Impact of district heating and cooling on the potential for the integration of variable renewable energy sources in mild and Mediterranean climates

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Abstract

Europe's decarbonisation ambitions can't be achieved without the full and rapid decarbonisation of its buildings which represent over 36% of its greenhouse gas emissions, the majority of which are linked to space heating and domestic hot water preparation. District heating, and in recent times, cooling must play a large role in satisfying this demand, especially in densely populated urban areas which already hold over half of the World's population. Besides the decarbonisation potential linked to heating and cooling production, these systems hold a strong potential for increased flexibility in the power sector using power to heat technologies thus increasing the potential for the utilization of intermittent renewables such as wind and solar. The goal of this research is to demonstrate the impact district heating and cooling can have on the potential for the utilization of intermittent renewable electricity sources in mild and Mediterranean climates, which traditionally have lower shares of district energy systems. Additionally, this paper presents the newly implemented capabilities of the H2RES linear optimization tool to model district cooling systems alongside the existing capacity to model district heating systems. The results demonstrate a significant capacity of district heating and cooling systems to act as demand response tools thus greatly increasing the potential for the utilization of wind and PV for electricity generation. In some scenarios, up to 73% of the total electricity demand could be covered with wind and PV and a production of excess electricity of only 5% on an annual basis. The Republic of Croatia has been used as a case study for this research.

Highlights:

- District heating and cooling play a vital role in the EU's decarbonisation effort
- The H2RES tool has been upgraded to including district cooling
- Power to heat is a valuable demand response tool
- Wind and PV could cover up to 73% of Croatia's electricity demand in some scenarios
- District cooling has a significant positive impact on the reduction of curtailment

Key words: Energy planning, District heating, District cooling, System integration, Linear optimization

Abbreviations

ATA	Air to air

ATW	Air to water
CEEP	Critical excess of electricity
CHP	Combined heat and power
DC	District cooling
DH	District heating
DHC	District heating and cooling
EU	European Union
HDAM	Hydroelectric dam
HPHS	Pump storage hydroelectric power plant
HROR	Run of river hydroelectric power plant
PV	Photovoltaics

Nomenclature

C	Variable cost incurred by dispatching a given technology
CEEP	Generation of CEEP
CEEP_cost	CEEP cost
CO_2Levels	Generation of CO_2
CO_2Price	CO_2 price
D	Capacity at which a given technology has been dispatched
eff	Energy efficiency of a given technology
FuelCost	Unit cost of fuel for a given technology
HSk	Unit capital cost for heat storage
Hsto	New installed capacity of heat storage
I	Cost of decommissioning of a given technology
Imp	New decommissioning of a given technology
Inv	New installed capacity of a given technology
K	Unit capital cost for a given technology, fixed across the duration of the scenario
NonFuelCost	Other variable costs incurred by dispatching a given technology
p	Time period, hour
R	Ramp up and down costs of a given technology
Ramp	Ramp up and down of a given technology
t	Technology
TC	Unit capital cost for a given technology, variable based on an annual technology cost curve
y	Year

1. Introduction

The successful achievement of the EU decarbonisation missions and targets by 2030 [1] and 2050 [2] will greatly hinge on the successful decarbonisation of the heating and cooling sectors, as buildings represent the largest single energy consumer, 40%, and greenhouse gas emitter, 36%, across the EU [3]. The fact that 55% of the World's population already lives in densely populated urban areas and current projections show that this figure could increase to 68% by 2050 [4], additionally highlights the need to address the issue of sustainable supply of heating and cooling. At present, energy supply for space heating and domestic hot water preparation represents the largest energy demands in terms of total annual and peak loads in 25 of 27 EU member states when heating, cooling and electricity demand is compared [5]. However, the widespread electrification as well as increased cooling demand due to climate change [6] as well as the increase in purchasing power and living standards could change this in the future.

District heating (DH) and district cooling (DC) play a key role in the decarbonisation of buildings and even processes, especially in densely populated urban areas. The importance of DH in terms of enabling the utilization of various renewable energy sources such as solar [7] and geothermal [8] energy, heat pumps [9][10] as well as waste heat [11][12], for example from data centres [13], has been widely documented. Similarly, DC can enable the use of free cooling [14], waste energy [15], renewables such as solar energy [16] and help diversify energy supply for cooling [17]. It is also most suitable for densely populated urban areas where it can facilitate significant efficiency gains and decarbonisation [18][19][20]. Additionally, joint operation of district heating and cooling (DHC) can achieve higher efficiencies [21] and synergies through the exploitation of the same renewable sources such as solar [22] and geothermal [23].

The suitability of DHC greatly depends on the energy demand densities, availability of cheap energy sources and the overall setup of the respective energy system as a whole [24]. Even with these limitations, the potential for the commercially viable utilization of these systems, and especially DH is significant [25][26]. The results of our previous research for example demonstrate that, depending on the assumed network costs, DH could feasibly supply upwards of 50% of Croatia’s heating [27] while DC could supply upwards of 25% of Croatia’s cooling demand [28].

A key benefit of DH systems is their potential to provide flexibility to the overall energy system if correctly configured [29]. The use of power-to-heat technologies such as heat pumps, heat storage and combined heat and power (CHP) units can enable systems to interact with the power system and provide additional potential for the integration of variable renewable energy sources such as wind and solar [30][31]. For instance, in systems with a high share of such variable sources a critical excess of electricity production (CEEP) can become an issue and cause curtailment of production. Heat pumps and electric heaters can instead transform this electricity into heat and either distribute it via a DH network or store it for later use. At instances when a lack of electricity occurs, these systems can be switched off and stored heat can be used while CHP units can be engaged to produce additional power and heat which can be again either stored or supplied [32]. Such a configurations can provide benefits on both the heat and power markets and enable additional revenues and market opportunities to DH operators. This potential can be additionally exploited if DC is integrated into the overall system as well.

Although they possess significant potential for the exploitation of intermittent renewable energy sources such as wind and PV and for the utilization of DHC, territories in mild and Mediterranean climate zones are often underutilizing these potentials and are rarely addressed in current literature. The goal of this research is to demonstrate the impact of both DH and DHC on the potential for the uptake of intermittent renewable energy sources in mild and Mediterranean climates. This has been achieved through the use of a novel energy system modelling and optimization tool, H2RES [33], which has been further upgraded for this purpose. The Republic of Croatia has been used as a case study as it covers both climate zones.

2. Methods and tools

As the need for clean, renewable energy rises, solar and wind will play increasingly important roles in Europe's energy systems. Their utilization will in turn require increasing energy storage and flexibility options to cope with their inherent intermittency. DHC systems, alongside the potential for the decarbonization of the heating and cooling sectors, can provide flexibility services using power to heat technologies and heat storage systems. In practice, this means that when excess electricity is generated by intermittent sources, it can be transformed into heat by electric boilers or heat pumps and either used or stored. These systems can also be turned off when a lack of electricity occurs, and stored heat can be used to satisfy the heating demand. Finally, if CHP plants are used, they can be turned on to generate electricity even when no heat is needed as it can again be stored easier and cheaper then electricity. The utilization of DC together with heat pumps to generate and even store cooling energy can further enhance these capacities due to the introduction of a higher energy demand in summer, when DH usually operates at lower capacities, and an overall higher energy demand throughout the year. This added flexibility allows for more intermittent energy sources to be added into an energy system while keeping CEEP at an acceptable level.

