Energy 153 (2018) 311–323

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Technical and economic feasibility of sustainable heating and cooling supply options in southern European municipalities-A case study for Matosinhos, Portugal

Eftim Popovski [a, *], Tobias Fleiter [a], Hugo Santos [b], Vitor Leal [b], Eduardo Oliveira Fernandes [b]

[a] Fraunhofer Institute for Systems and Innovation Research, Breslauer Str. 48, 76139, Karlsruhe, Germany
[b] Institute of Science and Innovation in Mechanical and Industrial Engineering, Rua Dr. Roberto Frias, 400, 4200-465, Porto, Portugal

ARTICLE INFO

Article history:
Available online 9 April 2018

Keywords:
District heating and cooling
Excess heat utilization
Individual heating and cooling
CO_2 emission reduction
Heat pumps
Sustainable cities
energyPRO
Energy planning
Heat supply

ABSTRACT

Energy demand for heating and cooling constitutes almost 50% of the total energy demand in Europe and strongly depends on fossil fuels. Decarbonising this sector and providing a sustainable supply should be a main goal of climate policy. The technical and economic feasibility of supply options depends strongly on local conditions. The focus of this research is to assess the cost-effectiveness of sustainable heat and cold supply solutions under southern European conditions. We use the city of Matosinhos (Portugal) as an example. The methodology includes estimation of thermal demands and hourly simulation of alternative supply scenarios.

The results show that, from a socio-economic perspective, the use of excess heat from a refinery via a DHC network might be the economically most competitive option. In addition, the heat pump system combined with photovoltaics is cost-effective from a socio-economic perspective compared to the status quo if the capital costs of the status quo are also accounted for. This justifies support policies to also make it cost-competitive from a private economic perspective, which it currently is not. Sensitivity analyses were conducted for the most influential factors like capital investment costs, interest rate, and fuel prices.

1. Introduction

Accounting for about 50% of final energy consumption, heating and cooling represents the biggest energy use sector in the EU [1], which is still dominated by fossil fuel use and responsible for a major share of EU GHG emissions. For these reasons, the European Commission drafted the EU Heating and Cooling Strategy [2] in February 2016. This strategy represents the first EU initiative addressing the demand and supply for heating and cooling in buildings and industry in an integrated framework.

The decisions about heating and cooling investments and infrastructure are, however, mostly local in nature because they are taken by municipalities, utilities and private investors. The potentials and costs of using RES vary heavily across regions in Europe and are determined by local conditions. EU strategies need to take these diverse local particularities into account. While there have been many city-level assessments of heating and cooling supply options in northern European countries and Scandinavian countries in particular [3–5], so far, there has been less focus on southern European countries. Many municipalities and regions in southern Europe have important characteristics in common: They often do not have a district heating/cooling infrastructure, and space cooling is much more important than in northern European countries [1]. At the same time, solar irradiation in the South is higher, making solar-based solutions more cost-effective. In this paper, we assess heating and cooling supply options for the city of Matosinhos in Portugal. We focus on replacing the existing natural gas boilers with heat pumps, a solution with and without PV, and the construction of a new district heating and cooling network.

DHC is widely recognised as an important element in any future smart and sustainable energy system [6–9] able to balance fluctuating RES electricity generation with power-to-heat solutions and exploit the large volumes of industrial excess heat for heating and

* Corresponding author.
E-mail address: eftim.popovski@isi.fraunhofer.de (E. Popovski).

https://doi.org/10.1016/j.energy.2018.04.036
0360-5442/

Abbreviations

CAPEX	Capital expenditure
CC	Compression chiller
DHC	District heating and cooling
FED	Final energy demand
GHG	Greenhouse gas
H&C	Heating and cooling
HP	Heat pump
LCOC	Levelized cost of cooling
LCOH	Levelized cost of heat
LCOE	Levelized costs of electricity
O&M	Operation and maintenance
PV	Photovoltaics
RES	Renewable energy source
RES-H&C	Renewable energy source for heating and cooling
RFO	Residual fuel oil
4GDH	4th Generation district heating

cooling purposes [10,11] which have often been overlooked in energy planning models. Feasibility studies about the potential of utilizing excess heat in district heating networks indicate that 46% of the total excess heat in EU27 corresponds to 31% of the total building heat demand [12], with the chemical industry and refineries having one of the highest excess heat/fuel use proportion of up to 24% [13]. The construction of an efficient 4GDHC can, in principle, provide multiple benefits for municipalities. Several DHC networks are already in operation in cities like Barcelona, Paris, Stockholm, etc. [14,15]. However, in Portugal, there is only one network currently in operation in Lisbon [16]. A similar DHC network could be built in Matosinhos to supply the heating, hot water and cooling demand of nearby residential and commercial buildings.

Furthermore, the DHC network could also be supplied by a broad range of renewable and recycled energies, thus extending the benefits of such a solution. In the case of Matosinhos, the interesting opportunity explored in this research is to use the excess heat from the local refinery. Refineries are well suited to supplying district heating networks, because they provide a relatively continuous stream of excess heat. The high shares of refineries' excess heat in even large district heating grids show the huge capacity available [17–20]. This solution has the potential to not only increase the efficiency of the refinery, but also to provide a sustainable heating and cooling supply for the local community by using heat that would otherwise be wasted.

The aim of this paper is to assess the technical and economic feasibility of sustainable heat supply technologies in order to reduce the CO_2 emissions from heating and cooling. To capture the local circumstances, we conduct a case study for the city of Matosinhos in Portugal. Sustainable heat supply options are assessed including a DHC network supplied by industrial excess heat, and heat pumps in combination with PV. These supply options are compared to the system in operation today (natural gas boilers and compression chillers).

The methodology is based on hourly simulation of heat supply and includes estimations of heat demands, resource potentials and techno-economic technology data. Finally, a sensitivity analysis is conducted to assess the impact of changes in interest rates, investment costs, and fuel costs.

This paper is structured into seven parts: the introduction (1), the description of the status quo of energy demand in the analysed area (2), methodology and input data used for the analyses (3), results from both a private and a socio-economic perspective (4), sensitivity analyses (5), discussion (6), and conclusion (7).

2. Matosinhos case study and modelled area

The city of Matosinhos, Portugal was analysed in detail in order to explore the current challenges of deploying a higher share of RES-H&C. Matosinhos is in the northern part of Portugal, situated directly on the Atlantic coast, north of Porto (Portugal's second largest city), and covers an area of approximately 62 km^2. In 2009, primary energy use in Matosinhos was just over 5.2 TWh/y, of which 4.6 TWh were of fossil origin. Only 14% of the primary energy resources were used directly, mainly in the form of natural gas, while the remaining 86% of primary energy were converted into electricity (34%) and petrochemical fuels (52%). Primary energy use per inhabitant was 31 MWh/y in Matosinhos, somewhat higher than Portugal's average of about 24 MWh/y. Approximately 34% of the electricity came from renewable sources. Fig. 1 presents the primary energy use and final energy demand in 2009. From a demand perspective, buildings were responsible for 37% of final energy use (20% residential, 17% commercial buildings), while the transportation sector used 32% and industry 27% of the final energy. In total, 4.3 TWh final energy were used in the city.

Fig. 2 shows a map of the area analysed. It currently comprises about 69 buildings but has the potential for gradual expansion. 63 of the 69 buildings are part of a large new development area (called Norte Center). Building types range from office to commercial and residential spaces, including a hotel and a conference center. While the Norte Center represents a large majority of the number of buildings, it corresponds to only about 58% of the total built area (about 240 000 m^2). The other 6 are large commercial buildings constructed nearby over the last 9 years. Four of these are large stores (Decathlon – sports goods, Conforama – household furniture and appliances, Leroy Merlin – DIY and gardening supplies; and IKEA –furniture). In addition, Mar Shopping is a fairly large mall (physically connected to the IKEA store), and the Exponor, one of the largest exhibition centres in Portugal. Altogether, these 6 buildings encompass about 175 000 m^2 of the built area. There is also a recently built logistics center nearby which might present significant cooling demand in the future and be relevant from the perspective of grid expansion, but was not included in this exercise.

3. Methodology and data

The methodology used in this research contains five main steps.

1. The thermal demand is estimated in order to establish an hourly demand profile for heating, cooling, and hot water for each building type for the year 2015.
2. Resource potentials are estimated like the available excess heat and rooftop area for PV.
3. Definition of techno-economic parameters including performance and costs of technologies as well as energy and CO_2 price assumptions.
4. Definition of technology scenarios for the simulation analysis.
5. Simulation using the energy system model energyPRO,[1] which performs an hourly simulation of heat supply technology dispatch under the condition that demand is met at all times. Heat pump performance depends on temperature ranges. Results also include key economic indicators. The software is used for techno-economic analyses of energy projects and can

[1] The tool developed by EMD International is a commercial software for techno-economic analyses of energy projects. The tool only optimizes operation, not investments (www.emd.dk/energypro/).

