Sveučilište u Zagrebu

FACULTY OF MECHANICAL ENGINEERING AND NAVAL ARCHITECTURE

BORNA DORAČIĆ

LEVELIZED COST OF EXCESS HEAT METHOD FOR THE ASSESSMENT OF ITS UTILISATION IN DISTRICT HEATING SYSTEMS

DOCTORAL THESIS

Zagreb, 2022

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"He who dares, wins!"

Derek "Delboy" Trotter

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SUMMARY

To fulfil the climate neutrality goals of the European Union, as set out in the Green Deal, it is necessary to move towards sustainable energy solutions in all the subsectors of the energy sector. This is especially relevant for heating, which is responsible for 80% of the final energy consumption in the European buildings. However, 64% of the heating demand is currently covered by the fossil fuels, which shows the urgent need to act. In high density heat areas, district heating has already proven to be a sustainable solution since it enables the utilisation of renewable energy sources and the use of highly efficient production technologies. Nevertheless, most of these systems still use fossil fuels, which shows the high need for transferring to the sustainable, low temperature 4th generation district heating systems of the future.

The main heat sources for these systems would be renewables such as solar thermal, geothermal and biomass, but also excess heat sources, which represent heat produced during the certain industrial or service sector process and wasted in the environment. Excess heat sources have shown to have a high technical potential in the European Union and other countries and continents. Some sources even report that the amount of available excess heat in Europe is high enough to cover the demand of both the households and tertiary buildings. Despite it, this source remains underutilised and the research in this area is scarce.

In this thesis, the feasibility of excess heat utilisation in district heating systems was analysed by developing and implementing the levelized cost of excess heat method. The method was used to show the spatial feasibility of these sources for both high temperature and low temperature excess heat. The impact of certain parameters of the levelized cost of heat (including the capacity factor in different system configuration and the temperature level of the excess heat source) has been analysed to show their effect on the overall feasibility of this source. Furthermore, the importance of using dedicated thermal storage units for excess heat to increase their utilisation and subsequently the feasibility has been analysed and discussed. Finally, the participation of high and low temperature excess heat sources on the wholesale heat market has been studied, specifically calculating their feasibility by using levelized cost of excess heat. The results of this thesis show the high potentials of excess heat sources from the economic perspective, but also emphasize the need for shifting towards the 4th generation district heating to make the low temperature excess heat utilisation feasible.

SAŽETAK

Kako bi se ispunili ciljevi klimatske neutralnosti Europske unije, navedeni u Europskom Zelenom Planu, potrebna je tranzicija prema održivim energetskim rješenjima u svim sektorima energetike. To je posebno važno za sektor grijanja, koji je odgovoran za 80% finalne potrošnje energije u europskim zgradama. Međutim, 64% toplinskih potreba je trenutno pokriveno izgaranjem fosilnih goriva, što pokazuje hitnu potrebu za djelovanjem. U područjima visoke gustoće toplinskih potreba, centralizirani toplinski sustavi su se već pokazali kao održivo rješenje jer omogućuju korištenje obnovljivih izvora energije i visokoučinkovitih tehnologija. Ipak, većina ovih sustava još uvijek koristi fosilna goriva, što pokazuje veliku potrebu za prelaskom na održive, nisko temperaturne centralizirane toplinske sustave 4. generacije.

Glavni toplinski izvori za sustave 4. generacije bili bi obnovljivi izvori kao što su sunčeva energija, geotermalna energija i biomasa, ali i otpadna toplina koja predstavlja toplinu proizvedenu tijekom određenog procesa u industrijskom ili uslužnom sektoru i koja se gubi u okoliš. Pokazalo se da izvori otpadne topline imaju visok tehnički potencijal u Europskoj uniji, ali i drugim državama. Neki radovi čak navode da je količina raspoložive otpadne topline u Europi dovoljno visoka da pokrije toplinske potrebe kućanstava i zgrada uslužnog sektora. Unatoč tome, ovaj izvor ostaje nedovoljno iskorišten te je broj istraživanja u ovom području relativno malen.

U ovom doktorskom radu analizirana je isplativost iskorištavanja otpadne topline u centraliziranim toplinskim sustavima razvojem i primjenom metode niveliranog troška otpadne topline. Metoda je korištena kako bi se pokazala prostorna isplativost visoko temperaturnih i nisko temperaturnih izvora otpadne topline. Analiziran je utjecaj pojedinih parametara niveliranog troška otpadne topline (uključujući faktor kapaciteta u različitim konfiguracijama sustava i temperaturu izvora otpadne topline) kako bi se pokazao njihov utjecaj na ukupnu isplativost ovog izvora topline. Nadalje, analizirana je i diskutirana važnost korištenja toplinskih spremnika za otpadnu toplinu kako bi se povećala njihova iskorištenost. Analiza je obuhvatila i povećanje isplativosti sustava prilikom korištenja toplinskih spremnika. Konačno, istraženo je i analizirano sudjelovanje visoko i nisko temperaturnih izvora otpadne topline na tržištu toplinske energije, sa posebnim fokusom na izračun isplativosti korištenjem metode niveliranog troška otpadne topline. Rezultati ovog rada pokazuju visoke potencijale izvora otpadne topline, ali i naglašavaju potrebu za prelaskom na centralizirane toplinske sustave 4. generacije kako bi se potaknulo iskorištavanje nisko temperaturne otpadne topline.