The H2RES model has been used to assess the potentials of DH and DHC to reduce CEEP in systems with a high share of wind and solar energy. For this purpose, the model presented in [33] has been additionally upgraded with the capacity to model DC systems.

2.1. The H2RES model

The H2RES model [33] is a long-term energy planning linear optimization model that considers hourly resolution scale for energy dispatch, while choosing optimal investment plans at a yearly level for all technologies considered in the planning strategy. H2RES is particularly developed to model and analyse the penetration of variable renewable sources in an energy system as well as sectoral coupling via Power-to-X technologies (PtX). Hence, H2RES enables the analysis of decarbonization strategies among the power, heating and cooling, transport, and industry sectors using Power-to-Heat, Power-to-EV, Power-to-Power, and Power-to-hydrogen technologies. The optimization performed minimizes the total cost incurred in supplying all demand carriers, including variable, capital, and policy costs. Figure 1 shows a general representation of the H2RES model. The H2RES model is built in Python and is solved using the GUROBI solver for linear optimization models.

H2RES considers three main set of decisions. First, it models yearly capacity investments (sizes) for all technologies (e.g., power plant size or H2 storage size). It then considers that when a capacity addition is made for a given technology, this addition becomes available at the beginning of the year. Also, H2RES follows this capacity over the planning years and performs a decommission (percentage of the capacity added) based on decommission curves predefined by the users. Secondly, given the capacity investment plans, H2RES models the dispatch for all technologies. Dispatch of the technologies is considered at an hourly resolution for every year of the planning horizon. The hourly resolution allows the user to better represent the relation between variable renewable sources and Power-to-X technologies. The dispatch of each technology is also subject to the initial capacity, capacity investments, availability factors (for variable sources) and the decommission that the technology suffers. The third set of decisions for H2RES corresponds to storage levels (hydro-dam, heat, H2, EV, and stationary batteries). Storage levels for each unit or technology, when available, are also represented with an hourly resolution for every year considered in the planning horizon and are subject to maximum storage levels, defined by initial capacities, future investment, and decommission curves.

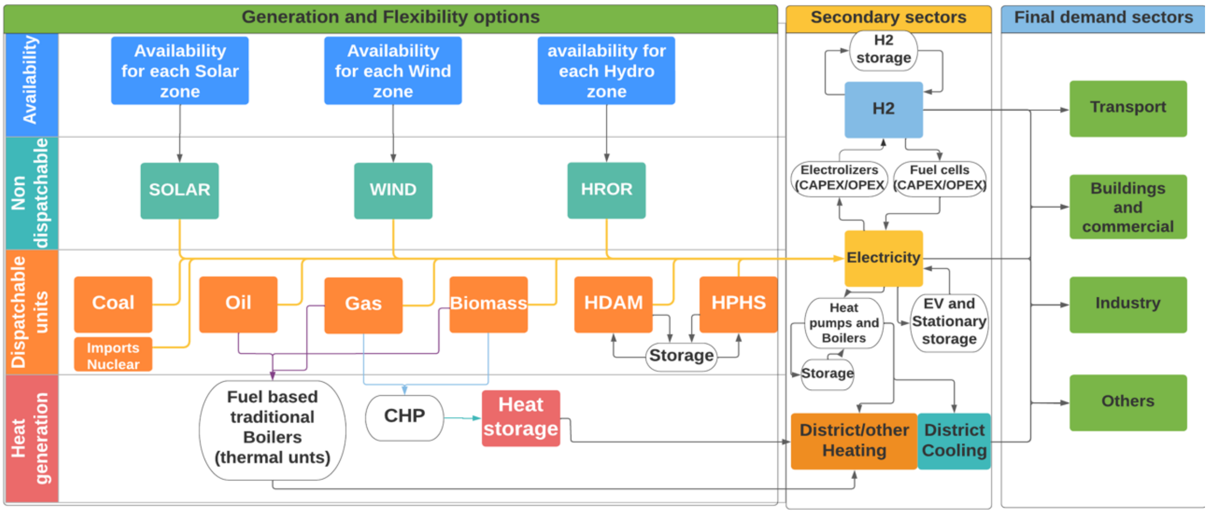


Figure 1: Representation of the H2RES model

Investments, dispatch, and storage level decisions in H2RES are made with the main objective of minimizing total annual discounted cost over the planning horizon (see Equation 1) subject to a set of constraints. The cost minimization components are variable dispatch cost, capital investment, ramp up-down costs of power plants, import costs, emissions costs, energy transformation cost (e.g., cost of electrolysers) and the cost associated to CEEP. The cost minimization is obtained while guaranteeing that a set of constraints are met. Such constraints consider dispatch and technical constraints (e.g., ramp constraints of power plants), balancing of supply and demand for all markets and hours (time periods), storage constraints, policy constraints (e.g., CO2 limits, targets of renewable electricity, and/or CEEP limits) and maximum-minimum penetration levels of certain technology options in different markets. Note that H2RES allows the setting of limits on both CO2 emissions and CEEP levels, while it also allows the user to assign costs to these parameters. Therefore, H2RES is designed to assess scenarios in which both CO2 and CEEP levels are either penalized or limited by the users.

$$\sum_{y}\sum_{p}\sum_{t} df_y\big[C_{t,p,y}D_{t,p,y} + TC_{t,y}K_tInv_{t,y} + R_{t,p,y}Ramp_{t,p,y} + I_{p,y}Imp_{p,y} + CO_2Price_yCO_2Levels_{t,p,y} + CEEP\_costCEEP_{t,p,y} + HSk_tHsto_{t,y}\big] \qquad \textbf{Equation 1}$$

The component $C_{t,p,y}D_{t,p,y}$ in the objective function (Equation 1) represents the variable cost ($C_{t,p,y}$) incurred by dispatching ($D_{t,p,y}$) a given technology (t), in a period or hour (p), and in year (y). The variable cost, $C_{t,p,y}$ (see Equation 2), considers the fuel cost and non-fuel cost, allowing to account for different cost structures for distinct types of technologies. This component is general across all technologies in H2RES, including the dispatch cost of power and DHC technologies (e.g., electric boilers or heat-pumps). Similarly, the component $TC_{t,y}K_tInv_{t,y}$ represents the cost (K and TC) incurred by commissioning a given technology (power, heating or cooling). The unit costs are separated into a fixed value across the duration of the entire scenario (K) and a variable section dependent on annual cost curves (TC). The last term

$HSk_t Hsto_{t,y}$ represents the capital investment cost (HSk) for heat storage (Hsto) in district heating networks.

$$C_{t,p,y} = \left[\frac{FuelCost_{t,p,y}}{eff_{t,p,y}} + NonFuelCost_{t,p,y}\right] \quad \textbf{Equation 2}$$

Although the version of H2RES used in this research does not consider network flows (trade) among different regions (rather, it considers a national system), the model considers different heat and cooling demand curves for different zones within the system (see Table 1 for further details on input data and curves). Similarly, H2RES has the possibility to including the necessary number of wind and solar production zones within the national planning system. In this way, H2RES provides the option to assess the role of areas or regions with high or low capacity factors (assuming that transmission infrastructure is always available) with different availability profiles. Similarly, adding different demand zones (heat and cooling), each represented by an individual hourly profile (demand curves are exogenous and defined in the input data) allows the user to assess the electrification or decarbonization of heat and cooling systems with different characteristics (availability of DH, DC and DHC, availability of power-to-heat technologies, and integration of renewable energy with different demand profiles). Also, the introduction of different zones allows the consideration of different COP (coefficient of performance) as well as other efficiencies and losses associated to heat-pump technologies, influencing their ability to provide heat and cooling energy over seasons and day-night periods. Further details of the heat and cooling sectors in H2RES are described below.