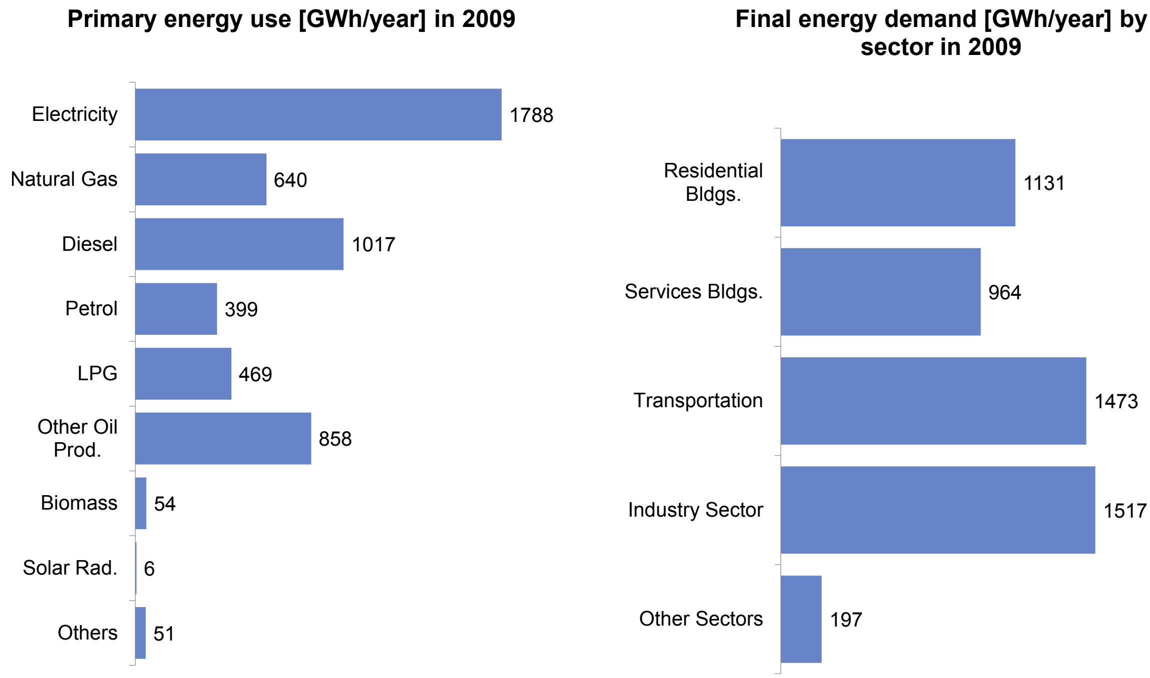

Fig. 1. Primary energy use and final energy demand in 2009 [21–24].

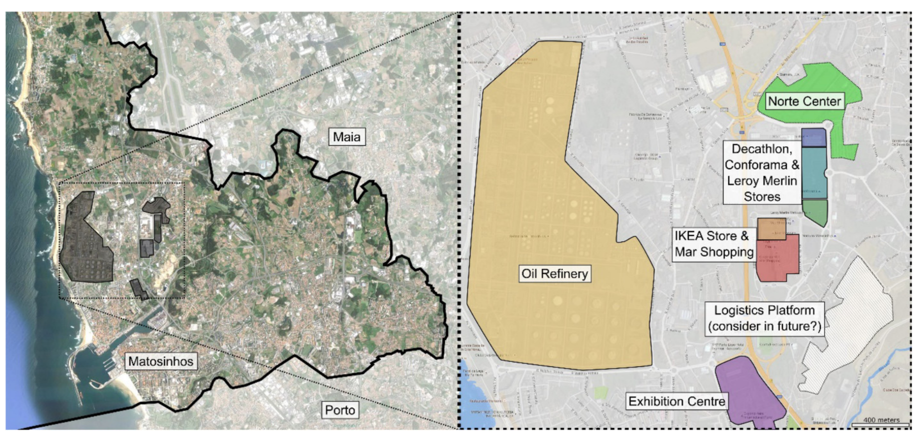

Fig. 2. Map of Matosinhos (left), surrounded by Porto to the south and Maia to the northeast, and a detailed view of the analysed area and buildings (right). (source: Google Maps).

conduct system optimization of supply dispatch based on different technical properties of units, investment costs, fuel costs, taxes and levies, fuel prices etc.

The individual steps and data used are described in the following sections.

3.1. Estimation of heating and cooling demands

The aim of estimating the thermal demand is to establish an hourly profile for a whole reference year for heating, cooling and hot water demand based on useful energy for each building, taking into account the floor area assigned to each use typology (commercial, office, residential or hotel). As it was not possible to collect data from the individual buildings, the H&C demand is estimated based on specific values from similar buildings in the Porto region as assessed in a previous study conducted by the Porto Energy Agency [25]. The process essentially went through the following steps:

1 Determine heating/cooling area for each of the 69 buildings by use/typology (as some buildings may have more than one type of use, e.g. a 10-story high-rise might have 10% of the heating/cooling area as stores/commercial uses – for instance, in the ground floor – and 90% residential in the remaining floors);
2 Define hourly heating/cooling/hot water demand profile for the coldest/hottest day in the year for each typology;
3 Determine the effective heat and cold demand for each typology and for the whole year considering the average daily external temperature and targeting known typical yearly energy demands;
4 Compile three complete demand profiles for heating, cooling and hot water demand per building for the whole year.

(1) For each of the 69 buildings considered in the case study, the first step was to find information about the floor area. There are detailed public documents available for the Norte Center complex, where all the areas including their typology are given (i.e. offices, residential, commercial, hotel). For the

remaining buildings, assuming that their total area is assigned to commercial use, Google Maps was used to measure the building's footprint (e.g. the Leroy Merlin store was estimated to cover approximately 12,000 m^2, which are assumed to be representative of the commercial area).

(2) The typical heating, cooling and hot water profiles per typology were adapted from a previous study [25] used to plan a potential district heating and cooling network to be built in Porto's city center. Among other typologies, that study determined the average heating, cooling and hot water energy densities (W/m^2) and the total yearly thermal energy demand ($kWh/m^2.y$) for each of the four building typologies relevant to this report (offices, commerce, residential and hotels). These results were obtained via an assortment of benchmarking exercises for a large number of buildings in Porto [25] including direct measurements, bill estimates, dynamic building modelling, etc. Furthermore, demand profiles were also determined for hourly heating and cooling demand as a percentage of the maximum power available for the 24 h of the coldest and hottest days of the year, respectively.

(3) Average external daily temperatures were used to calculate the effective heat and cold demand per hour and per topology for a whole year. While this procedure does not guarantee complete accuracy, it enables an hourly breakdown of the data that would otherwise not be possible. However, the total yearly amounts do add up to those determined in step 2.

To accomplish this, two reference temperatures are particularly relevant: one establishes at which external temperature the systems are turned on, and the other establishes the temperature at which the equipment starts to be used at full capacity. In-between these two temperatures, the equipment power is modulated proportionally. The reference temperatures were then adjusted so that they offer realistic set points and yearly demands that are comparable to other similar buildings in the region.

As an example, heating systems in offices are turned off whenever the average outside daily temperature is higher than 15 °C. If the temperature dips below 10 °C (which corresponds to the daily average in the coldest month [26]), then the system is operated at full power regardless of the specific temperature. This means that, for each hour of that day, the hourly heat demand profile for offices for the coldest day is directly multiplied by the average power density (meaning that, at 9 a.m., the system is operating at full power, i.e. at 50 W/m^2). If the average daily outside temperature is 11 °C, then the heating power is only 4/5 of the maximum power. For hot water, it was assumed that demand remains constant throughout the year with no correlation between demand and outside temperature.

Having calculated the above, it only remains to multiply the reference hourly demand values by the floor area in each building considering its typology or mix of typologies. Fig. 3 illustrates the yearly H&C demand profile for one of the evaluated sites in 2015. It can be observed that the demand for cooling (air conditioning) compensates the low heating demand during the summer period, resulting in a more even energy demand over the year. A small amount of heating demand is still visible during the summer to meet the demand for hot water.

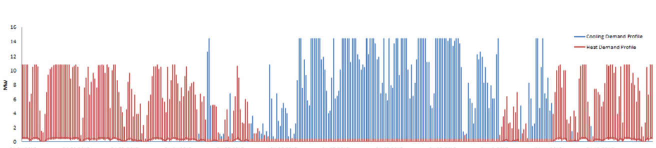

Fig. 3. Estimated heating, hot water, and cooling demand profile for the Norte Center, 2015.

3.2. Resource potentials: Estimation of available excess heat and rooftop area for photovoltaics

3.2.1. Available excess heat from the refinery

The heat recovery potentials are evaluated from Ref. [27] whereas the local refinery capacity is assessed based on the data provided from its website and the refinery's data book [28]. The fuels most consumed in the refinery are gas (as a mixture of fuel gas produced in the refinery enriched with natural gas), natural gas and, to a lesser extent, residual fuel oil (RFO), which is being progressively replaced. The total fuel gas consumption is around 179 000 tons and the RFO consumption is around 22 000 tons. This results in a total heat consumption for the year 2013 of around 2500 GWh. In this case, the economic potential (positive business case over 25 years at 10% discount rate) for heat recovery in the refinery is estimated to be about 8% [29] or 200 GWh/y. Utilizing excess heat sources above 90 °C results in a lower potential of about 77 GWh. This is sufficient to supply the total demand of the DHC network (~59 GWh) for the evaluated buildings, assuming supply temperatures of 80 °C and return of around 40 °C. In order to define the COP of the absorption chiller, the water temperature of 90 °C is used for the generator and 20 °C (sea water [30]) for the condenser cooling. Table 1 provides an overview of the excess heat potential of the individual heat sources with a temperature above 90 °C.