PROŠIRENI SAŽETAK

Ključne riječi: Centralizirani toplinski sustavi, Otpadna toplina, Nivelirani trošak otpadne topline, Energetsko planiranje, Obnovljivi izvori energije, Tržište toplinske energije

Ciljevi Europske unije u pogledu smanjenja emisija stakleničkih plinova do 2050. godine su već sada vrlo ambiciozni te zahtijevaju trenutačno djelovanje. To se naročito odnosi na toplinski sektor, s obzirom da 40% potrošnje finalne energije otpada na potrošnju u zgradama, a 80% te vrijednosti se odnosi na toplinsku energiju za zagrijavanje prostora [1]. Nadalje, 50% ukupne potrošnje finalne energije u Europi otpada na grijanje i hlađenje, što dodatno potvrđuje važnost ovog sektora za dekarbonizaciju europskog gospodarstva do 2050. godine. Kao idealno rješenje u područjima visoke gustoće toplinskih potreba, kao što su gradovi, nameću se centralizirani toplinski sustavi. Oni proizvode toplinsku energiju na centralnoj lokaciji u visokoučinkovitim postrojenjima te ju distribuiraju do krajnjih korisnika putem toplovoda. Već su mnogo puta dokazane prednosti ovih sustava, kao na primjeru Danske gdje autori zaključuju da podizanje udjela centraliziranih toplinskih sustava u pokrivanju toplinskih potreba rezultira značajnim smanjenjem emisija stakleničkih plinova, i troškova te uštedama goriva [2]. Međutim, većina ovih sustava, naročito u zemljama istočne i jugoistočne Europe, mora se unaprijediti na visokoučinkovitu i održivu 4. i 5. generaciju sustava [3] kako bi se umanjio utjecaj na okoliš te omogućilo korištenje nisko temperaturnih izvora topline.

Kao glavni izvori u sustavima 4. generacije spominju se obnovljivi izvori poput energije sunca, geotermalne energije te biomase [4], kao i otpadna toplina dobivena iz različitih procesa u industrijskom ili uslužnom sektoru. Upravo otpadna toplina predstavlja iznimno zanimljiv toplinski izvor, s obzirom da su dokazani tehnički potencijali, kako na razini Europske unije [5], tako i u ostalim državama poput Kine [6] i Japana [7]. Na primjer, smatra se da je količina dostupne otpadne topline u Europi dovoljno velika da pokrije toplinske potrebe svih europskih kućanstava i zgrada uslužnog sektora [8]. Međutim, kako bi različiti proizvođači otpadne topline mogli istu predavati u postojeće centralizirane toplinske sustave, potrebno je omogućiti pristup treće strane, tj. implementirati deregulirano tržište toplinske energije [9]. Većina toplinskih tržišta u Europi je i dalje monopolistička, što znači da jedna tvrtka drži monopol nad proizvodnjom, distribucijom i prodajom toplinske energije te na taj način onemogućuje pristup treće strane kao i ekonomske i ekološke prednosti koje bi rezultirale omogućavanjem većem broju aktera da sudjeluju na tržištu toplinske energije. Kao dobar primjer se spominje Litva,

gdje je neovisnim proizvođačima topline dozvoljeno predavanje toplinske energije u distribucijsku mrežu što dovodi do smanjenja troškova za krajnje korisnike [10].