H2RES differentiates between DH and individual heating demands. Both demand types can be supplied by a set of technologies, including traditional fuel boilers (coal, gas, biomass boilers), electric boilers, and different heat-pump technologies. Each of these technologies is defined by a set of technical characteristics, including variable cost, efficiencies, COP, and lifetimes, among others. In the case of DH demand, CHP plants are available. H2RES assumes that each CHP plant is connected to a DH system with heat storage that can be optimized (size and usage of heat storage). It also models losses in heat storage, input, output and losses among the time periods of the scenario, and in energy transformation processes. Additionally, H2RES allows the use of power to heat technologies through the introduction of Electric Boilers and Heat-pumps as well as heat storage. Additionally, there is no limit in terms of how many DH systems can be modelled with H2RES. Note that DH system are by default connected to CHP plants, however, if no CHP pant is to be considered, the capacity of such can be set to zero, removing this option from the system. A depiction of the heat sector in H2RES is shown in Figure 2.

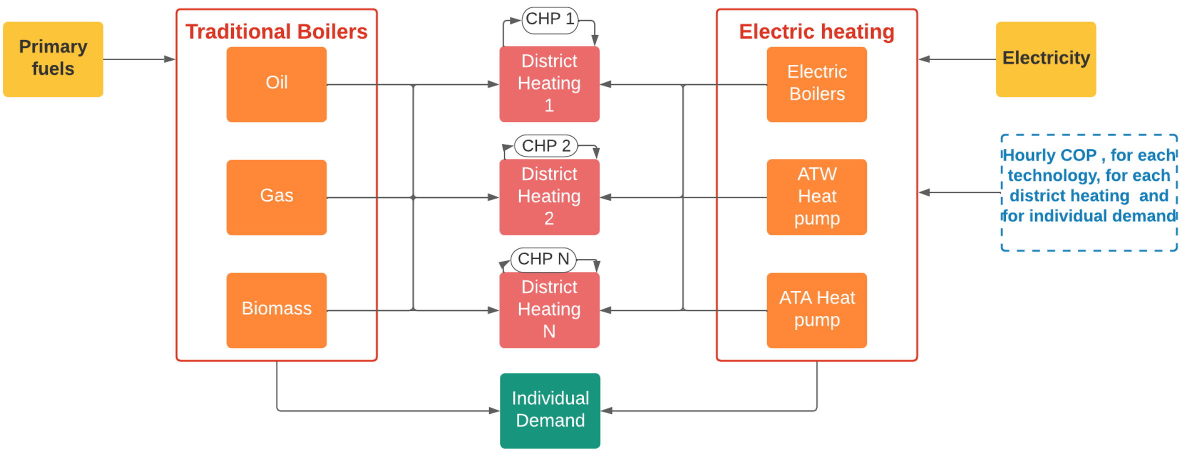


Figure 2: Representation of the Heating sector in H2RES

For the purpose of this research, individual cooling demand and DC systems were developed and incorporated into the base module of H2RES (not available in previous versions of the model published in scientific literature). DC follows a similar modelling paradigm as DH. H2RES considers different cooling demand profiles for different systems (representing different regions, cities, or areas with independent cooling demands). It is assumed that heat-pump technologies are available to meet cooling demand. Note that such heat-pump technologies, if installed, also provide heat when heat demand in DH systems is present. Therefore, H2RES optimizes the size (capacity) and usage of heat-pumps during both heating and cooling seasons with the goal of minimizing total supply cost while considering the technical characteristics of the different technologies (variable cost, losses, efficiencies, COPs, others). Finally, as any technology in H2RES, heat pumps are also subject to decommission. Therefore, if a long-term planning scenario is analysed, heat-pump for cooling systems can be replaced for cheaper and more efficient technologies in future periods. It is important to note that H2RES can model any technology for which the user can supply the needed inputs which include the investment and other costs, efficiencies, ramp-up and down speeds and limits to the installed capacities. The current version of the H2RES model does not take grid losses into account, however they can be added as an additional demand. These functionalities will be added in future versions.

Table 1: Main input data files in H2RES

Demand file	Definition/Parameter	Notes
Demand data	Electricity demand per demand sector	Hourly electricity demand profile for each year in MWh
Heat demand data	General demand	Hourly individual heat demand profile for each year in MWh
	Industry demand	Hourly industry heat demand profile for each year in MWh
	DH demand	Hourly DH demand profile per DH network for each year in MWh
Cooling demand data	DC zones	Hourly DC demand profile per DC network for each year in MWh

	General demand	Hourly individual cooling demand for each year in MWh
H2 demand data	Hydrogen demand per demand sector	Hydrogen demand for each period and year in MWh
Fuel price data	Fuel price	Variable (fuel) price of fuel for each of the fuels considered in H2RES.
Availability factors	availability factor	Availability factor for all non-dispatchable zones, including wind, solar and HROR zones
Inflow data	Water inflows	Water inflows (scaled to capacity) for each of the HDAM and HPHS units defined in the power generator data files.
Import-export	Import and export net transfer capacity	Imports net transfer capacity (MWh) are always required.

3. Scenarios and implementation

As stated in the introduction, The Republic of Croatia has been used as a case study for this research. This Section provides details on the inputs and scenarios used in this process. It is also important to note that, even though H2RES supports multi-year scenarios, this research focuses on single-year scenarios meaning that some aspects of its functionalities, for instance decommission, are not utilized.

As H2RES is not a computationally demanding model, the scenarios developed for the purpose of this research have been implemented on a consumer grade laptop with an intel i7 processor and 16 GB of RAM. Each individual scenario has been calculated in less than 5 minutes.

3.1. Scope of the case study

The case study has considered the total electricity demand of the Republic of Croatia as stated in [34]. The heating and cooling demands of 9 cities have been considered, out of the 556 cities and municipalities in Croatia. The cities have been selected based on their location and size (6 largest continental/mild climate and 3 largest costal/Mediterranean climate cities) and the consideration if they already have a DH system (8 of the 9 cities have a DH system of some scale). There are currently no DC systems present in Croatia which also means that there are none in the 9 selected cities. Table 2 presents the scope of the case study. The 9 selected cities represent 37% of the total Croatian heating and 34% of the total Croatian cooling demand. The heating demands have been taken from [27] and cooling demands have been taken from [28].