3.2.2. Available rooftop area for photovoltaics

For the scenario with the PV system (Scenario number 4), a yearly net metering is assumed. The main goal when designing the PV field was to produce the same amount of electricity that is consumed by the heat pump and the chiller unit on a yearly basis. Even though production and consumption do not match on an hourly or daily basis, it can be assumed that the rest of the electricity produced is consumed internally or fed into the electricity grid, where a net metering is applied. Although increasing numbers of PV installations using net metering will have substantial effects on electricity grids as argued in Chapter 6 and elaborated in Refs. [48,49], a more detailed analysis of this issue is not presented in this research. Fig. 4 shows the hourly PV production and electricity demand for H&C, whereas Fig. 5 illustrates the annual PV production and electricity consumption for heating and cooling at one site (Leroy Merlin Store). The high coincidence of heating and cooling demand with PV production is due to the above mentioned scaling of demand to outdoor temperature and is site and design-specific. It has to be noted that the daily energy peak of south-oriented PV designed to maximize energy production rarely coincidences with the peak electricity demand. Based on the observations and calculations presented in Table 2, it can be concluded that the area required for the PV units is available in principle. In addition to the area included in the Table, the parking areas could also be used for PV installations.

3.3. Techno-economic data

Techno-economic data comprise the efficiencies and prices of technologies, but also assumptions on energy prices and CO_2-intensities. In addition, the technical and economic parameters of the potential DHC grid are estimated.

Since the linear heat densities of the district heating and cooling grid are higher than 1.8 MWh/m*y, it can be assumed that the heat losses from the DHC network are around 10% [31]. Based on the literature research, the capital costs of the district heating network with an average diameter of 120 mm are around 615 EUR/m [32],

Table 1
Excess heat potential in refineries for heat sources above 90 °C based upon [29].

Process type	Unit operation	Heat source medium	Excess heat flow [kWh/boe]	Source temperature [°C]
Cracking	Fluid catalytic cracking	Gas	7.3	150
Cracking	Catalytic hydrocracking	Gas	14.3	150
Combination/rearrangement of hydrocarbons	Catalytic reforming	Gas	3.2	150
Distillation	Atmospheric distillation	Gas	3.3	150
Distillation	Vacum distillation	Gas	0.9	150
Coking	Delayed coking	Gas	2.7	150
Combination/rearrangement of hydrocarbons	Catalytic reforming	Water	12.6	90
Combination/rearrangement of hydrocarbons	Alkylation	Water	27.6	90
Total excess heat supply flow [kWh/boe]			**71.9**	
Total oil production in the year 2013 [boe]			**1,071,429**	
Total excess heat potential [GWh/a]			**77**	>90 °C

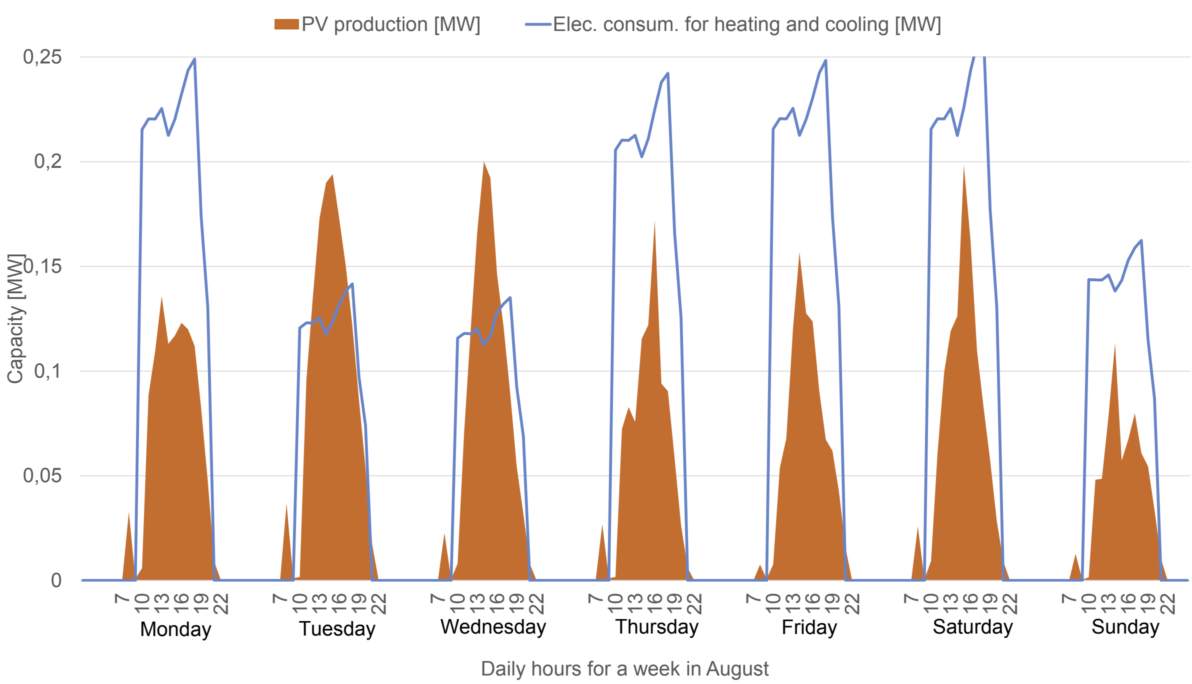

Fig. 4. Hourly (for a week in August) PV production and electricity consumption for heating and cooling (site: Leroy Merlin Store). Nominal power = 270 kW; Number of modules = 806; required area = 4700 m^2; roof area = 8350 m^2.

and the costs of the district cooling network are 1500 EUR/m (average diameter 500 mm) [33]. In order to provide a better estimation of the capital costs of the DHC network, a few locations were considered with the maximum trench length of 5 km. The trench length is a provisional one connecting three points between the refinery, Exponor exibition center, and Norte Center. The feasibility of the district heating and cooling network depends mainly on the linear heat density. Typically, it is not economical to install a DHC for densities lower than 1.2 MWh/m*y [31]. The density is calculated by dividing the total demand by the trench length. In this case, the density is 2.92 MWh/m*y for the heating network and 5.62 MWh/m*y for the cooling network. The total capital costs are calculated for an operating life of 30 years. The corresponding cost constant (average size-independent construction costs by trench length) and cost coefficient (directly proportional to the pipe diameter) are $C_1 = 214$ EUR/m and $C_2 = 1725$ EUR/m^2 for the outer city areas based upon a survey conducted in Ref. [34]. Additionally, 10 EUR/MWh are assumed as operating and maintenance costs for the DC network for heat supplied to the grid [35], whereas 20 EUR/MWh [36] are considered for the DH network. In Table 3 an overview of the district heating and cooling data is presented.

Table 4 shows the actual and forecasted energy prices for an average consumer in the commercial sector. Natural gas and electricity prices are assumed to increase, whereas a constant price of 15 EUR/MWh is expected as compensation to the refinery for the excess heat, based on other cases where excess heat from a refinery is consumed [17]. For the decentral PV LCOE, price projection costs from Ref. [37] were used for Portugal. Table 5 shows the specific CO_2 emission factor and the share of RES in electricity generation for 2015 and 2030, whereas Table 6 lists the technology assumptions such as specific investment costs, efficiency, lifetime, variable and fixed operation and maintenance costs.

3.4. Scenario definition and model simulation

The scenarios are distinguished by the heat and cold supply options. Techno-economic data are similar across all scenarios as defined above. Further, for all scenarios, it is assumed that the heat demand of buildings remains unchanged until 2030, i.e. building renovation measures were not considered. Nevertheless, it is expected that the renovation potential would be small anyway since all of the target buildings were built less than 10 years ago. Therefore, the focus of the analysis is on the supply side. Different

