage. In figure 2 the location for new solar collector field is shown, the total area of the addressed land is about 20.000m^2.

Solar generation forecast is required during the power plant daily optimization, to acquire such information generation forecast can be made by using historical data related with climatic information. The most relevant information can be extracted from irradiation and temperature at the power plant site and it is used to improve forecasting accuracy (Inman et al., 2013; Perez-Mora et al., 2015)(Perez-Mora et al., 2015).

Fig. 2: New solar system location.

2.3. CHP system

The proposed diesel CHP system is, as well, designed to harvest the absorption chiller requested heating energy during the summer simulation. Therefore the heat to be recovered fulfils the requirements set form the existing absorption chillers. The CHP system is designed with generation flexibility by adding two engines of half of the required power instead of a single unit. The CHP system present the following features and design data summarized as:

- 2 CHP diesel engines of 1700kW$_t$,
- CHP performance figures are η_e=0.45; η_t=0.45,
- Installation site and pipework already existing and free of charge,
- Flue smokes recovered at a heat exchanger which output temperature is 90ºC,
- High temperature circuit heat recuperation output temperature is 90ºC,
- Nominal heating generation = 3400 kW$_t$,
- Nominal electricity generation = 3400 kW$_e$,
- O&M cost is fixed in 20€/MWh$_e$ generated, overall maintenance included,
- CHP electricity price equal to the wholesale market,
- Approximated cost of installation = 265€/kW$_t$,
- O&M stops not included on the simulation. Motor availability = 100%,
- Useful life: 25 years, including overall,
- Capital cost of installation turnkey = 900.000€.

In the same way as in solar, the heating generation can be used in both DH directly or in DC once is converted by the absorption chillers. In addition to the CHP system, the existing heating and cooling storages are kept to improve power plant performance. Moreover, the diesel boiler and electric chillers as kept as auxiliary systems in case of power shortage.

In this case the fuel price uncertainty impacts harder than in the previous case since is the only and main energy source for heating generation at the power plant. This system is tied, as well, to the wholesale energy price which variations affect in two ways to the generation; positively when selling electricity from the CHP and negatively when generating cooling with the electric chillers.

2.4. Proposed scenarios

In order to study several cases where the two proposed systems can be compared and evaluated the scenarios are created by the variation of selected figures. The following ranges and variables are modified:

- Tilt angle and collector area. The tilt is ranged from 20º to 65º in 5º step. The area is calculated so the peak power in the summer week is equal to 3400kW$_t$.
- Fuel price, the variability of the Brent crude oil price impacts strongly on CHP generation, moreover when the auxiliary system is fed with diesel as well.
  The purchase diesel prices used range from 0.3€/l to 1.0€/l with a 0.1€/l step; such values depend on Brent crude oil price and national taxes. As an example, for a given Brent price of 50$ the price per litre is 0.4€/l and 150$ correspond to 1.0€/l. These variations bring a huge uncertainty for the power plant manager and energy consumers.
- Wholesale price, OMIE, hourly values of electric energy price. The average price of OMIE has been increasing rapidly in the past decade. The values vary hourly and there are great price differences among seasons, even though the daily trend is similar. The values for the selected weeks are shown in figure 3. To create new scenarios the shape of curve and trend are kept the same and the hourly figures are increased by a percentage. The value of increasing percentages range from 0% to 50% increase with a 5% step.

To compare the different scenarios four weeks, considered standard demand wise, are selected. Such weeks are considered representative for the whole year, and thus, its demand is used as annual demand once is multiplied by an annual conversion factor. Figure 3 shows wholesale energy price, heating and cooling demand on the selected weeks. In table 2 the energy loads for the different weeks are shown.

Tab. 2: Heating and cooling demands in the DHC

Week	Dates	Heating	Cooling
Winter	19/1/15 – 25/1/15	219.68MWh	3.50 MWh
Spring	20/4/15 – 26/4/15	76.70 MWh	10.66 MWh
Summer	20/7/15 – 26/4/15	8.15 MWh	142.53 MWh
Autumn	19/10/15 – 25/10/15	39.23 MWh	33.76 MWh
TOTAL	Annual	4481 MWh	2483 MWh