Table 2 Scope of the case study

City	Heating demand MWh	Cooling demand MWh	Location	DH
Zagreb	8.257.006,82	2.121.063,25	Continental	Yes
Osijek	1.091.397,66	290.098,76	Continental	Yes
Split	928.099,75	606.437,04	Costal	Yes
Velika Gorica	655.852,50	170.538,14	Continental	Yes
Rijeka	653.951,94	437.963,20	Costal	Yes
Slavonski Brod	584.941,17	158.793,92	Continental	Yes
Karlovac	547.486,55	149.557,51	Continental	Yes

Sisak	464.509,38	128.251,98	Continental	Yes
Zadar	403.957,07	255.586,36	Costal	No
Total	13.587.202,83	4.318.290,16		
Croatia	36.288.855,02	12.521.269,96		
Coverage	37%	34%		

3.2. Demand and supply distributions

The hourly electricity demand for Croatia has been taken from [34]. The hourly space heating demand has been modelled for two climate zones, Continental based on the City of Zagreb and Coastal based on the City of Split using a degree hour analysis which resulting in two unit curves. The hourly domestic hot water demand has been taken from [35]. The final unit heating demands have been calculated using an 18% share of hot water demand against space heating demand for the Continental and 30% for the Costal climates. The Continental share has been taken from real data available in the City of Zagreb while the Costal share has been assumed considering the difference in overall heating degree days between Zagreb and Split. The hourly cooling demand distributions have been created as a combination of space cooling and baseline cooling demands and again for the same two climate zones based on Zagreb and Split. The baseline cooling demand has been created using the first week of the Gothenburg hourly DC demand distribution available in the EnergyPLAN model [36]. The space cooling demand has again been calculated as a degree hour analysis for two climate tones again represented by the City of Zagreb (continental) and City of Split (Costal). The final distribution has been created with an assumed share of the baseline demand of 60% in the Continental and 40% in the Costal climates as no data is available for Croatia.

The hourly supply distributions include the hourly electricity production from wind and solar and they have been taken from [37].

3.3. Technical and economic parameters

The following technical parameters have been used as inputs for the model:

1. Photovoltaics
    a. Hourly availability factor (0 – 1)
2. Wind powerplants
    a. Hourly availability factor (0 – 1)
3. CHP
    a. Electrical efficiency: 0,306
    b. Thermal efficiency: 0,647
    c. Power loss factor: 0,18
4. Heat pumps
    a. Heating COP: hourly model from [34]
    b. Cooling COP: hourly model from [34]
5. Heat storage:
    a. Storage self-discharge rate: 0,04

The investment costs for the technologies have been taken from [38]. Additionally, the system cost of CEEP has been set to 4.000 EUR/MWh

3.4. Scenario creation

To isolate and highlight the impact DH and the combination of DHC has on the potential for the utilization of intermittent renewable energy sources, two lines of scenarios have been developed:

1. DH plus renewable electricity generation;
2. DHC plus renewable electricity generation.

Renewable electricity generation in all scenarios means a combination of wind and PV (photovoltaics) in four intervals, namely steps of 2.000, 4.000, 6.000 and 8.000 MW of both wind and PV (for example in the 2.000 MW scenario this means 2.000 MW of wind and 2.000 MW of PV power simultaneously). These installed capacities and with that the hourly production of electricity from intermittent renewable sources have been used consistently across all scenarios. No additional electricity sources outside of the ones connected to the DHC systems have been permitted.

The energy systems in the scenarios with DH were permitted to utilize CHP, heat pumps, electric boilers and heat storage in order to satisfy the heating demand. In the scenarios with cooling, heat pumps were the only allowed source of cooling.

This has resulted in the development of the following 7 scenarios presented in Table 3.

Table 3 List of the developed scenarios

Scenario name	Description
REF	Reference scenario with no DH or DC
H1	DH share of 30% of total heat demand
H2	DH share of 50% of total heat demand
H3	DH share of 90% of total heat demand
HC1	DH share of 30% of total heat and DC share of 10% of total cooling demand
HC2	DH share of 50% of total heat and DC share of 30% of total cooling demand
HC3	DH share of 90% of total heat and DC share of 50% of total cooling demand

Additionally, each scenario except REF has been additionally tested with two limits to the use of electric boiler as a source of heating and power to heat capacities. For this purpose, two sub-scenarios have been created for the 6 scenarios with limits set to 600 MW and 2.500 MW of electric boilers.

In all six scenarios with DH and/or DC, the heat capacity of the CHP units has been set to match the peek heat demand in the individual systems so that the power to heat units can be optimized to the electricity demand and not the heat demand as well.

4. Results

The results of the performed assessments can be seen in the figures and tables below. Figure 3 presents the results of all 7 scenarios including the reference and the 6 combinations of DH and DC with a set limit for the use of electric boilers of 600 MW across all considered systems. Figure 4 presents the same results but with the limit on electric boilers set to 2.500 MW.