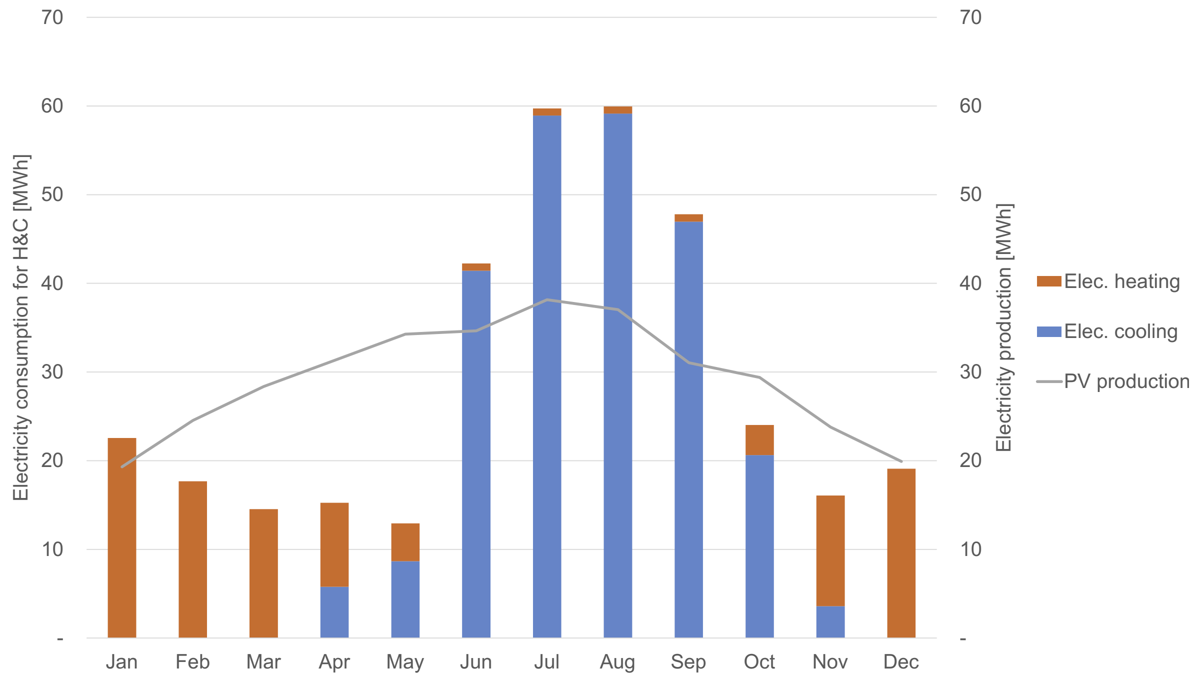

Fig. 5. Annual PV production and electricity consumption for heating and cooling (site: Leroy Merlin Store). Nominal power = 270 kW; Number of modules = 806; required area = 4700 m^2; Roof area = 8350 m^2.

Table 2
Photovoltaic and roof area allocation.

Location	Roof size[a] [m^2]	PV area[b] [m^2]	Useful area[c][m^2]	Difference [m^2]
Decathlon (with parking)	13 640	3650	9550	5900
Exponor	29 200	17 290	20 440	3150
IKEA	16 400	14 770	11 480	−3290
Mar Mall	35 000	24 590	24 500	−90
Parking of IKEA and Mar Mall	25 500		17 850	17 850
Leroy	8350	4700	5845	1145
Conforama[d]	8350	3860	5845	1985
Norte Center	240 000	86 000	168 000	82 000

[a] Based on Google maps.
[b] The PV area is 3 times larger than the PV unit area in order to avoid any shading effect.
[c] Useful area of 70% assuming the rest of the roof is either used by other equipment or is not available for architectural reasons.
[d] Conforama (same as Leroy-assumption).

Table 3
District heating and cooling data.

	Heat density [MWth/m]	Heat losses [%]	Average diameter [mm]	Cost const. [EUR/m]	Cost coeff. [EUR/m2]	O&M [EUR/MWh]
District heating	2.92	10	120	214	1725	20
District cooling	5.62	10	500	214	1725	10

supply options were modelled and simulated using energyPRO. The software optimizes the operation of the simulated systems to the defined preconditions such as weather data and technical properties of the technologies involved. Seven individual sites (as presented in Fig. 2) were modelled. The scenarios defined are described in the following. For the status quo scenario, we define two variants. One includes the capital costs of technologies, while the other does not. The actual gas boilers and compression chillers installed in the buildings are of different ages and, in some buildings (Norte center), they were not installed at the time of the study. Thus, the two status-quo scenarios provide a range for the real status quo costs. In Table 7 an overview of the modelled scenarios is presented.

Table 4
End-user average energy prices for 2016 and 2030 [EUR/MWh].

Energy carrier	Price for 2016 (incl. tax, no VAT)	Price for 2030 (incl. tax, no VAT)
Natural gas	36	42
Electricity	119	128
Decentral PV LCOE	126	98
Excess heat supplied to the DHC grid	15	15

1. *Status quo (excl. capital costs)* – Decentralized scenario (without district heating network) where each site uses natural gas boilers as a heat source and a vapour-compression chiller as a

Table 5
Gross electricity generation forecasts until 2030 [38].

Gross electricity generation	2016	2030
CO_2 emission factor [kg/MWh]	369	80
Share of RES [%]	52.1	86.7

*Natural gas CO_2 emission factor of 205 kg/MWh.

cooling source; this scenario only considers O&M as well as fuel costs – capital costs are excluded, because the systems are (mainly) already in operation. This scenario serves as a basis to compare costs with possible new installations.

2. *Status quo (incl. capital costs)* – Same as the first scenario but with the addition of the full capital costs (CAPEX).
3. *Heat pump plus compression chillers (HP + CC)* – Decentralized scenario in which the natural gas boilers are replaced by air source heat pumps; the cooling units (vapour-compression chiller) remain the same as in the status quo scenario.
4. *Heat pump plus compression chillers with photovoltaic (HP + CC + PV)* – Decentralized scenario in which the natural gas boilers are replaced by air source heat pumps and a PV system is sized to produce the total combined electricity consumption of the heat pump and the chiller unit.
5. *Refinery excess heat* – Centralized solution assuming the construction of a new district heating and cooling network (approx. 5 km trench length) for which a heat recovery system (shell and tube heat exchanger and absorption chiller) is installed in the local refinery to use the available excess heat.

4. Results

The results are presented for a simple socio-economic perspective (1.5% discount rate, no taxes or profit margins, no external costs) and from a private economic perspective, which includes all the taxes (excl. VAT) and applies a 7% interest rate. Note that some socio-economic assessments might also include external costs, which are excluded in our analysis, which is why we call this a simple socio-economic perspective. Including external costs would make fossil-based H&C supply more expensive. The results are presented for the period 2015–2030 and are assessed in terms of CO_2 emissions, energy supply mix and the LCOH&C. CO_2 emissions are accounted according to a use balance, which allocates the emissions from electricity generation to electricity consumers.

4.1. CO_2 emissions

Fig. 6 shows the results of the different scenarios for the final energy demand for heating, cooling and hot water in the buildings considered. The demand is the same as in the year 2015 (the buildings were constructed recently and comply with current building codes). The presented CO_2 reductions refer to the CO_2 emissions in 2015. The CO_2 reduction in the status quo scenarios (Scenarios 1 and 2) results from the forecast increased share of RES in the electricity generation mix for Portugal presented in Table 5. It can be observed that additional CO_2 emission reductions of 55% are achieved by replacing the natural gas boilers with heat pumps. This large decrease depends strongly on the increased share of RES in gross electricity generation and will probably increase further beyond 2030.100% reduction of CO_2 emissions can be accomplished by either utilizing the excess heat from the refinery (assuming no additional CO_2 emissions from the excess heat) or by installing PV units (assuming net metering). In hours during which the electricity produced by the PV units exceeds the combined demand of the heat pumps and chillers, the excess electricity will be consumed internally by other loads in the same buildings [52].

4.2. Socio-economic perspective

We apply a simple socio-economic perspective to assess the cost. For the simple socio-economic results presented in Fig. 7, it can be observed that the excess heat scenario (scenario 5) is by far the most cost effective solution if capital investment costs are taken into account, and is on a similar cost level with the status quo scenario that does not include CAPEX. The LCOH are higher for heat pumps compared to the status quo including CAPEX. However, adding PV can reduce the costs which are then comparable with the status quo if CAPEX is included. With regard to the total system costs, it can be observed that the system costs for space cooling are almost double those of space heating. Consequently, the total H&C costs are dominated by space cooling.

4.3. Private-economic perspective

In this section, all the results are based on private economic perspective calculations, which include all the taxes (excl. VAT) and a 7% interest rate.

Table 6
Technology assumptions in 2015.

	Investment (CAPEX)	Efficiency/SEER	Lifetime	Variable O&M	Fixed O&M
Natural gas boiler	250 EUR/kW_{th} [39]	90%	25 years [39]	7.2 EUR/MWh [39]	4 EUR/kW [39]
Compression chiller	650 EUR/kW_{th} [40]	230–380% [41]	20 years [40]	2 EUR/MWh [40]	4% of Inv [40].
Photovoltaic	1350-1550 EUR/kW [45]	[b]17.32% [46]	20 years [45,46]	–	0.5–1% of Inv [47].
Shell & tube heat exchanger	2000 EUR/m^2 [17]	85% [27]	15 years [27]	2% of CAPEX	[a]1.5% of Inv.
Absorption chiller	250 EUR/m^2 [29]	65% [29]	20 years [29]	[a]2 EUR/MWh	[a]4% of Inv.
Air source heat pump	700 EUR/kW_{th} [42]	200-500% [44]	20 years [43]	1.5 EUR/MWh [43]	1% of Inv [43].

[a] Assumptions based on [17,40].
[b] Performance ratio = 0.84 [47].

Table 7
Overview of modelled scenarios.