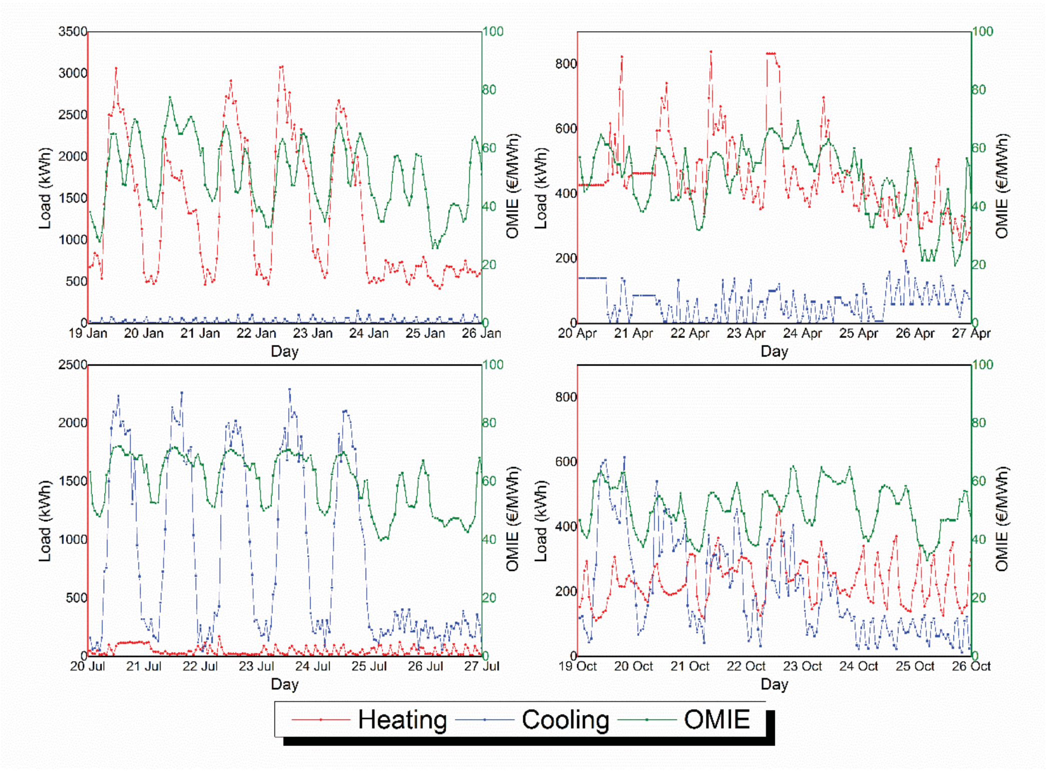

Fig. 3: Typical week loads and OMIE price.

3. Methodology

The methodology followed to compare the different scenarios and systems is explained in this section.
To study the proposed scenarios it is necessary to develop an optimization tool to find the best fitting between generation and demand. Besides the detailed generation knowledge of the power plant, to achieve a proper energy curve fitting, an accurate estimation of the solar thermal generation, cooling energy demand and wholesale price of electricity is required; in this work, to run simulations of scenarios, historical values are used from the year 2015.

Creating a plant simulator to include such information into the model attempts to improve the generation strategies by reducing expenses and maximizing revenues. Once this model is operational and includes the requested information, a decision maker tool, based on Mixed Integer Linear Programming (MILP) (Carpaneto et al., 2015), is used. This tool supports the plant manager decision process while aiming to optimize heating and cooling energy generation.

In this work a tool is proposed to optimize the generation of a hybrid poly generation plant. The tool, XEMS13, has been developed in the Energy Department of Politecnico di Torino (Italy) and some parts have been developed in collaboration with the company Sampol Ingenieria y Obras (Spain). The tool is extensively explained on (Perez-Mora et al., 2016a).

The optimization tool is used to set new scenarios and configurations for heating and cooling generation and to seek optimal demand matching. The savings coming from primary energy consumptions are compared with the investment cost of such system modification during its lifetime to determine the suitability of the investment. In particular, four relevant weeks are selected, one for each season of the year. These four weeks represent the whole year in terms of demand diversity, and therefore, the economic results calculated in the simulations can be extrapolated to a whole year.

In a first instance, different tilt angles are used to create different solar generation scenarios. The tilt angle ranges from 20º to 65º, covering from summer to winter solar generation optimization. Once those scenarios are set with different angles and a range of fuel and wholesale energy prices, the best tilt angle is selected for the purpose by looking to the economic expenses along the year.