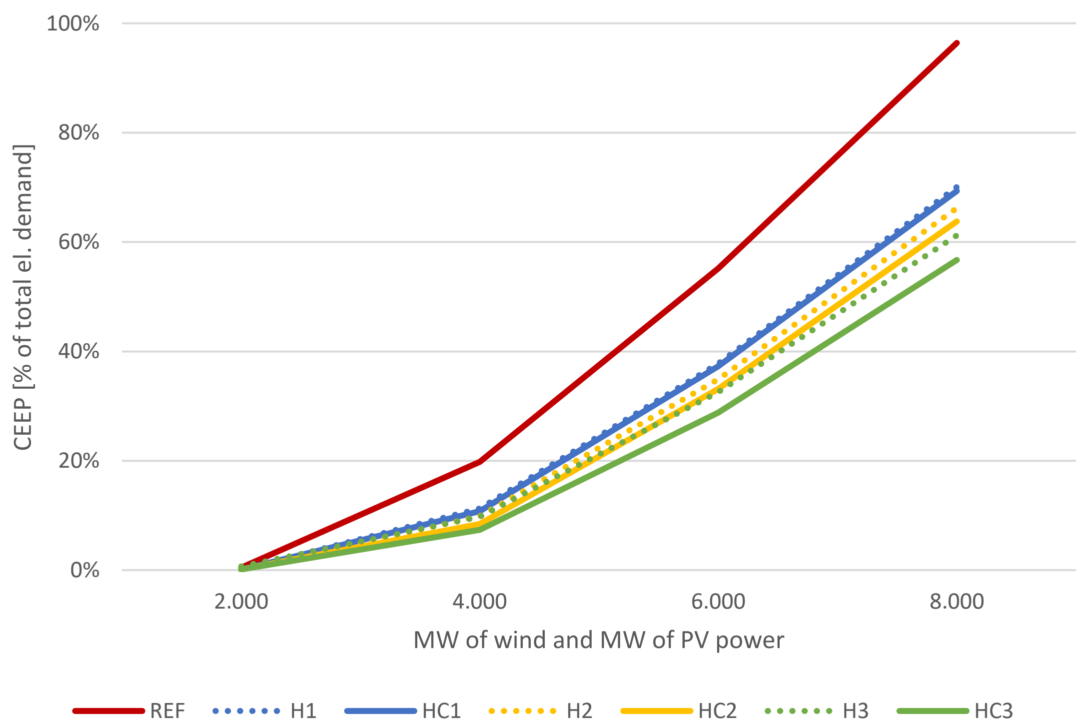


Figure 3 CEEP for all scenarios with electrical boiler limit of 600 MW

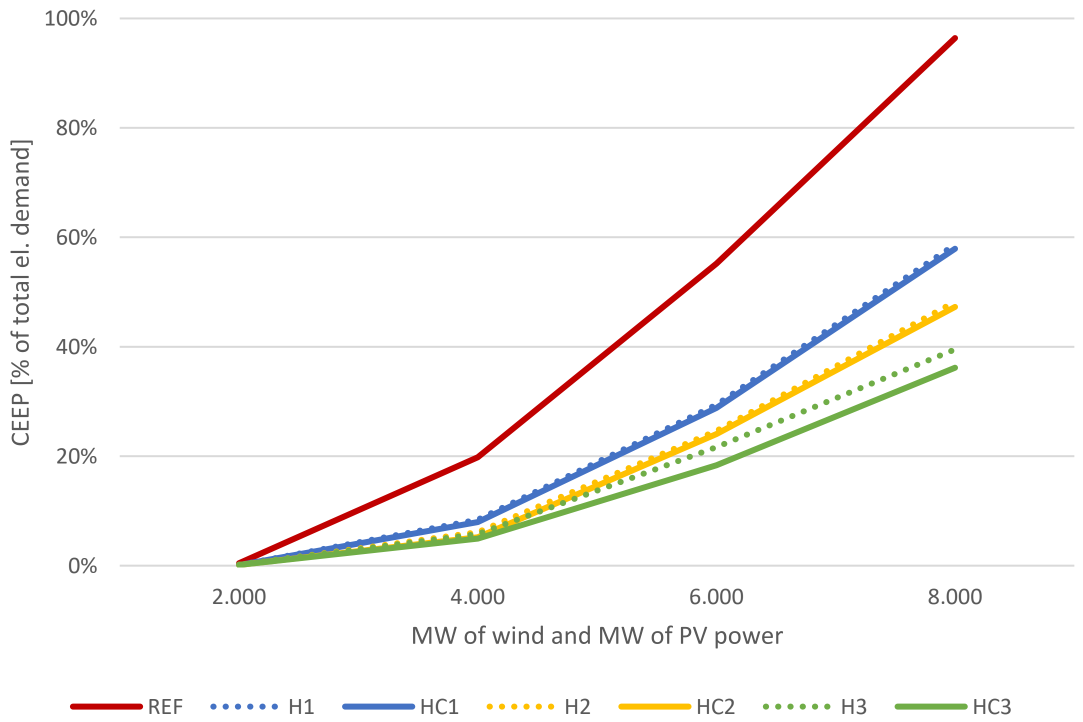


Figure 4 CEEP for all scenarios with electrical boiler limit of 2.500 MW

Table 4 shows the CEEP of the reference scenario and the six scenarios which include DH and/or DC with both electric boiler limits. It is evident from the presented results that the increase in the DH and DC capacities impacts the potential for the utilization of intermittent renewables favorably. If we compare the reference with any of the other six scenarios, we can observe a sharp decline in CEEP. For instance, in the case of the highest installed capacity of wind and PV power, 8.000 MW each, we can see that the CEEP is above 96% of the total electricity demand. If we compare that to scenario HC3 we can see that the number drops to roughly 57% in the case in which we limit the capacity of the electric boilers to 600MW total across all system and to roughly 36% if we set the limit to 2.500 MW. We can also observe a noticeable impact of DC on the reduction of CEEP across all cases. If we disregard the results for the 2.000 MW of installed wind and PV as the CEEP is almost negligible, the average reduction in CEEP when DC is added to the systems is close to 12%. Considering the relatively small cooling demand compared to heating as well as the fact that DH was set to values ranging from 30-90% compared to the 10-50% for DC, this can be considered a significant impact. If we look at the results of HC3, the system could easily absorb 4.000 MW of wind and 4.000 MW of PV which would produce upwards 17,13 TWh of electricity with roughly 5% CEEP. The total electricity demand in this case, including electricity for heat production, is 23,5 TWh, meaning that wind and PV could cover 73% of the total electricity demand. In comparison, the total electricity demand for the entirety of the Republic of Croatia is 18,32 TWh in the reference case.

Table 4 CEEP for all scenarios

		Installed wind and installed PV power [MW]			
Max. el. boiler	**Scenario**	**2.000**	**4.000**	**6.000**	**8.000**
	REF	0,45%	19,81%	55,19%	96,41%
600 MW	**H1**	0,12%	11,27%	37,77%	70,06%
600 MW	**HC1**	0,11%	10,78%	37,30%	69,34%
600 MW	**H2**	0,14%	9,87%	34,93%	66,20%
600 MW	**HC2**	0,13%	8,46%	33,15%	63,77%
600 MW	**H3**	0,68%	9,76%	32,57%	61,21%
600 MW	**HC3**	0,14%	7,35%	28,80%	56,72%
2.500 MW	**H1**	0,12%	8,39%	29,42%	58,67%
2.500 MW	**HC1**	0,11%	7,96%	28,81%	57,91%
2.500 MW	**H2**	0,14%	6,14%	24,64%	48,23%
2.500 MW	**HC2**	0,13%	5,19%	24,03%	47,28%
2.500 MW	**H3**	0,20%	5,78%	21,65%	39,52%
2.500 MW	**HC3**	0,14%	4,94%	18,35%	36,17%

Table 5 and Figure 5 present the installed capacities of Heat pumps for all six scenarios with a 600 MW limit on electric boilers across all scenarios. Table 6 and Figure 6 present the same results for a 2.500 MW limit. It is important to note that the installed capacities are aggregated across all systems, however the model selects them per system and utilizes them only in the one they are linked to. The utilization of Heat pumps varies across the scenarios, and it greatly depends on the availability of electric boilers. Due to their lower investment price and lower efficiency, the model prefers electric boilers at higher penetrations of intermittent renewables as they are capable of absorbing more electricity at a lower cost. This is especially evident in scenarios with a smaller share of DHC in which the system can't utilized the large amount of heat which would be produced by efficient heat pumps so it chooses to gradually reduce investments in heat pumps and replace them with electric boiler to utilize excess electricity. This impact is less evident in larger systems which a higher heating and cooling demands. In some of these cases, the investments into Heat pumps continue to increase, especially when electric boilers are limited, to enable to utilization of the produced electricity. Heat pumps are also essential in the scenarios with cooling as they are the only source of cooling the system permits.