Scenario	Heating source	Cooling source	Electricity source	District H&C network?
1.Status quo (excl. CAPEX)	Natural gas boiler	Compression chiller	Grid	–
2.Status quo (incl. CAPEX)	Natural gas boiler	Compression chiller	Grid	–
3.Heat pump + comp. chillers (HP + CC)	Heat pump (air-source)	Compression chiller	Grid	–
4.Heat pump + comp. chillers & PV (HP + CC + PV)	Heat pump (air-source)	Compression chiller	PV and grid	–
5.Refinery excess heat	Excess heat	Absorption chiller	Grid	yes

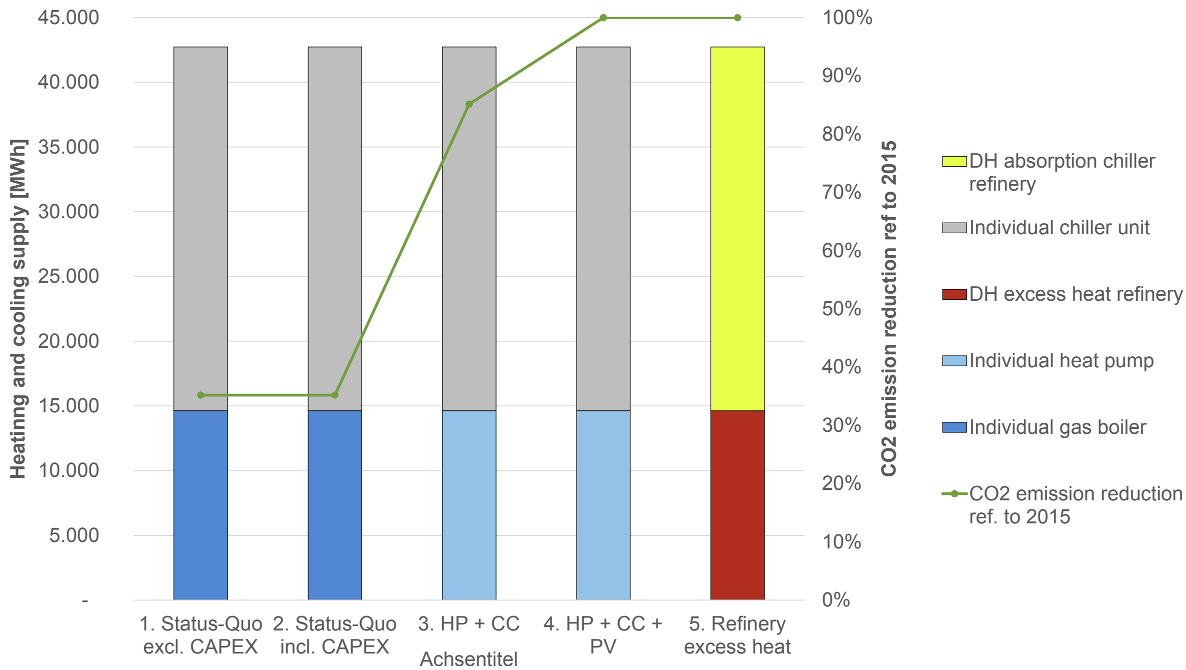

Fig. 6. H&C supply technology mix (left axis) and CO_2 emission reduction (right axis) for different scenarios in 2030 Heat pumps include ambient heat and electricity; CO_2 emission reductions are compared to 2015.

Fig. 8 shows the annual net costs for heating and cooling and the levelized costs (LCOHC) for end consumers for the different scenarios. It can be seen that the least expensive scenario with included CAPEX is scenario 5, which utilizes the excess heat from the refinery, whereas the most expensive scenario is number 3, which considers the replacement of the natural gas boilers with air source heat pumps. The addition of PV has a positive influence on the heating and cooling costs due to the lower electricity production costs of PV in comparison to the electricity price from the grid and the expected PV cost reductions in 2030 [37]. While the general

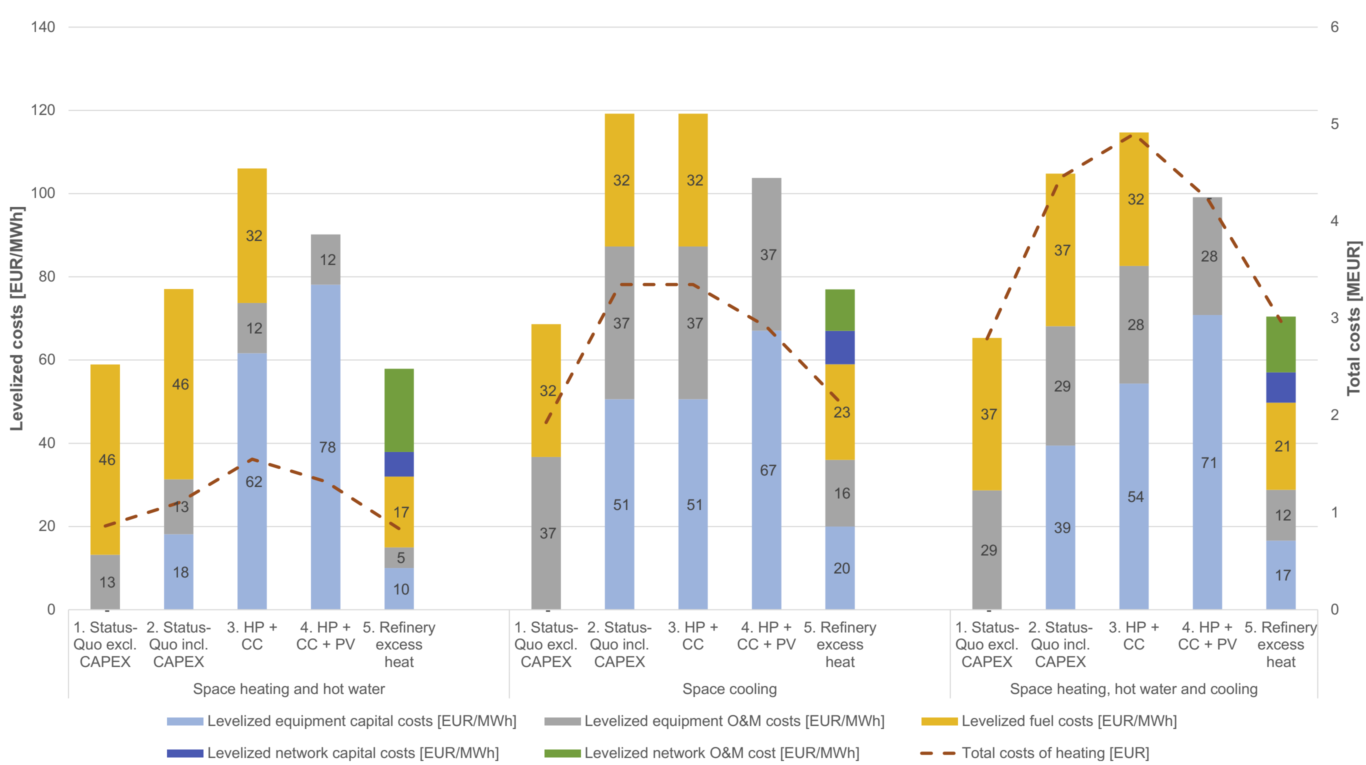

Fig. 7. 2030 Annual net costs for heating and cooling [MEUR] (right axis) and levelized costs [EUR/MWh] (left) All costs are from a socio-economic perspective assuming 1.5% interest rate and excluding all taxes and levies.

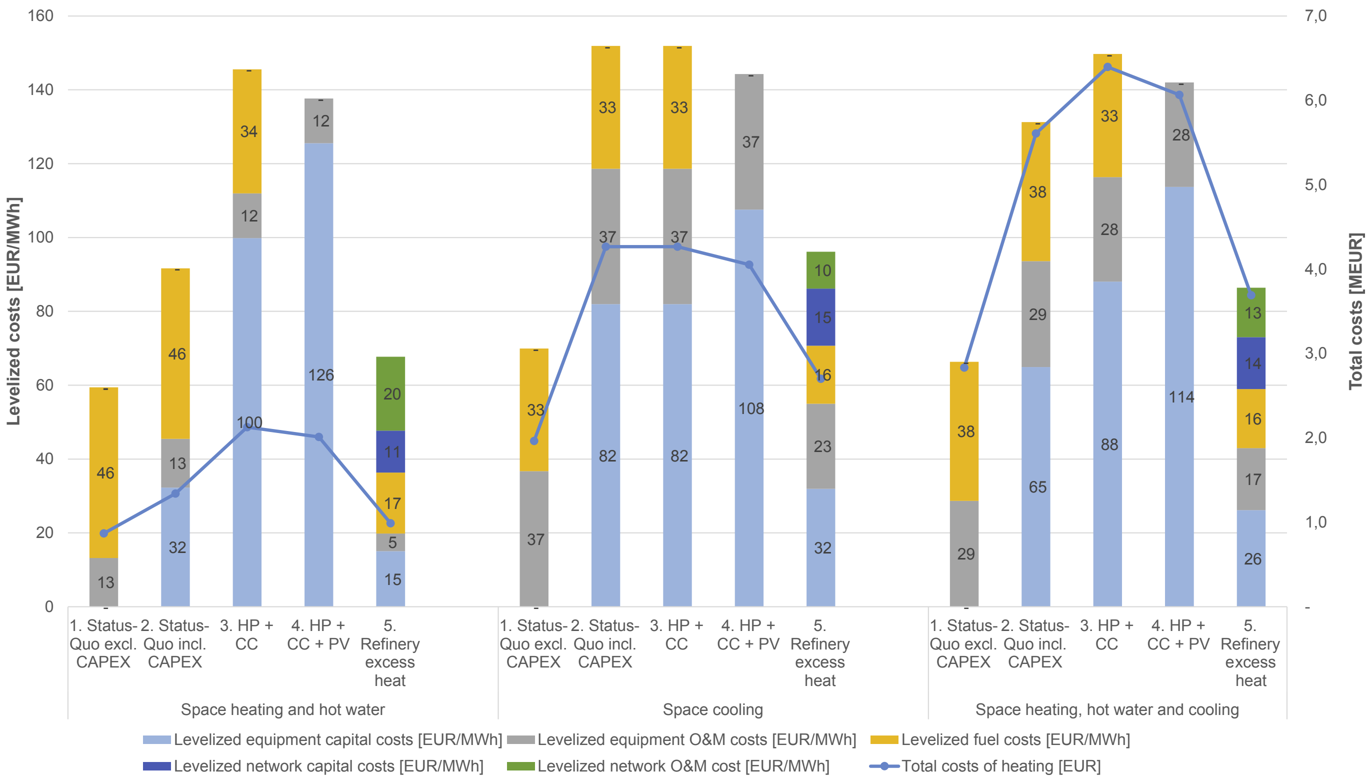

Fig. 8. Annual net costs for heating and cooling [MEUR] (right axis) and levelized costs [EUR/MWh] (left axis) in 2030 for final consumers. All costs are private economic costs assuming 7% interest rate and including all taxes and levies (excl. VAT).

pattern is similar to the results for the simple socio-economic perspective, there is an increasing gap between the RES-based solutions (scenarios 3–5) and the status quo (with and without CAPEX). This is mainly driven by a higher share of capital costs for the DHC network and heat exchangers, but also for heat pumps + PV compared to natural gas boilers.