Iako je količina postojeće otpadne topline značajna, kako bi se omogućilo njeno korištenje u centraliziranim toplinskim sustavima potrebno je uložiti u tehnologiju za njeno iskorištavanje. Ovisno o temperaturi samog izvora otpadne topline, podjela se simplificirano može izvršiti na izmjenjivače topline ukoliko je temperatura pojedinog izvora veća od temperature u distribucijskoj mreži centraliziranog toplinskog sustava te dizalice topline ukoliko je temperatura manja. Upravo stoga što se radi o dodatnom ulaganju u opremu, nameće se metoda niveliranog troška energije, kao mjerodavan kriterij za određivanje isplativosti iskorištavanja različitih izvora otpadne topline. Ova metoda uzima u obzir sve troškove tijekom životnog vijeka projekta, tj. tehnologije kako bi se odredio specifični trošak energije proizvedene iz određene tehnologije, uzimajući u obzir vremensku vrijednost novca. Na taj način se dobiva minimalna cijena koju toplina proizvedena na ovaj način treba postići na tržištu da bi se isplatilo ulaganje. Kao kriterij za ulaganje, ova metoda se često koristi za usporedbu različitih tehnologija proizvodnje električne energije. Na primjer, korištena je za usporedbu nuklearnih i plinskih elektrana [11], konvencionalnih elektrana i vjetroelektrana [12], kao i za usporedbu tehnologije sunčevog dimnjaka i ostalih obnovljivih izvora energije [13]. S druge strane, pregledom postojećih istraživanja, zaključuje se da se u toplinskom sektoru spomenuta metoda znatno manje koristi. Na primjer, koristi se za analizu isplativosti mjera energetskih ušteda i proizvodnje toplinske energije u Europskoj Uniji [14] te solarnih kolektora sa Fresnelovim ogledalima [15]. U konačnici može se zaključiti da, iako je često korištena u drugim sektorima, ova metoda se trenutno ne primjenjuje za analizu isplativosti i izračun raznih parametara otpadne topline u centraliziranim toplinskim sustavima.

CILJ I HIPOTEZA

Ciljevi ovog istraživanja mogu se sažeti u sljedeće tri točke:

1. Uspostaviti kriterije za utvrđivanje isplativosti ulaganja u opremu za iskorištavanje otpadne topline korištenjem metode niveliranog troška otpadne topline

2. Demonstrirati isplativost korištenja otpadne topline u centraliziranim toplinskim sustavima s različitim konfiguracijama tehnologija za proizvodnju topline, primjenom prethodno razvijene metode

3. Procijeniti funkcionalnost lokalnog dereguliranog tržišta toplinske energije

Hipoteza ovog istraživanja je da se metoda niveliranog troška otpadne topline treba koristiti kao kriterij za iskorištavanje otpadne topline iz industrijskog i uslužnog sektora u centraliziranim toplinskim sustavima, pri čemu se dobiva minimalna cijena koja bi omogućila različitim proizvođačima otpadne topline da sudjeluju na lokalnom dereguliranom tržištu topline.

ZNANSTVENI DOPRINOS

Znanstveni doprinosi ovog istraživanja su metoda niveliranog troška otpadne topline za procjenu njenog korištenja u centraliziranim toplinskim sustavima, uzimajući u obzir sustave sa različitim izvorima topline te metoda za procjenu funkcionalnosti lokalnog dereguliranog tržišta toplinske energije.

METODE I POSTUPCI

Ciljevi ovog doktorskog rada su obrađivani u 5 objavljenih znanstvenih radova te prikazani rezultati kronološki prate spomenute radove. Kroz objavljene radove je potvrđena postavljena hipoteza te su postignuti prethodno navedeni ciljevi. U sljedećim odlomcima će se ukratko predstaviti glavni rezultati pojedinih radova.

U radu PAPER 1 korištenjem niveliranog troška topline razvijena je metoda za izračun isplativosti integracije otpadne topline u centralizirani toplinski sustav, koja uzima u obzir i udaljenost izvora otpadne topline do glavne mreže centraliziranog toplinskog sustava. Uz to, integracijom sa geografskim informacijskim sustavom metoda se može primijeniti i za definiranje gradskih područja u kojima je isplativo spajanje potrošača na centralizirani toplinski sustav, što može značajno doprinijeti budućem planiranju toplinskih sustava u gradovima. Rezultati pokazuju isplativost visoko temperaturnih izvora otpadne topline, čak i kada su locirani na većim udaljenostima od samog mjesta potrošnje. Ovisno o određenim parametrima, kao što su specifična cijena toplovoda i količina dostupne otpadne topline, maksimalna isplativa udaljenost izvora otpadne topline u analiziranom slučaju može biti više od 23 km, a rezultati su pokazali da i u slučaju nepovoljnih parametara integracija otpadne topline ostaje isplativa ukoliko se izvor nalazi u neposrednoj udaljenosti mreže toplovoda. Ovim radom je pokriven prvi cilj doktorskog rada.