Accordingly, to calculate the generation during the useful life of the solar system the annual generation is multiplied times the useful life, without taking into account the effects of ageing.

The better optimized solar system is then compared with the CHP system to calculate savings on O&M. Those savings are, afterwards, compared with the capital cost of both systems in order to find the scenarios where each system is more interesting. Such comparison brings then the conclusions for the different systems and its influences from scenarios.

To compare the results, Interest Rate of Return (IRR) of the system cost, fuel or primary energy price increases are not considered during the systems useful life. Energy price and fuel are modified to generate different scenarios, but they fixed along the useful life of the system.

4. Results

In this section the results obtained by the optimization tool, XEMS 13, are shown.
At first the solar generation calculated using the different tilt angles presented along with the calculated collector area for each scenario. Using the solar generation and DHC demand profiles, the power plant optimization is carried out to compare the influence of a field optimized for summer, winter or annual generation. From the studied options the one serving better the purpose of this work is selected.
The final economic results from the solar collector field is then compared with the results given by the CHP system and their investment costs.

4.1. Solar generation

The first obtained results are the solar generation depending on the tilt angle used. As mentioned before, the solar collector area is dimension so its peak generation on the summer week is equal to 3400kW$_t$. This procedure brings along a calculation of the required solar collector area for each tilt angle. Obviously, the collector area increases with the increase of tilt angle since the lower angles provide its maximum generation during summer. In figure 4 it is show as well the weekly generation of the proposed solar system for each tilt in MWh. The generation shown is by means of total collector installed area. This fact is the reason why the summer week generation is more or less steady comparing with the winter generation which increases rapidly with the increase of tilt.

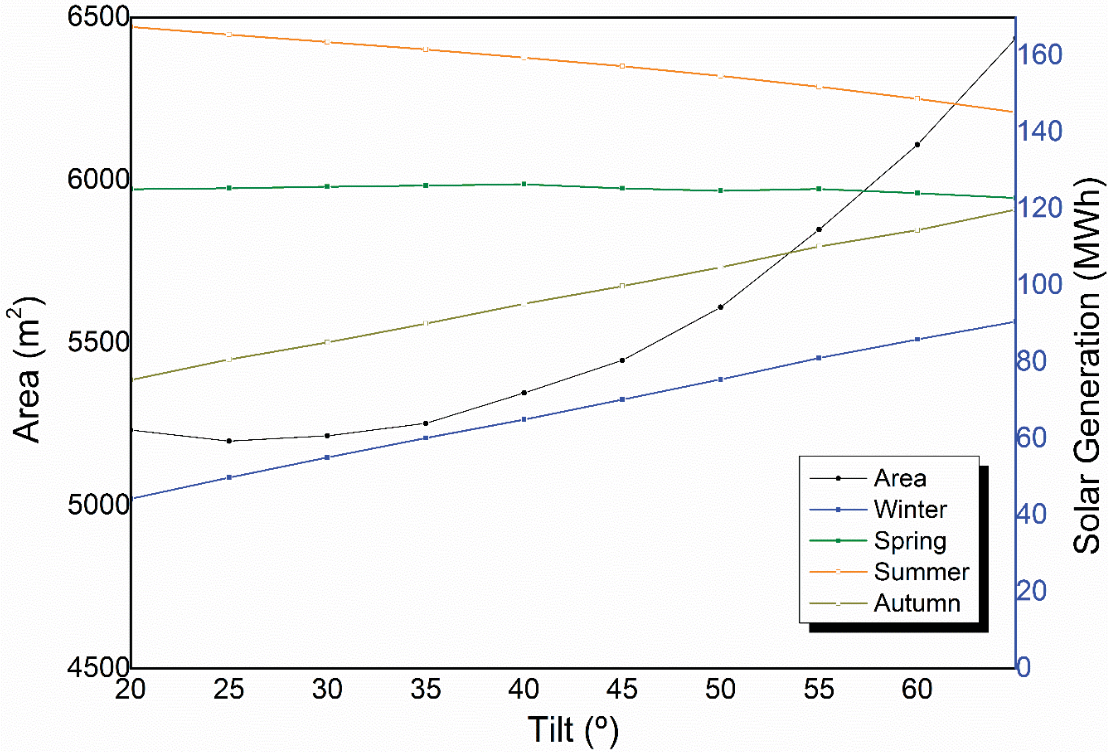

Fig. 4: Solar generation and collector area depending on tilt angle.