5. Sensitivity analyses and policy recommendations

Sensitivity analyses were conducted for the private-economic perspective for the most influential factors like capital investment costs, interest rate, and fuels costs. Fig. 9 shows the sensitivity analyses for interest rates ranging from 3% to 11%.

It can be observed that lower interest rates narrow the gap between natural gas boilers and heat pumps due to the high share of capital costs for heat pumps (and PV systems). However, even with a discount rate of 3%, heat pumps (incl. PV) still cannot compete with natural gas boilers for heat generation at the assumed prices for natural gas.

Fig. 10 shows the sensitivity analyses for capital costs ranging between −50% and +50%. It can be observed that, due to a different cost structure, capital costs are very important for heat pumps, but less so for the natural gas boilers. This situation is reversed with regard to fuel costs (see Fig. 11). Note that natural gas boilers are very mature technologies and hold less potential for future improvements and cost reductions, while heat pumps offer a higher potential for technology learning that might lead to future CAPEX reductions. In this regard it is interesting to look at a mixed sensitivity with a lower heat pump CAPEX but unchanged natural gas boiler CAPEX. With a 50% cost reduction, heat pumps would be cost-effective compared to natural gas boilers.

Fig. 11 illustrates the sensitivity analyses for different fuel costs in a range of −50% to +50% price difference. The fuel sensitivity shows that the LCOH for the natural gas-based solution (scenarios 1 and 2) are more heavily dependent on the fuel costs than is the case in the other systems. This makes any scenario with natural gas boilers more vulnerable to economic changes resulting in increasing fuel prices.

6. Discussion

The CAPEX of the status quo are a decisive factor for the cost-effectiveness of the RES-based scenarios (scenarios 3–5). Including CAPEX in the status quo scenarios makes the RES-based scenarios much more competitive. Due to the age of the current system, a realistic capital depreciation might be somewhere in-between the scenarios 1 and 2. Waiting for the next window of opportunity when the current system is to be replaced can be an option, but policy instruments can also improve the private economic feasibility of RES systems, especially if these are cost-effective from a simple socio-economic perspective.

Furthermore, we calculated with a relatively low natural gas price of 36 euros in 2016, assuming a moderate increase to 42 euros in 2030. Higher natural gas prices will, of course, make the RES-based solutions more cost-competitive.

From a private-economic perspective, the heat pumps and heat pump + PV systems have higher LCOH than the natural gas boiler system including CAPEX. The difference is mainly driven by the high capital costs for the heat pump and the high electricity price compared to natural gas prices. From a simple-socio economic perspective, the heat pumps plus PV system is competitive if heating and cooling are considered together. For heating only, the natural gas boilers have lower costs even if CAPEX is included. The sensitivity analysis shows that heat pumps' CAPEX would need to fall by more than 50% to make them cost-competitive. Including the external costs of CO_2 emissions might even bridge the remaining

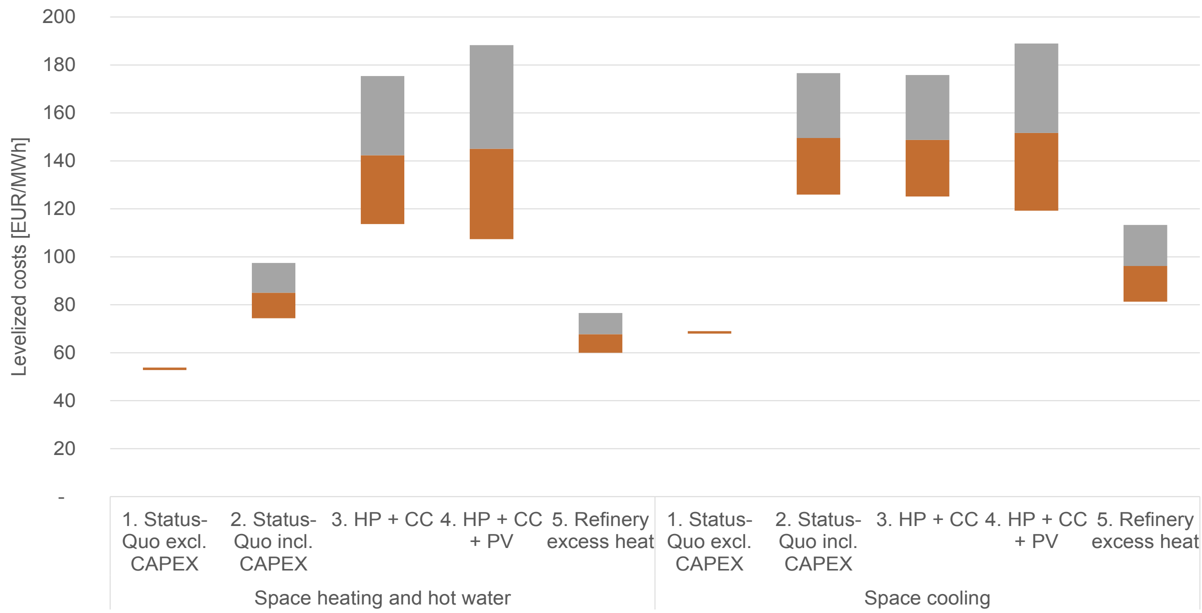

Fig. 9. Interest rate sensitivity for 2016 based on private-economic perspective (range between 3% and 11%).

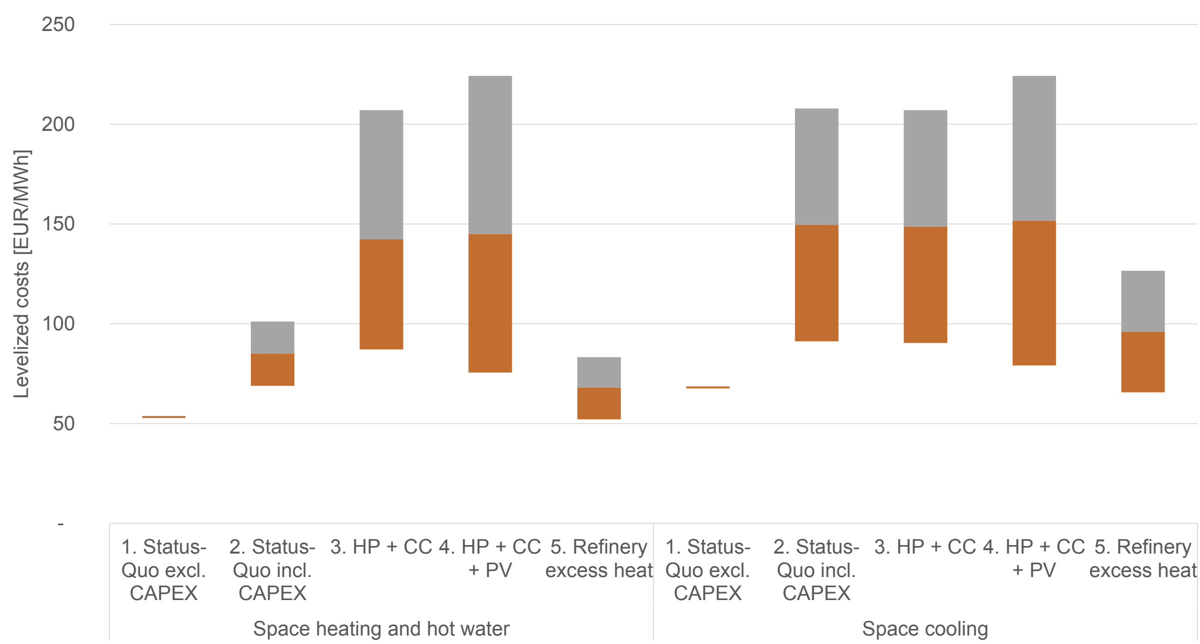

Fig. 10. CAPEX sensitivity for 2016 based on private-economic perspective (range between −50% and +50%).

gap. In this case, policies to make RES-based systems more attractive from a user perspective are well justified.