U radu PAPER 2 je prethodno razvijena metoda proširena kako bi se uzeli u obzir i nisko temperaturni izvori otpadne topline, kao i promjena faktora kapaciteta ovih izvora ovisno o različitim konfiguracijama sustava. Analiza je rađena na satnoj razini u vremenskom okviru od godinu dana te je u svrhu modeliranja različitih konfiguracija sustava korišten alat energyPRO [16]. Pritom je uzeta u obzir i varijacija dostupnosti otpadne topline na satnoj razini. Rezultati pokazuju da je iskoristivost otpadne topline znatno manja od 100% ukoliko se u sustavu nalaze i solarni kolektori, s obzirom da tijekom ljeta zbog njihovog niskog troška imaju prednost nad otpadnom toplinom zbog čega se ista ne koristi. Ostale tehnologije proizvodnje toplinske energije se nisu pokazale kao konkurenti visoko temperaturnoj otpadnoj toplini, međutim potrebno je naglasiti da čak i kada u sustavu nema solarnih kolektora, iskoristivost ovog izvora je znatno manja od 100% zbog njegovog nepodudaranja sa toplinskim potrebama. Ovo se naročito može primijetiti u ljetnim mjesecima kada se velike količine otpadne topline ne mogu iskoristiti zbog niskih toplinskih potreba. Stoga je jasan zaključak da je za postizanje visokih faktora kapaciteta ovog izvora potrebno korištenje toplinskog spremnika. Nadalje, kada se uzme u obzir temperatura izvora otpadne topline, može se primijetiti kako nivelirani trošak otpadne topline znatno raste sa smanjenjem temperature izvora. Međutim, to se odnosi na integraciju otpadne topline u centralizirane toplinske sustave 3. generacije s visokim temperaturama polaza. Ukoliko se temperature krajnjih korisnika, a samim time i polaza u toplovodu smanje, isplativost nisko temperaturne otpadne topline raste, tj. njen nivelirani trošak topline pada. U sklopu ovog rada je pokazan i utjecaj temperature otpadne topline na njenu maksimalnu isplativu udaljenost od krajnjih korisnika. Ovim radom se obrađuju prvi i drugi cilj doktorskog rada.

U radu PAPER 3 analizirana je integracija toplinskih spremnika za skladištenje otpadne topline, na temelju prethodnih rezultata. Korištenjem metode niveliranog troška topline, analiziran je trošak sustava za različite veličine toplinskog spremnika, uključujući kratkoročne čelične spremnike i ukopane sezonske spremnike te utjecaj veličine toplinskog spremnika na iskorištavanje otpadne topline. Pokazano je da se isključivo sezonskim toplinskim spremnikom može postići teoretski potpuno iskorištenje otpadne topline, zbog velikih nesrazmjera između dostupne otpadne topline i toplinskih potreba tijekom ljetnih razdoblja. Isto tako je pokazano da su sezonski toplinski spremnici i najekonomičnije rješenje s obzirom na njihov nizak specifični trošak, koji rezultira najnižim troškom cjelokupnog sustava. Kada se takav spremnik koristi, moguće je iskoristiti 100% dostupne visoko temperaturne otpadne topline, bez obzira na postojanje solarnih kolektora u sustavu, kao tehnologije s nižim troškovima. Ovim radom se obrađuje drugi cilj doktorskog rada.

U radu PAPER 4 je analizirana integracija visoko i nisko temperaturne otpadne topline u deregulirano tržište toplinske energije. U svrhu toga je korišten model DARKO koji omogućuje modeliranje dan unaprijed tržišta toplinske energije, uzimajući u obzir sve specifičnosti toplinskog sektora. U prvom koraku je pokazana općenita korist implementacije dereguliranog tržišta toplinske energije, kao i dodatna korist omogućavanja otpadnoj toplini i solarnim kolektorima da sudjeluju na takvom tržištu. To se može iščitati iz izračunate ukupne dobrobiti za cjelokupni sustav, koja je u svakom slučaju bila pozitivna i koja je rasla integracijom spomenutih izvora topline. Maksimiziranje ukupne dobrobiti predstavlja i funkciju cilja ovog modela. Nadalje, korištena je metoda niveliranog troška otpadne topline kako bi se odredila minimalna cijena koju taj izvor mora imati na tržištu toplinske energije kako bi bio isplativ. Usporedbom niveliranog troška otpadne topline i prosječne postignute cijene na tržištu toplinske energije za pojedini izvor topline dobiva se informacija o njegovoj isplativosti. Na taj način je potvrđena hipoteza ovog doktorskog rada. Također je u radu analiziran utjecaj integracije otpadne topline na postignutu cijenu na tržištu toplinske energije, koja se značajno smanjuje kada se koriste ovi izvori. U konačnici se može zaključiti da su visoko temperaturni izvori otpadne topline uvijek isplativi na analiziranom tržištu, dok trošak nisko temperaturnih izvora, bez obzira na njihovo korištenje u određenim satima tijekom godine, jednostavno ostaje previsok da bi bili isplativi u visoko temperaturnim centraliziranim toplinskim sustavima. Ovim radom su pokriveni ciljevi dva i tri doktorskog rada.