Table 5 Installed capacity of Heat pumps [MW] for all scenarios with a 600 MW limit on electric boilers

	Installed wind and installed PV power [MW]			
Scenario	**2.000**	**4.000**	**6.000**	**8.000**
H1	3.643	1.761	839	702
HC1	3.615	1.861	787	817
H2	2.171	1.113	1.812	2.133
HC2	2.510	2.273	2.368	2.415
H3	1.332	2.500	3.081	3.570
HC3	3.789	3.789	3.789	3.904

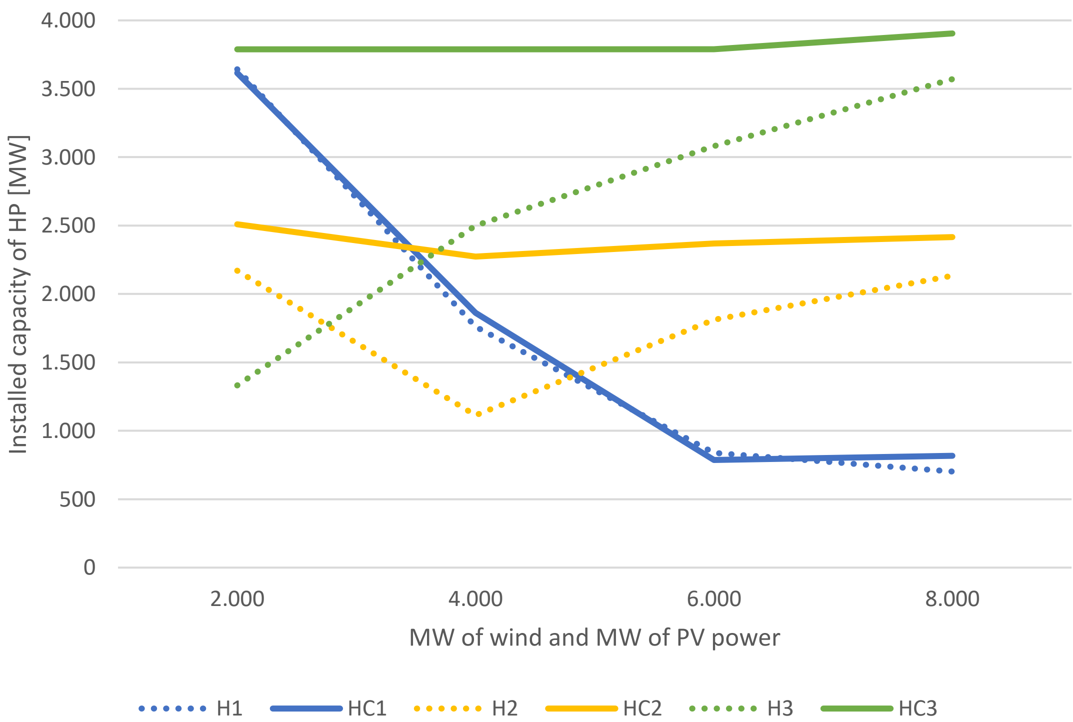


Figure 5 Installed capacity of Heat pumps [MW] for all scenarios with a 600 MW limit on electric boilers

Table 6 Installed capacity of Heat pumps [MW] for all scenarios with a 2.500 MW limit on electric boilers

	Installed wind and installed PV power [MW]			
Scenario	**2.000**	**4.000**	**6.000**	**8.000**
H1	3.643	1.623	484	0
HC1	3.615	1.749	758	758
H2	2.171	553	908	0
HC2	2.510	2.273	2.273	2.273
H3	131	0	288	1.353
HC3	3.789	3.789	3.789	3.789

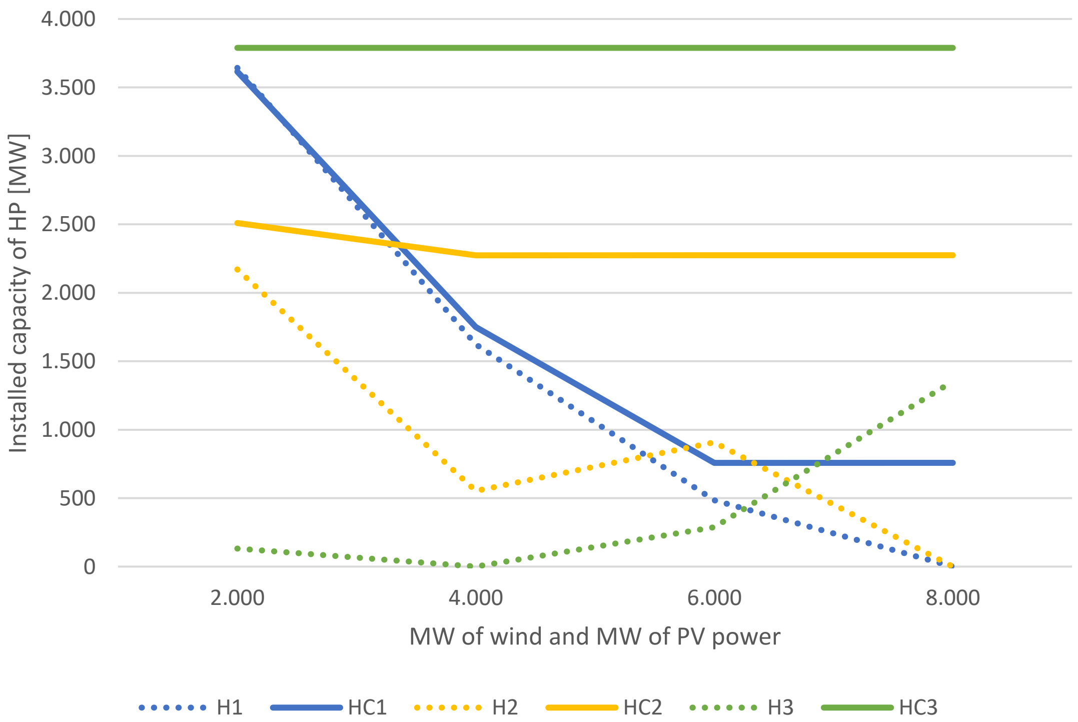


Figure 6 Installed capacity of Heat pumps [MW] for all scenarios with a 2.500 MW limit on electric boilers

Table 7 and Table 8 as well as Figure 7 and Figure 8 present the investments into electric boilers. As mentioned above, due to their low cost and low efficiency, the model prioritizes them as a power to heat option. It can be seen that the model continuously increases the investments into this technology up to the set limit as well as that the investments are lower in the scenarios with DC. This is to be expected as heat pumps are the only available source of cooling, so their utilization reduces the need for electric boilers.