Various policy instruments to make RES-H&C more cost-effective are being discussed. A consistent policy mix is probably needed that integrates financial incentives as well as regulation-based instruments [50,51]. Over the past several years, the Portuguese Energy Agency (ADENE www.adene.pt/) has supported funding programmes for energy efficiency (FEE) and innovation support for energy technologies (FAI). As an example, one of these programmes provided financial support of up to 50% of the investment and service costs for solar thermal collectors [55]. Continuing and expanding these financial support schemes could be crucial to increase the deployment of renewable heating and cooling technologies.

As stated before, it has to be noted that there are further considerations to be taken into account for net-metering like the economic consequences for the network costs and the need for flexibility that is paid for by other market participants [48,49]. On the other hand, any excess electricity produced by the PV units can be used internally by other non-H&C loads including lighting and electric equipment. The demand for lighting in commercial buildings alone can amount to between 30 and 35 $kWh/m^2.y$ as stated in Ref. [52].

The supply option with the DHC network using excess heat from the refinery is the economically most competitive option under the assumptions taken. Implementing this option, however, requires the active involvement of multiple stakeholders including the refinery, the building owners, the city and the utility. Barriers have to

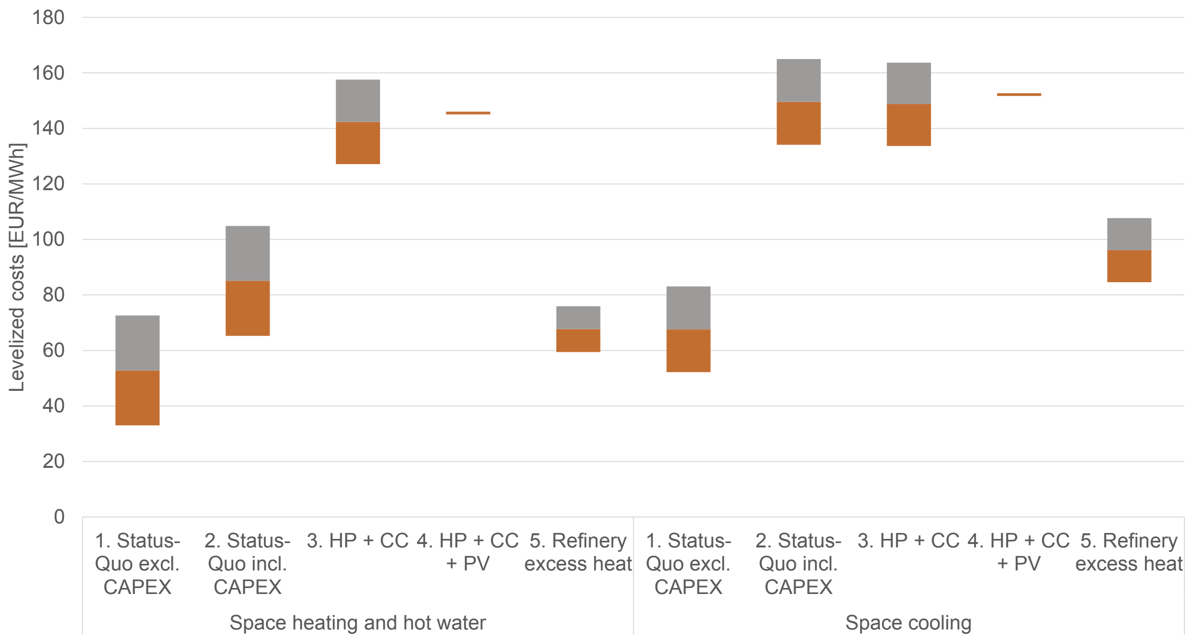

Fig. 11. Fuel costs sensitivity for 2016 based on a private-economic perspective (The price of excess heat is considered as a fuel price in scenario 1).

be overcome like the perception of high mutual dependence, (perceived) risk and uncertainty. Advantages like the mitigated uncertainty about future gas or electricity prices have to be underlined. Possible policy instruments on the local level include active municipal energy planning, zoning, and non-profit grid operation [53]. Nationally, a risk hedging strategy might be helpful. Business models and financial advantages for the individual actors need to be analysed and clearly communicated. For instance, assuming that the refinery receives 15 euros/MWh heat supplied to the DHC network, the financial revenue for the refinery would sum up to about 700,000 euros per year. In case the refinery regards investments in heat exchangers and other equipment as too risky, a contracting model might help, in which the utility also pays for the equipment at the refinery. This can also overcome the barriers related to the very short payback time expectations of 2–3 years that industrial companies often apply to energy projects. Such payback time expectations are obviously not applicable to the DHC technology with lifetimes of 30 years and longer. Beyond financial incentives, supplying excess heat to DH is a good way to improve the refinery's public image as similar cases in Europe have shown, e.g. in Karlsruhe. On the other hand, as the IEA has forecast [54] that the share of petroleum products in the EU's primary energy demand will decrease from 33% in 2014 to 25% in 2040 (or a decrease from ca. 470 Mtoe in 2014 to around 410 Mtoe in 2030), the business outlook for the refinery sector is currently very uncertain. The rate of decline will largely depend on the effectiveness of broader decarbonisation, energy efficiency measures and the integration of alternative fuels and technologies, in particular, for heating, cooling and transport. For these reasons, clustering this sector with other sectors by providing additional services and benefits can offer economic opportunities for investments. Initially, the DHC network designed for this case study can only supply the evaluated buildings with the possibility of further expansion, especially in the commercial district that also has a demand for heating or cooling throughout the year. Currently, about 70 TWh excess heat are used, which equals roughly 3% of the refinery's total final energy demand. Compared with other refineries in Europe, the refinery in Matosinhos probably has the potential to provide much more heat than assumed in this scenario, making it possible to connect more buildings to the DHC network in the future.

The costs of the DHC network could decrease even more if absorption chillers were installed inside the buildings. It has to be noted that, in this case, the size of the DH network would increase in order to supply enough heat for both hot water demand and absorption chillers. An additional piping network might be required to provide ocean water to customers with absorption chillers. In any case, this optimization has to be carefully designed and evaluated based on additional calculations, which are not part of this case study.

7. Conclusion

We analysed the technical and economic feasibility of alternative sustainable heat and cold supply options for selected buildings in the city of Matosinhos, Portugal. While heating and cooling investments depend to a very large extent on local circumstances, many cities in southern European countries share similar characteristics. These include the high importance of space cooling, no DHC infrastructure and relatively good solar irradiation. In this sense, some of the results and lessons learned here are informative for other southern municipalities as well.

The levelized costs of heating and cooling (LCOH&C) were analysed for the current system (natural gas boilers and compression chillers) including and excluding capital costs (because most of the systems were built in the last 10 years), and for alternative RES-based systems. These systems include heat pumps, heat pumps plus photovoltaics and the construction of a DHC network fed by excess heat from the local refinery. All systems were calculated from two perspectives: a simple socio-economic perspective (3% discount rate, excluding taxes, no external costs) and a private economic perspective (7% discount rate, including taxes).

The results show that, from a simple socio-economic perspective, the heat pump and compression chiller system has the highest LCOH&C. Including a PV system makes it competitive with the status quo, but only if capital costs are included. When considering heating only, the heat pump system has higher LCOH compared to natural gas boilers including capital costs. The use of excess heat from the refinery via a DHC grid shows LCOH&C at a similar level to the current system without considering capital costs (socio-economic perspective). From the private economic perspective, the cost-effectiveness of RES-based systems is lower. The low natural gas prices are one main reason for this, but the discount rate in combination with high capital costs for heat pumps, PV and the DHC system are other important factors.

The results for the socio-economic perspective justify policy instruments like grants or soft loans to make the RES-based systems cost-effective from a private economic perspective as well. This is probably similar for many other southern European municipalities, particularly when comparing heat pumps plus PV with natural gas boilers.

The availability of huge excess heat resources close to the city is more particular to Matosinhos, but also observed in many other cities throughout Europe. Using the excess heat can represent a window of opportunity to construct a DHC grid, which can be extended at a later time and also fed by renewables like solar thermal, biomass, or even other excess heat sources.

Thus, transforming the H&C supply of large buildings to RES-based or CO_2-neutral systems can be cost-competitive even without accounting for external costs. Possible opportunities are provided by the replacement cycles of existing equipment, new developments or the availability of industrial excess heat. Additional policies are required to make the RES-based systems competitive from a private economic perspective, too. All the activities require the active involvement of the city and a strategic approach to energy planning.

Acknowledgements

We would like to thank Lukas Kranzl, Marcus Hummel and Richard Büchele of TU Wien, Jan Steinbach and Ali Aydemir of Fraunhofer ISI, and Marie Münster, Stefan Petrović, and Sara Ben Amer-Allam from the Technical University of Denmark (DTU). Furthermore, we thank the anonymous reviewers for the helpful comments that improved the quality of this paper. This work has received funding from the European Union's Horizon 2020 research and innovation programme within the progRESsHEAT project (grant agreement No. 646573).