The largest solar collector area calculated for any tilt is 6436m^2, being the lower solar collector area equal to 5198m^2, both collector field sizes are able to fit in the proposed land. A larger solar collector area increases linearly the initial investment on the system.

4.2. Solar optimization

Once the solar generation is calculated for the different tilts, the system optimization is carried out. In this optimization the whole system is simulated, including cooling, auxiliary systems and storages. As result, the economic cost of running the plant is given, this result is influenced by the different scenarios proposed in which wholesale energy market and fuel prices are modified.

From those simulations the results show the generation cost for the selected four weeks as a 3D map, as could be obvious, the higher the fuel and energy price is the higher the operation of the power plant becomes. In figure 5 the O&M cost for the selected four weeks on the ten proposed cases are shown and it is possible see how the O&M cost varies in the different scenarios. The figure shows as well how the variation of fuel and wholesale price affects in the same way to all the scenarios, and thus, the result maps are parallel surfaces. The result surfaces of the different scenarios decrease their generation cost with the increase of solar tilt angle, being the most expensive O&M for a 20º tilt angle and the cheapest for 65º tilt angle. It is possible notice than the fuel price increase has a stronger impact in the final power plant operation cost than the wholesale energy price increase.

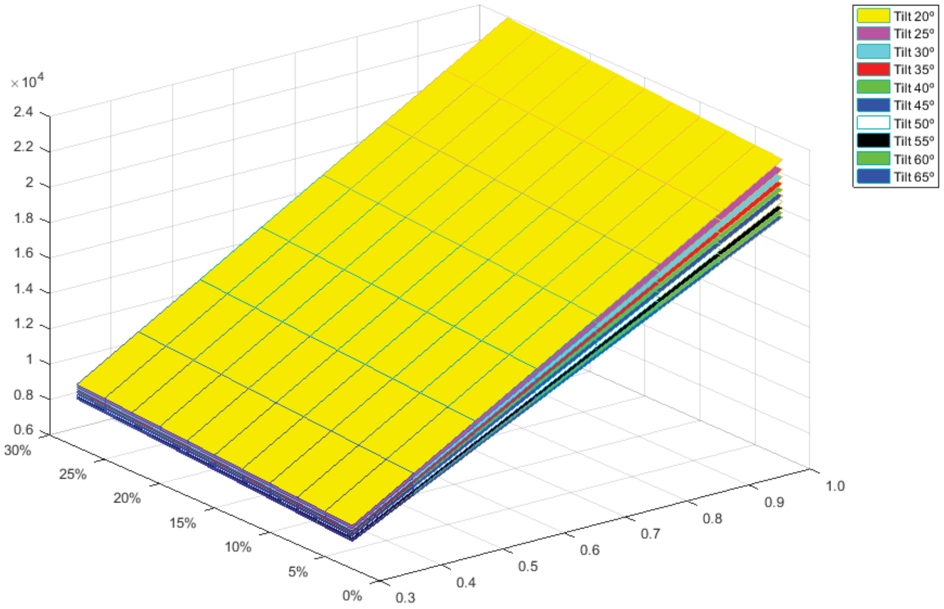

Fig. 5: Solar system tilts generation cost.

The cost for power plant operation is calculated as the sum of solar O&M cost plus the O&M cost of auxiliary systems at the power plant and is shown in figure 6. Solar O&M is fixed in 1€/MWh$_t$ generated at the collector field. The scenario selected to show the power plant generation cost in figure 6 is the one corresponding with the situation nowadays, the figures for the wholesale market correspond to the 0% price increase and the cost per litre of fuel is 0.4€/l. Nevertheless, this value does not influence how the final result looks like, as has been shown the generation cost are parallel surfaces for the different tilt angles, therefore, the only significant variable is the tilt angle. In the figure 6 is shown how the increase of annual solar generation increases, and thus, the solar O&M cost with the increasing tilt angle; this is due the increase of solar collector area. In the other hand, the operation cost decreases with increasing tilt angle, this is due the increase of annual solar yield. Figure 6 also shows the final cost of the solar collector field repowering plus the O&M cost of the whole power plant, including solar field, calculated for a useful life of 25 years and excluding ageing impact. The cheapest solution taking into consideration generation cost and initial investment is given for a tilt angle of 45º. In this scenario the solar annual yield is 5449MWh which represents a solar fraction of 63.22% of the total heating and cooling demand. The total installed area of solar collectors is equal to 5446m^2 which corresponds to a investment cost of 1.352.000€.