U radu PAPER 5 su analizirane dvije različite strategije formiranja ponuđene cijene na tržištu toplinske energije s aspekta proizvođača topline. Fokus je bio na korištenju marginalnog troška te ukupnog troška za definiranje spomenute cijene. Pokazano je da analizirane strategije imaju najveći utjecaj na iskorištavanje nisko temperaturne otpadne topline, s obzirom na varijabilnost njenih pogonskih troškova vezanih uz potrošnju električne energije za dizalice topline. Dok korištenjem ukupnih troškova nisko temperaturni izvori otpadne topline mogu postići višu cijenu na tržištu toplinske energije, korištenjem marginalnih troškova se postiže veći stupanj iskorištavanja ovih izvora s obzirom na nižu cijenu. Usprkos tome, nisko temperaturni izvori otpadne topline ostaju neisplativi na ovakvom tržištu, bez obzira na korištenu strategiju. U konačnici je analiziran i utjecaj promjene cijena na tržištu električne energije na iskoristivost nisko temperaturne otpadne topline. Pokazano je da višegodišnje varijacije cijene električne energije znatno utječu na iznos satne ponude nisko temperaturne otpadne topline na tržištu toplinske energije, a samim time i na iskorištenje ovih izvora topline. To se naročito odnosi na one izvore nisko temperaturne otpadne topline sa nižim temperaturama. Ovim radom se dodatno obrađuje treći cilj doktorskog rada.

.

KEYWORDS

District heating

Excess heat

Levelized cost of excess heat

Energy planning

Renewable energy sources

Heat market

KLJUČNE RIJEČI

Centralizirani toplinski sustav

Otpadna toplina

Nivelirani trošak otpadne topline

Energetsko planiranje

Obnovljivi izvori energije

Tržište toplinske energije

LIST OF ABBREVIATIONS

CHP_BIO	Biomass cogeneration
COP	Coefficient of Performance
CROPEX	Croatian Power Exchange
DARKO	Day Ahead Market Model
EH_HOSP	Excess heat from hospital
EH_IND	Excess heat from industry
EH_SMARK	Excess heat from supermarkets
EU ETS¸	EU Emission Trading System
EU	European Union
GIS	Geographic Information System
HOBO_GAS	Natural gas heat only boiler
LCOEH	Levelized cost of excess heat
LCOH	Levelized cost of heat
MCP	Market clearing price
TS_EH	Thermal storage for excess heat
TS_SOLAR	Thermal storage for solar thermal

NOMENCLATURE

c^{do}	Overall cost function of hourly demand orders on the heat market, €
c_{el}	Price of electricity, € kWh^{-1}
$c_{el,th}$	Costs of the required electricity consumption of the heat pump, € kWh^{-1}
$c_{excess\ heat}$	Price of excess heat, € kWh^{-1}
c_{fuel}	Fuel cost, € kWh^{-1}
c_h	Price of heat, € kWh^{-1}
c_p	Cost of distribution network installation, € m^{-1}
c_{pipes}	Discounted cost of pipes, € m^{-1}
CRF	Capital recovery factor, -
c^{so}	Overall cost function of simple hourly orders on the heat market, €
D_{pv}	Present value of depreciation, -
E_{DH}	Heat demand being covered by conventional district heating, kWh
E_{EH}	Available excess heat, kWh
E_{total}	Total heat demand of the analysed area, kWh
i	Capacity factor of the heat production facility, %
I_c	Capital cost of the heat production facility, € kW^{-1}
I_{HE}	Capital cost of the heat exchangers, € kW^{-1}
I_{HP}	Capital cost of the heat pump, € kW^{-1}
l_s	Average specific distribution network length, m
l	Average length of distribution network in a 100x100 m area, m
n	Number of 100x100 m areas, -
$O_{HE,total}$	Total operation and maintenance costs of the heat exchangers, € kWh^{-1}
$O_{HP,total}$	Total operation and maintenance costs of the heat pump, € kWh^{-1}
O_{total}	Total operation and maintenance costs of production facility, € kWh^{-1}

P_{do}^{i}	Price of demand orders in the trading period i, € MWh^{-1}
P_{so}^{i}	Price of simple orders in the trading period i. € MWh^{-1}
Q	Heat demand of a single 100x100 m area, kWh
Q_{do}^{i}	Quantity of demand orders in the trading period i, MWh
Q_{so}^{i}	Quantity of simple orders in the trading period i. MWh
R	Potential revenue for a district heating system in a 100x100 m area, €
R_{EH}	Extra revenue, €
r_{heat}	Revenue from heat, € kWh^{-1}
T	Tax rate, %
w_{tot}	Social welfare, €
x_{do}^{i}	Demand orders acceptance ratio in trading period i, %
x_{so}^{i}	Simple orders acceptance ratio in trading period i, %

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1 INTRODUCTION

1.1 Background

In terms of the development of the European energy sector, the focus of the EU is on reducing its environmental effect, all the while increasing the security of supply. This is especially highlighted in the recently published Green Deal [17], the plan of the European Commission for the sustainable economy in the EU. The goal is to make the EU economy climate neutral until 2050, by reducing the greenhouse gasses emissions to net zero levels. Even the goals for 2030 are already ambitious and demand an immediate action to achieve them. They include the improvement of energy efficiency by at least 32.5%, increase of the share of renewable energy to at least 32% and reduction of greenhouse gasses emissions by at least 40% compared to 1990 levels [18]. These goals are made more ambitious in the Green Deal, with the proposed target of 55% of greenhouse gasses emissions reduction by 2030.