References

[1] Fraunhofer ISI, Fraunhofer ISE, TU Wien, TEP Energy, IREES, Observer. Mapping and analyses for the current and future (2020-2030) heating/cooling fuel development (fossil/renewables). Karlsruhe. 2017.
[2] European Commission, An EU strategy on heating and cooling, 1_EN_ACT_part1_v14, (16.02.2016).
[3] Ben Amer-Allam Sara, Münster Marie, Petrović Stefan. Scenarios for sustainable heat supply and heat savings in municipalities - the case of Helsingør, Denmark. Energy 2017;137:1252–63. https://doi.org/10.1016/j.energy.2017.06.091. S.
[4] Abdurafikov Rinat, Grahn Elina, Kannari Lotta, Ypyä Joel, Kaukonen Sampo, Heimonen Ismo, Paiho Satu. An analysis of heating energy scenarios of a Finnish case district. Sustain. Cities Soc. 2017;32:56–66. https://doi.org/10.1016/j.scs.2017.03.015.
[5] Bach Bjarne, Werling Jesper, Ommen Torben, Münster Marie, Morales Juan M, Elmegaard Brian. Integration of large-scale heat pumps in the district heating systems of Greater Copenhagen. Energy 2016;107:321–34. https://doi.org/10.1016/j.energy.2016.04.029.
[6] Lund H, Østergaard PA, Connolly D, Mathiesen BV. Smart energy and smart energy systems. Energy 2017;137:556–65. https://doi.org/10.1016/j.energy.2017.05.123.
[7] Lund H, Werner S, Wiltshire R, Svendsen S, Thorsen JE, Hvelplund F, et al. 4th Generation District Heating (4GDH). Integrating smart thermal grids into future sustainable energy systems. Energy 2014;68:1–11. https://doi.org/10.1016/j.energy.2014.02.089.
[8] Østergaard PA, Lund H, Mathiesen BV. Smart energy systems and 4th generation district heating. Int J Sustain Energy Plan Manag 2016;10:1–2. https://doi.org/10.5278/ijsepm.2016.10.1.
[9] Lund H, Möller B, Mathiesen BV, Dyrelund A. The role of district heating in future renewable energy systems. Energy 2010;35:1381–90. https://doi.org/10.1016/j.energy.2009.11.023.
[10] Münster Marie, Morthorst Erik Poul, Larsen V Helge, Bregnbaek Lars, Werling Jesper, Lindboe Hans Henrik, Ravn Hans. The role of district heating in the future Danish energy system. Energy 2012;48:47–55. https://doi.org/10.1016/j.energy.2012.06.011.
[11] Bühler Fabian, Petrovic Stefan, Karlsson Kenneth, Elmegaard Brian. Industrial excess heat for district heating in Denmark. 2017.
[12] Persson U, Möller B, Werner S. Heat Roadmap Europe: identifying strategic heat synergy regions. Energy Pol 2014;74:663–81. https://doi.org/10.1016/j.enpol.2014.07.015.
[13] Cornelis E, Van Bael J. How well can the potential of industrial excess heat be estimated?. In: Eceee industrial summer study proceedings; 2016. p. 199–206.
[14] Capital cooling energy service AB, district cooling showcases in Europe, report elaborated in the framework of the RESCUE project co-funded by the IEE program of the EU. 2016.
[15] Galindo Fernández, M., Roger-Lacan, C., Gährs, U., Aumaitre, V., Efficient district heating and cooling systems in the EU - case studies analysis, replicable key success factors and potential policy implications, EUR 28418 EN, doi: 10.2760/371045.
[16] Inpal Energy, web accesses: http://www.inpal.com/en/Pre-insulated-pipes-references-District-heating-expo98-lisbon-Inpal-Energy.html (last accessed on: 08.08.2017).
[17] Rink M. Nutzung industrieller Abwärme durch die Stadtwerke Karlsruhe zur Wärmeversorgung der Stadt Karlsruhe, Study on behalf of Umweltbundesamtes. 2013.
[18] Holmgren K. Role of a district-heating network as a user of waste-heat supply from various sources-The case of Göteborg. Appl Energy 2006;83:1351–67. https://doi.org/10.1016/j.apenergy.2006.02.001.
[19] Kordina H, Lagger A, Schalk V, Sommer F, Spreitzer A, Timmerer C. Energieversorgung-region schwechat. 2011.
[20] Bjørn H. German district heating delagation 19.11.2014 at AffakdVarme Aarhus,TVIS - a multicity district heating wholesaler. 2014.
[21] Matriz de Energia do Município de Matosinhos (Matosinhos Energy Matrix) – AdEPorto. 2009.
[22] Relatório de Sustentabilidade e Responsabilidade Social (Sustainability and Social Responsibility Report) – Matosinhos Municipality. 2014.
[23] Pordata – Base de Dados Portugal Contemporâneo (Portuguese Statistical Data Portal) – www.pordata.pt (accessed on 07.10.2016).
[24] Inquérito ao Consumo de Energia no Sector Doméstico (Survey of Energy Use in the Domestic Sector). INE & DGEG; 2011.
[25] Alves D, Leal V. Caracterização das necessidades de calor e frio numa perspectiva de Trigeração Urbana nas zonas prioritárias da RUTE, Fundação Gomes Teixeira and AdEPorto. 2010.
[26] IPMA: Climate Normals for Porto, http://www.ipma.pt/en/oclima/normais.clima/1981-2010/014/(accessed on 24.09.2016).
[27] Element Energy Ltd, Ecofys BV. Imperial college (center for process engineering), the potential for recovering and using surplus heat from industry, final report for DECC. 2014.
[28] Energia Galp. Matosinhos refinery, 2013 data book on health, safety and environment. 2013.
[29] Element Energy Ltd, Ecofys BV. Imperial college (center for process engineering), the potential for recovering and using surplus heat from industry, appendix for final report for the heat strategy and policy team department of energy and climate change. 2014.
[30] www.seatemperature.org/europe/portugal/matosinhos-september.htm (accessed on 24.09.2016).
[31] Laitila J, Otepka P. Guidebook on local bioenergy supply based on woody biomass. 2014. March.
[32] Andreas Pfnür A, Bernadetta Winiewska B, Bettina Mailach B, Bert Oschatz B. Dezentrale vs. zentrale Wärmeversorgung im deutschen Wärmemarkt. 2016.
[33] Skagestad B, Mildenstein P. District heating and cooling connection handbook, IEA programme of reaserch, development and demonstration on district heating and cooling. 1999.
[34] Persson U, Werner S. Heat distribution and the future competitiveness of district heating. Appl Energy 2011;88.3:568–76.
[35] Swedblom M, Mattsson P, Tvärne A, Frohm H, Rubenhag A. District cooling and the customers alternative costs, report elaborated in the RESCUE project. 2014.
[36] Nussbaumer M, Thalmann S. Sensitivity of system design on heat distribution costs in district heating. IEA Bioenergy Task 2014;32.
[37] Fraunhofer ISE. Current and future cost of photovoltaics. Long-term scenarios for market development, system prices and LCOE of utility-scale PV systems, study on behalf of agora energiewende. 2015.
[38] Capros P, et al. EU reference scenario 2016, energy, transport and GHG emissions trends to 2050. 2016.
[39] The Danish Energy Agency: Technology data catalogue. http://www.ens.dk/node/2252. (accessed on 15.03.2016).
[40] RESCUE project - district cooling and the Customer's alternative costs. 2014.
[41] Model YCAV Air cooled screw liquid chillers style a, YORK by johnson controls.
[42] Technology Roadmap IEA. Energy-efficient buildings: heating and cooling equipment. 2011.
[43] IEA Heat Pump Centre. Annex 32 economical heating and cooling systems for low energy houses, final report. 2011.

[44] Energiesysteme IDM. Heat pump manual. 2014.
[45] Fraunhofer ISE. Levelized cost of electricity renewable energy technologies. 2013.
[46] NREL. Best practices in PV system operations and maintenance, version 1.0. 2015.
[47] IEA PVPS. Analytical monitoring of grid-connected photovoltaic systems, good practices for monitoring and performance analysis. 2014.
[48] Eid C, Guillen J, Marin P, Hakvoort R. The economic effect of electricity net-metering with solar PV: consequences for network cost recovery, cross subsidies and policy objectives. Energy Pol 2014;75:244–54.
[49] Schill WP, Zerrahn A, Kunz F. Prosumage of solar electricity: pros, cons, and the system perspective. 2017. https://doi.org/10.5547/2160-5890.6.1.wsch.
[50] Kranzl Lukas, Hummel Marcus, Müller Andreas, Steinbach Jan. Renewable heating: perspectives and the impact of policy instruments. Energy Pol 2013;59:44–58. https://doi.org/10.1016/j.enpol.2013.03.050. S.
[51] Steinbach Jan, Seefeldt Friedrich, Brandt Edmund, Bürger Veit, Jacobshagen Ulf, Kachel Markus, et al. State budget independent, market-based instruments to finance renewable heat strategies. Energy Environ 2013;24(1–2):195–218. https://doi.org/10.1260/0958-305X.24.1-2.195. S.
[52] International Energy Agency. Light's Labour's lost. IEA Publications; 2006.
[53] Chittum Anna, Østergaard A Poul. How Danish communal heat planning empowers municipalities and benefits individual consumers. Energy Pol 2014;74:465–74. https://doi.org/10.1016/j.enpol.2014.08.001.
[54] International Energy Agency. World energy outlook 2016. IEA Publications; 2016.
[55] FEE. Fundo de Eficiência Energética, AVISO 12 – requalificação de Sistemas Solares Térmicos. 2015.