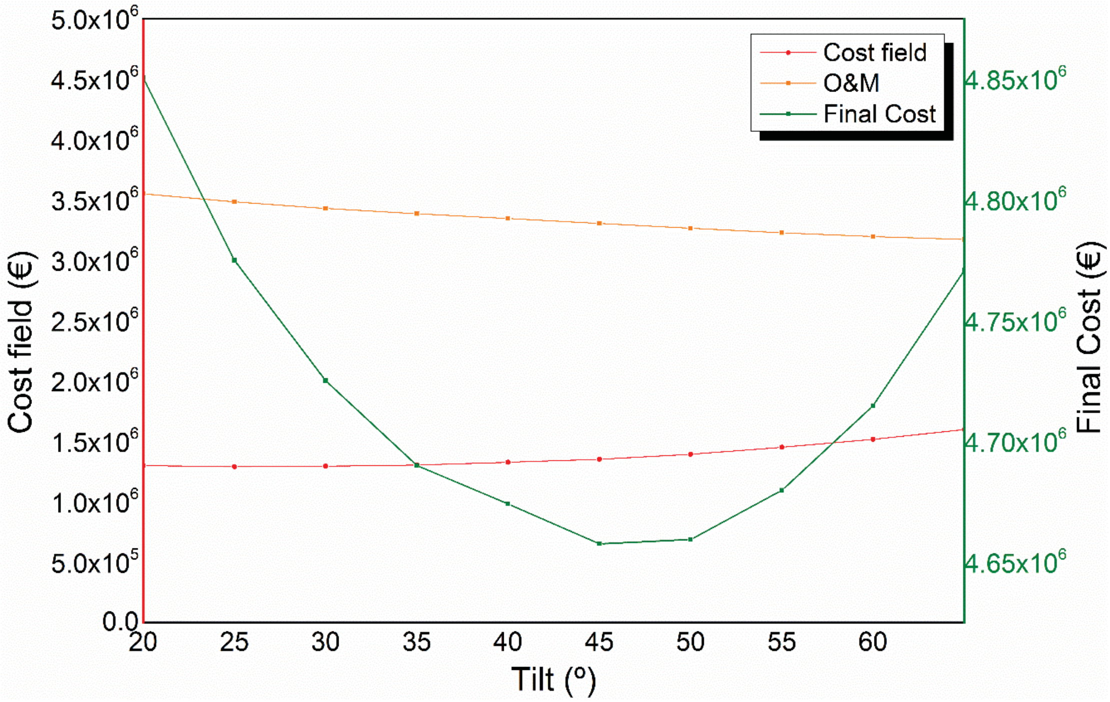

Fig. 6: Solar system total cost over useful life.

4.3. Repowering scenarios comparison

At last, the two proposed system are compared in this section. As shown in the previous section the tilt angle case which provides the most cost effective solution is 45º, therefore, this scenario is compared against the CHP scenario. To do so, systems operation costs through their useful life plus the capital cost of purchasing the systems are compared. For both systems the assumed useful life is 25 years.

In figure 7A, is shown the O&M cost over a year of the CHP system (O&M$_{CHP}$), in the proposed scenarios and in figure 7B, the O&M cost over a year for the solar system are shown (O&M$_{sol}$). In figure 7A it is possible notice that for some scenarios the cost of O&M in the CHP is negative, this means that it is profitable to run the CHP even when the thermal energy is not used. Those scenarios occur when the fuel is very cheap and the wholesale energy market price, OMIE, is very high, as happens for instance when the CHP generation is subsidized by electric generation.