Hence, in order to move towards the sustainable society of the future, suitable technologies need to be used in all the subsectors of the energy sector. In terms of heating, this means moving the focus in the high heat density areas from the individual heating solutions to district heating systems and the potential for this shift is significant. This can be easily shown by the fact that only 13% (9% in EU28 [19]) of the overall heat demand in Europe is covered by district heating [20], while 64% is being directly supplied by fossil fuels [21]. The predominant heating technology in households and commercial buildings are still individual heating solutions, usually as centralized boilers on the building level or individual furnaces. Such systems generally utilise fossil fuels, e.g. fuel oil or natural gas, and/or some form of biomass. All these sources have a negative environmental effect, especially biomass when utilised in old and inefficient furnaces which results in high emission of local pollutants and negative health impact on the local level as discussed in Ref. [22].

Nevertheless, certain countries already exhibit high shares of district heating, especially the northern European countries such as Sweden at 55% [23] and Lithuania at 57% [10], which recognized the benefits early on and act as lighthouses for the other countries. The significance of this technology was also recognized by the European Commission in the first EU Strategy on Heating and Cooling [24], where it is emphasized as a means of integrating renewables and providing additional flexibility to the energy systems.

It must be emphasized that district heating is not a new technology and its benefits have already been proven numerous times. For example, it was shown that increasing the share of district heating in Denmark to the optimal 70% would result in significant CO_2 emissions reduction, fuel savings, as well as cost reductions [25]. But in order to contribute to reducing the environmental effect of the heating sector and integrate into the smart energy systems of the future, district heating needs to evolve from the current second and third generation systems to the 4th and even 5th generation. The concept of the 4th generation has first been defined in Ref. [3] and it showed the need for lower temperatures in the distribution network, renewable energy sources for heat production, thermal storage systems, power to heat options, etc. Additionally, the specifics of the 5th generation include further decreased ultra-low temperature levels [26], as well as the bi-directional flow of heat [27]. A brief overview of the characteristic of different generations is shown in Figure 1.