Table 7 Installed capacity of Electric boilers [MW] for all scenarios with a 600 MW limit on electric boilers

	Installed wind and installed PV power [MW]			
Scenario	**2.000**	**4.000**	**6.000**	**8.000**
H1	133	600	600	600
HC1	93	600	600	600
H2	144	600	600	600
HC2	55	600	600	600
H3	600	600	600	600
HC3	72	600	600	600

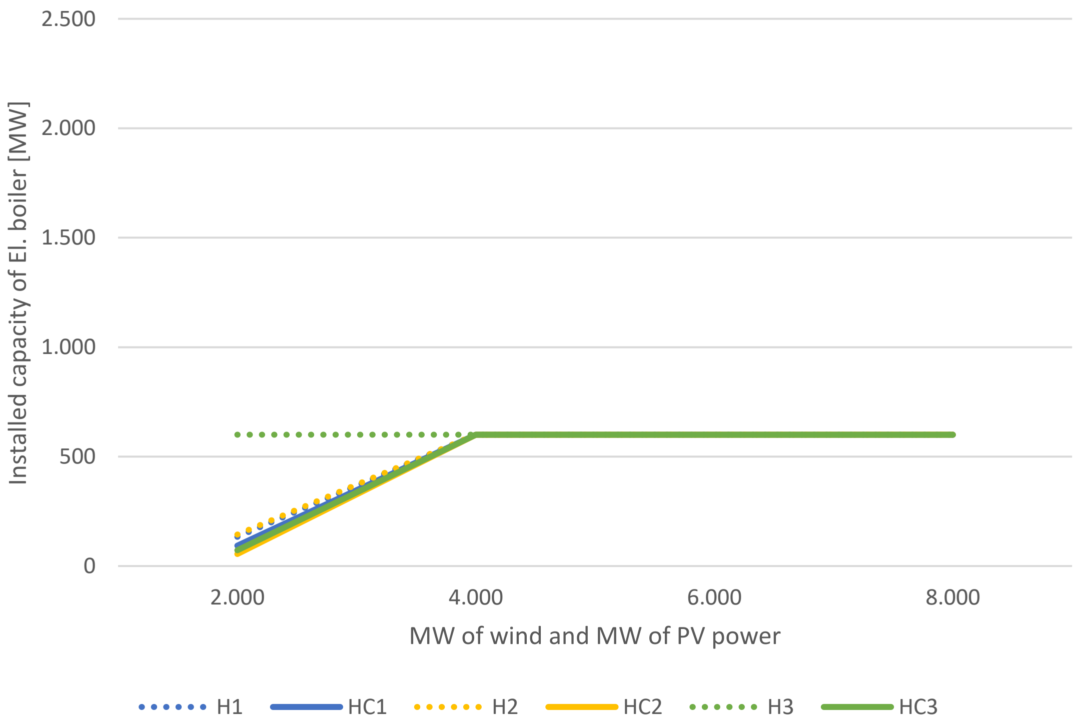


Figure 7 Installed capacity of Electric boilers [MW] for all scenarios with a 600 MW limit on electric boilers

Table 8 Installed capacity of Electric boilers [MW] for all scenarios with a 2.500 MW limit on electric boilers

	Installed wind and installed PV power [MW]			
Scenario	**2.000**	**4.000**	**6.000**	**8.000**
H1	133	1.528	2.000	1.875
HC1	93	1.515	1.991	1.822
H2	144	1.828	2.453	2.500
HC2	55	1.765	2.352	2.500
H3	1.408	2.379	2.500	2.500
HC3	72	1.327	2.500	2.500

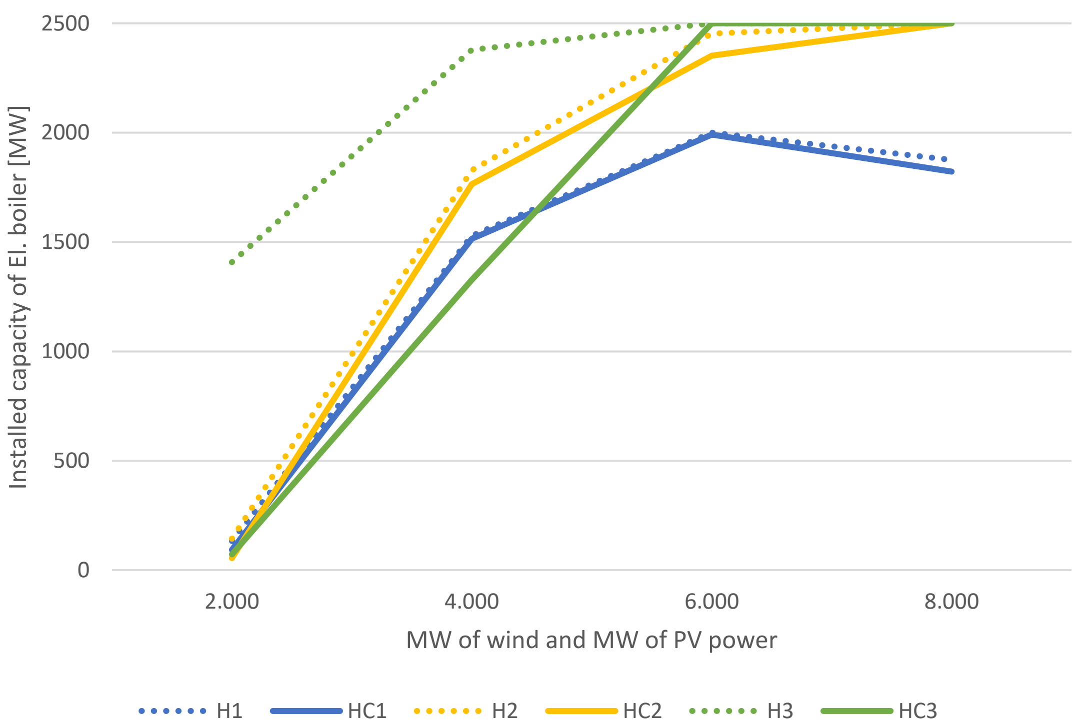


Figure 8 Installed capacity of Electric boilers [MW] for all scenarios with a 2.500 MW limit on electric boilers

Finally, Table 9 and Table 10 as well as Figure 9 and Figure 10 present the installed capacities of heat storage across all six scenarios and both electric boiler limits. It can be seen from the results that, as expected, an increase in the penetration of intermittent sources increases the need for energy storage. It is interesting to observe that higher shares of electric boiler led the model to select higher storage capacities. This can be attributed to the fact that CEEP has not been limited to a set value, but a cost has been attributed to it, meaning that at a certain level of investments into a combination of heat pumps and storage, the model decided that it is less costly to tolerate higher shares of CEEP then to continue investments into heat storage. It can also be seen that higher shares of DHC also reduced the need for heat storage due to the capacity of the larger systems to absorb more of the heat produced via power to heat systems.

Table 9 Installed capacity of Heat storage [MWh] for all scenarios with a 600 MW limit on electric boilers

	Installed wind and installed PV power [MW]			
Scenario	**2.000**	**4.000**	**6.000**	**8.000**
H1	11.352	11.781	15.261	64.569
HC1	11.217	11.781	15.298	66.787
H2	3.446	5.772	15.603	16.352
HC2	3.274	5.010	14.899	16.529
H3	0	2.158	2.628	5.010
HC3	0	1.796	2.615	2.664