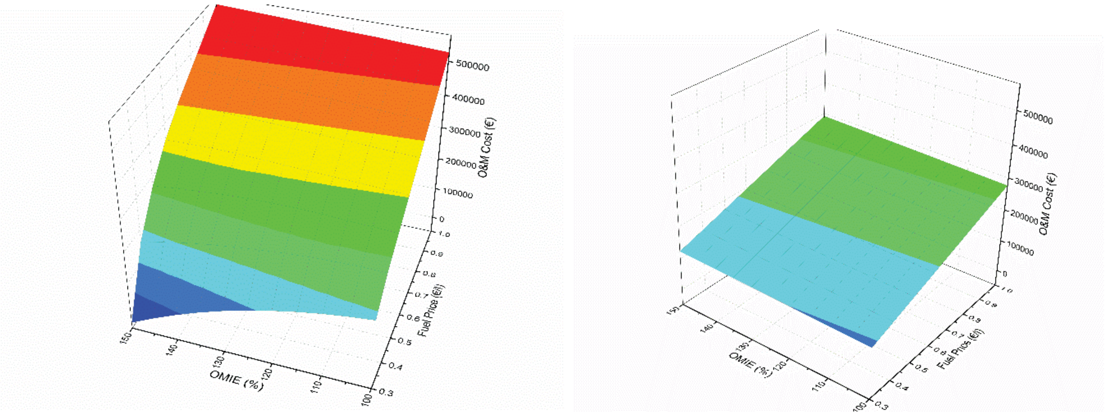

Fig. 7: O&M cost over a year for different scenarios for A) CHP system and B) Solar system.

In figure 8 the final cost of the systems over their useful life are compared, the calculation is done according to equation 2. The result given by equation 2 is positive for any scenario where it is more profitable to install a CHP system instead of a solar system. The useful life for both systems is fixed in 25 years. Figure 8 shows how most of the scenarios give negative values, this means that the solar generation system is more profitable than the CHP scenarios. The purple line is used as break-even point to separate scenarios where it is better to install a CHP system or solar system. The scenarios when is better to install a CHP system have, at least, a minimum increase of electricity price of 20% and the maximum fuel cost of 0.4€/l.

$$Result_{sys} = \left(C_{sol} + \sum_{n=1}^{25} O\&M_{sol_n} \right) - \left(C_{CHP} + \sum_{n=1}^{25} O\&M_{CHP_n} \right) \qquad \text{(eq. 2)}$$

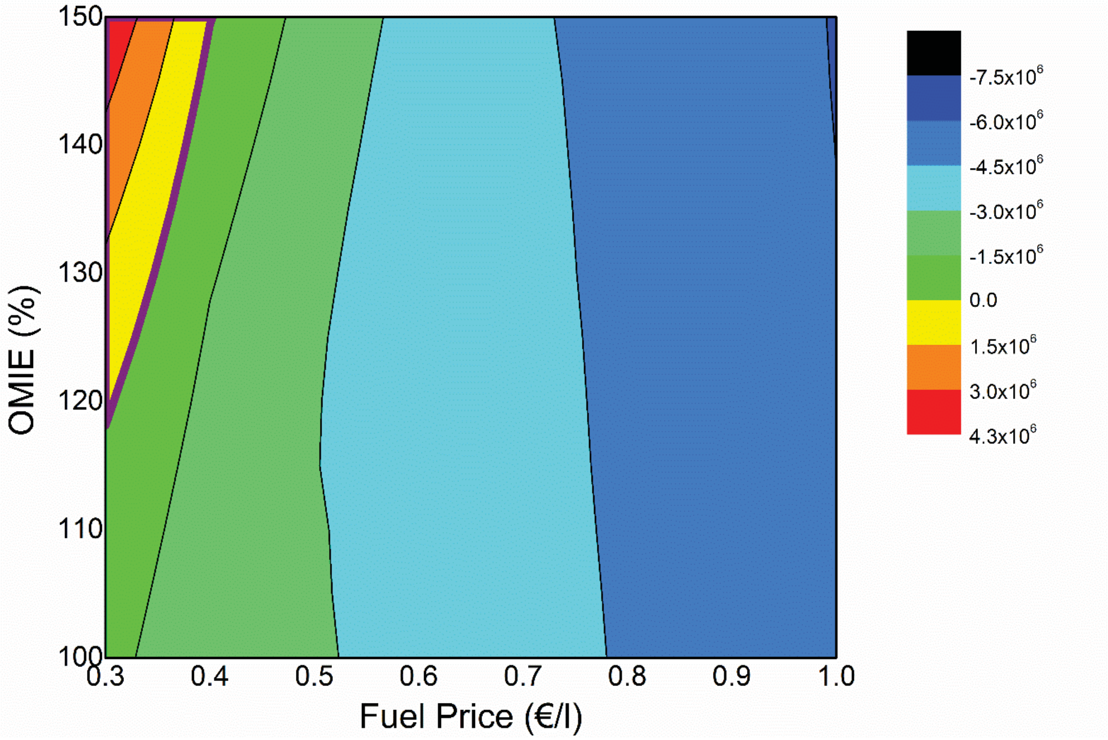

Fig. 8: Total cost comparison over useful life.