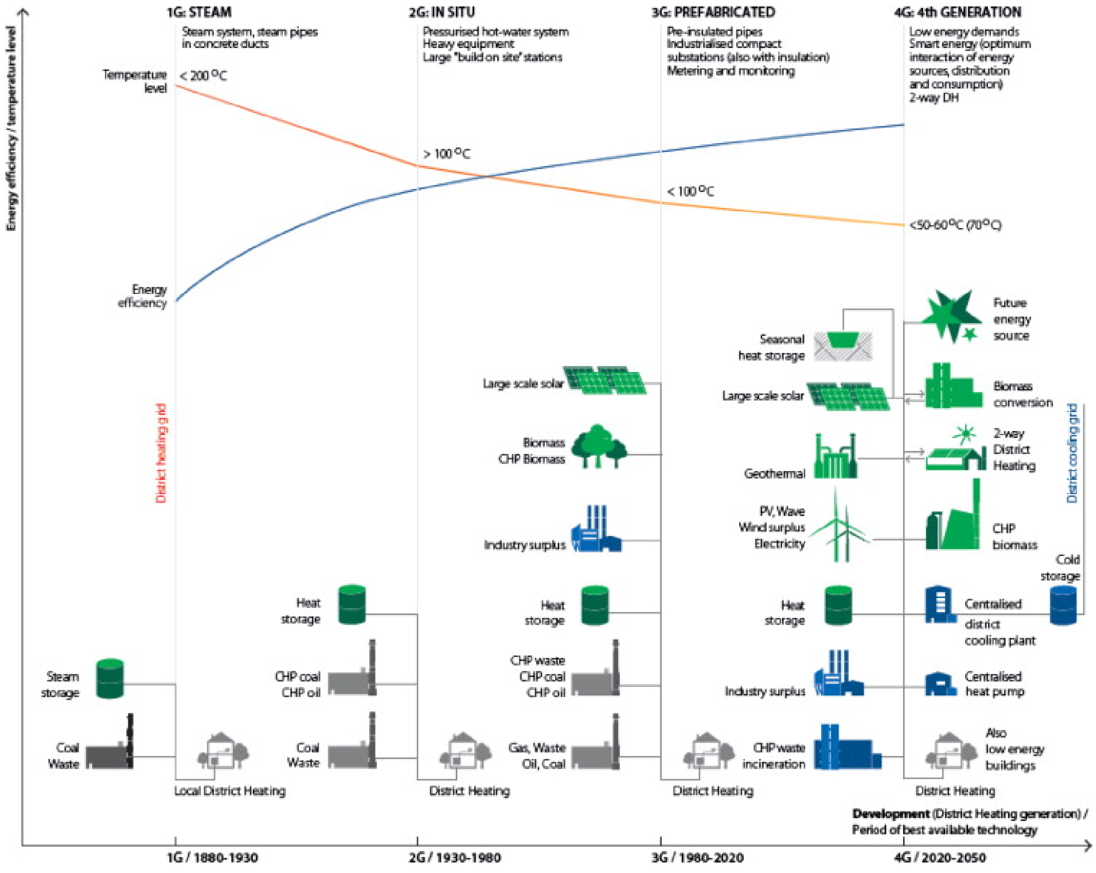


Figure 1 Four generations of district heating and their characteristics [3]

Despite some systems, mainly in Nordic countries, already operating as 4th generation, most of the district heating in Europe is still 2nd or 3rd generation, encompassing high supply and return temperatures and running mostly on fossil fuels. Not only do high distribution temperatures prevent the use of low temperature sources and inexpensive plastic pipes, but they also maintain high energy losses in the system. For example, this was shown in Ref. [28], where authors compared district heating systems in Croatia and Denmark and concluded that the heat losses in the Croatian system are approximately three times higher compared to the Danish system due to the old pipes and high system temperatures. In the end, these losses in the distribution system substantially impact the overall system performance as shown by analysing data from various plants in Italy [29]. Such inefficient district heating systems need to be upgraded to achieve 4th generation of district heating in the transition period [30].

From the perspective of transiting towards renewable district heating, the reason is naturally the lower environmental impact, but the additional benefit is the decrease of heat production costs, when compared to traditional fossil fuel systems, as shown in Ref. [31]. The most frequently used renewables include biomass (utilised through heat only boilers or cogeneration) and solar thermal and they are usually the main considered upgrading option for the existing systems [4]. Here it must be pointed out that using biomass in district heating does not result in high pollution and subsequent health impacts, in contrast to when it is used in individual household furnaces. This is due to the high efficiency and the filtration systems of the modern boilers and cogeneration units. Additionally, geothermal, power to heat (when electricity is produced by renewable technologies) and excess heat can also be used and have significant potentials. Various analyses have been performed and proved benefits for different combinations of renewables in district heating, including solar thermal and thermal storage [32], combination of biomass and solar thermal [33], combination of solar thermal and heat pumps [34] and geothermal energy [35]. Especially the combination and integration of different renewable sources with storage technologies will lead the way towards the integrated smart energy systems and the 4th generation of district heating [36].

When debating about the future low temperature systems, excess heat from various industrial and service sector activities emerges as a rather interesting source of energy. It is always discussed alongside all the other renewable energy sources despite usually not being renewable at its source. However, it does represent heat which is not being utilised for any meaningful purposes and which is produced as waste and rejected during the process in question. Therefore, if not used for industrial final energy demand or in district heating this heat would be wasted, and currently mostly is wasted, in the air or water, depending on the installed cooling system at the industrial or service sector facility. Hence this source has a significant potential to decrease the environmental effect and the costs of district heating in general and therefore benefit both the producers and consumers.

1.2 Motivation and general overview

As already mentioned, the goals of the EU in terms of reducing the greenhouse gasses emissions until 2050 are very ambitious and require a drastic shift towards low carbon technologies in the energy sector. This is especially relevant for the most energy intensive sectors. For example, buildings are responsible for 40% of the final energy consumption in Europe and heating is responsible for the 80% of that amount [1]. Moreover, as an energy subsector, heating and cooling is responsible for 50% of the overall final energy demand in Europe, which shows its relevance in the energy transition to the low carbon society.