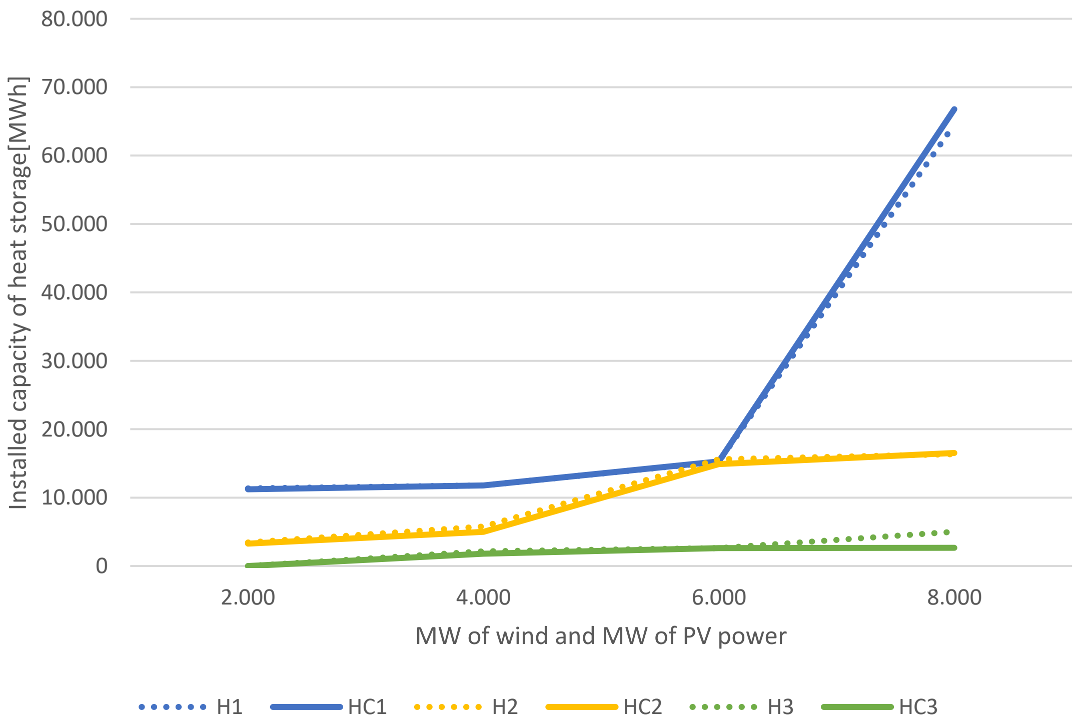
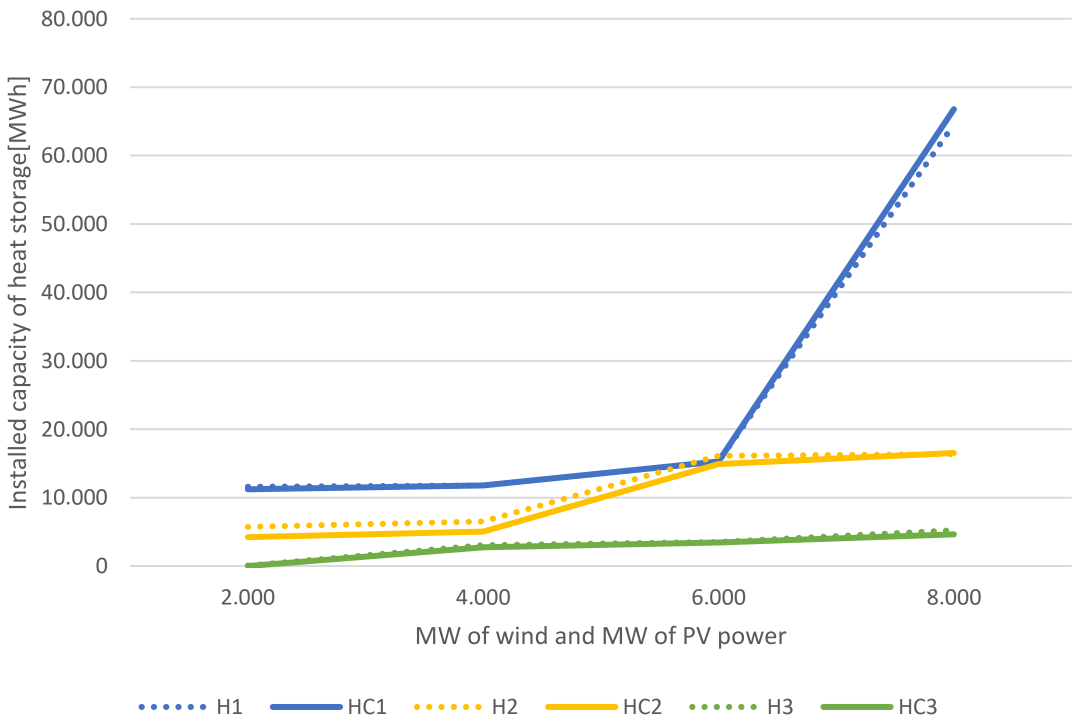


Figure 9 Installed capacity of Heat storage [MWh] for all scenarios with a 600 MW limit on electric boilers

Table 10 Installed capacity of Heat storage [MWh] for all scenarios with a 2.500 MW limit on electric boilers

	Installed wind and installed PV power [MW]			
Scenario	**2.000**	**4.000**	**6.000**	**8.000**
H1	11.585	11.781	15.261	64.569
HC1	11.217	11.781	15.298	66.787
H2	5.724	6.513	16.124	16.352
HC2	4.221	5.058	14.899	16.529
H3	76	3.056	3.526	5.227
HC3	0	2.750	3.425	4.633



404
405 **Figure 10 Installed capacity of Heat storage [MWh] for all scenarios with a 2.500 MW limit on electric**
406 **boilers**

407 ## 5. Conclusion

408 The research in this paper presents the capabilities of the upgraded linear optimisation tool
409 H2RES to set-up and model energy systems which consist of one electricity system and several
410 DH and DHC systems as well as the impact DH and DHC can have on the potential for the
411 utilization of intermittent energy sources such as wind and PV.
412 The presented version of H2RES has been updated to incorporate DC as one of its demand
413 streams. The tool can model one or several DC systems in parallel, all connected to same
414 overall electricity network, same as its previous capabilities to model DH. Additionally, the
415 DHC systems can be connected so that technologies, such as heat pumps, can satisfy both the
416 heating and cooling demand if set up in such a way.
417 The tool has been utilized to model an energy system consisting of several DHC systems in
418 Mediterranean and mild climates with a goal to assess their impact on the potential for the
419 utilization of intermittent renewables. As can be seen from the results, the impacts are
420 significant. When comparing the reference scenario with no DH or DC, we can see a sharp
421 increase in the generation of CEEP of up to 96% of the total electricity demand in the case with
422 8.000 MW of wind and 8.000 MW of PV. This figure drops to roughly 39% and 36% in the cases
423 with the highest levels of DH (H3) and DHC (HC3). If we look at the HC3 scenario, we can see
424 that at a level of 4.000 MW of wind and PV the CEEP is below 5% of the total electricity demand
425 which includes the electricity consumption of power to heat technologies when generating
426 heat. Wind and PV generate 17,13 TWh of the total 23,5 TWh of electricity consumed in this
427 scenario meaning that these two sources could generate 73% of the total electricity demand
428 while keeping CEEP below 5%. The reference electricity demand of the Republic of Croatia is
429 18,23 TWh. The results also demonstrate a significant impact of DC on CEEP especially
430 considering its low total demand compared to heating.

Overall, the presented research clearly demonstrates the positive impacts widescale DHC utilization can have on the potential for the penetration of intermittent sources for the generation of electricity if power to heat technologies are utilized.

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