5. Conclusions

In the present work a comparison between different repowering scenarios for an existing power plant has been carried out. The different scenarios include solar system configurations and a CHP system. The comparison is made with help of an energy optimizer, XEMS13, by means of generation cost of the whole system.

The first step taken is to select the optimum tilt angle of the solar collector field, to do so, the system is optimized using four typical weeks. The best performing tilt angle, in annual minimum generation cost, is 45º, followed closely by 50º, therefore, it can be concluded than, for the given demands in this case, the system is more economic when it is annually optimized. Even if the power is dimensioned to fulfil cooling requirements in summer, the presence of storage motivates the annual optimization over the summer optimization. The large collector area required to fulfil cooling requirement when the system is winter optimized makes it very expensive comparing with the other optimization cases.

In solar system calculation over its useful life, ageing is not taken into consideration as it is very difficult to estimate the real efficiency drop on the collectors and how it will affect the system performance. In the same way, the cost of land renting for the new solar collector field is not accounted in the calculations as it is considered part of the existing power plant land. If those two factors are taken into consideration the

comparison with CHP system shown in figure 8 would present more scenarios where the CHP system overrules the installation of a solar collector field.
Nevertheless, figure 8 shows how most of the scenarios suggest the installation of a solar collector field against a CHP system. This is mainly due a high O&M cost for the CHP system which represent almost twice the cost of the solar system O&M, the relation can be seen in figure 7, and the fact that the solar system cost, 1.352.000€ is greater than the CHP system, 900.000€, but the difference pays of along its useful life.
The cost of energy, regardless if heating or cooling in a mix like the given on this DHC, on a scenario as the current one where the cost of the fuel can be considered 0.4€/l and the wholesale price is taken from year 2015, is for the solar system 19.52€/MWh and for CHP system 32.19€/MWh. These values evidence that currently and with no subsidies were taken into account, it is better to repower the power plant with the installation of a solar system over a CHP system.

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References

Bava, F., Furbo, S., Perers, B., 2015. Simulation of a Solar Collector Array Consisting of two Types of Solar Collectors, with and Without Convection Barrier. Energy Procedia 70, 4–12. doi:10.1016/j.egypro.2015.02.091

Carpaneto, E., Lazzeroni, P., Repetto, M., 2015. Optimal integration of solar energy in a district heating network. Renew. Energy 75, 714–721. doi:http://dx.doi.org/10.1016/j.renene.2014.10.055

Fan, J., Chen, Z., Furbo, S., Perers, B., Karlsson, B., 2009. Efficiency and lifetime of solar collectors for solar heating plants. Proc. ISES Sol. World Congr. 2009 Renew. Energy Shap. Our Futur. 331–340.

Inman, R.H., Pedro, H.T.C., Coimbra, C.F.M., 2013. Solar Forecasting Methods for Renewable Energy Integration. Prog. Energy Combust. Sci. 39, 535–576. doi:10.1016/j.pecs.2013.06.002

Perez-Mora, N., Canals, V., Martínez-Moll, V., 2015. Short-Term Spanish Aggregated Solar Energy Forecast, in: Advances in Computational Intelligence. Springer-Verlag Berlin Heidelberg 2011, Palma de Mallorca, pp. 307–319. doi:10.1007/978-3-319-19222-2_26

Perez-Mora, N., Lazzeroni, P., Repetto, M., 2016a. XEMS13 : An Hybrid-Energy Generation Management System. IEEE eXpress 6.

Perez-Mora, N., Martinez-Moll, V., Canals, V., 2016b. DHC Load Management Using Demand Forecast. Energy Procedia 91, 557–566. doi:10.1016/j.egypro.2016.06.198

Sivak, M., 2009. Potential energy demand for cooling in the 50 largest metropolitan areas of the world: Implications for developing countries. Energy Policy 37, 1382–1384. doi:10.1016/j.enpol.2008.11.031