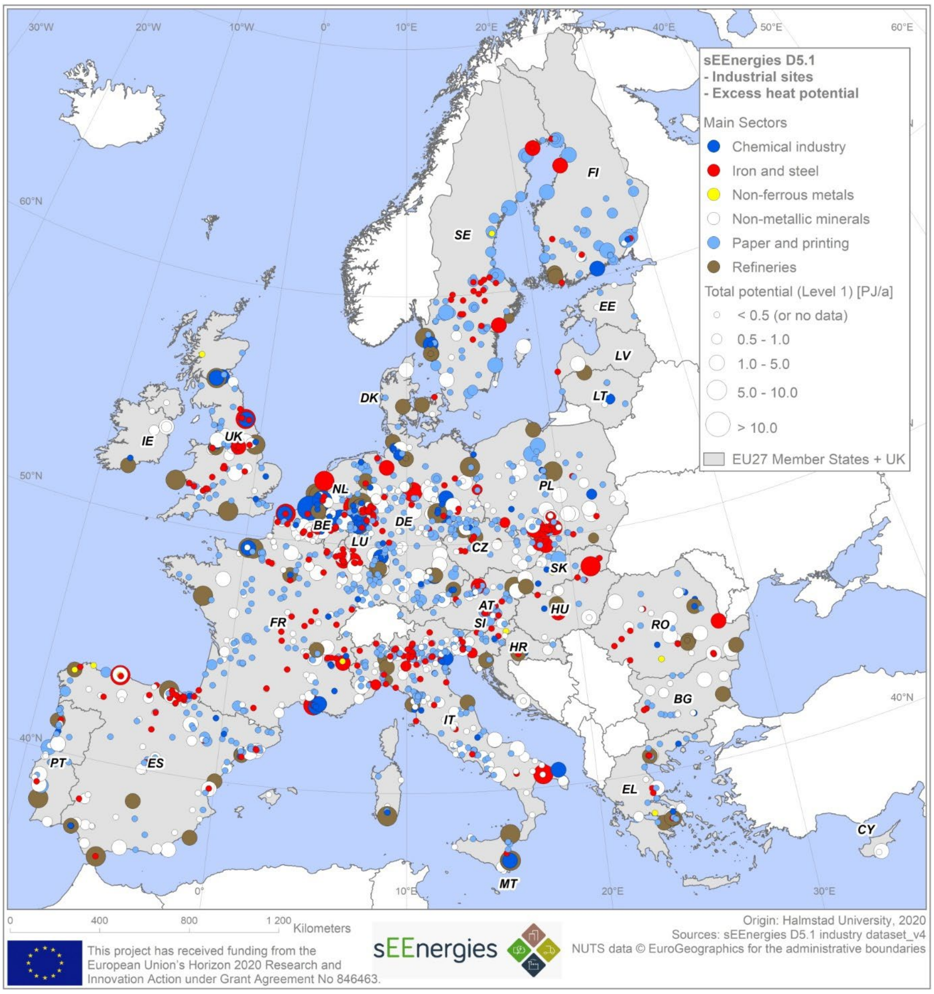


Figure 2 Map of excess heat potential from various energy intensive industries [37]

Based on the previous subchapter, it can be concluded that district heating is the most promising heating technology in the densely populated areas, but it needs to be upgraded from the current fossil fuel systems to the renewable based, sustainable heating systems of the future. Especially integrating district heating with the industrial and service sector activities to utilise the produced excess heat shows high potential.

There are currently high amounts of energy being completely wasted in the industrial sector, which could be partially or fully exploited in district heating. This is shown e.g. for the case of China, with losses in the industrial sector exceeding 50% [38]. On the EU level, the potentials of these sources have proven to be significant, as discussed in Ref. [8] where authors conclude that there is enough excess heat in Europe to cover the demand of both the households and tertiary buildings. However, this potential despite being substantial is currently not being used, as shown in [5] where authors also map excess heat potentials from energy intensive industries in order to graphically show the possibilities of this source. Updated figures show that 425 PJ of industrial excess heat is available at higher temperatures (95°C) and 960 PJ at lower temperatures (25°C) in EU28 [37]. These potentials for industrial excess heat utilisation are shown graphically in Figure 2. To support this conclusion, similar research has been conducted considering different excess heat sources and framework conditions. From that perspective, Ref. [39] has focused on the high potential of excess heat from thermal power plants in EU-28, authors in Ref. [6] analysed the potential of industrial excess heat in China, Ref. [40] focused on excess heat from the petrochemical industry in Sweden, while the results of Ref. [7] show the potential of excess heat in Japan. On the other hand, another form of excess heat located in the cities is urban excess heat, which is usually low temperature and comes from sources such as tertiary buildings (supermarkets, hospitals, etc.), data centres, electrical substations, metro stations, etc. The tool for determining its potential has been developed and elaborated in Ref. [41]. All these articles foster the conclusion that excess heat is currently mostly being unutilized despite its vast potentials which could strongly support the transition of district heating to a low carbon technology.

The benefits of using excess heat in district heating have been analysed in various framework conditions and showed their advantages from both the economic and the environmental point of view. For example, a system analysis of excess heat in different energy market scenarios in Sweden has been performed in Ref. [42] and showed that this source is economically feasible in all the investigated scenarios. Furthermore, in Ref. [43] authors study the optimal contribution of various industrial excess heat sources in the industrial cluster, focusing on the investment costs as the major cost category of this source. Alongside economic, environmental benefits have also been discussed in Ref. [44], while in Ref. [45] the focus is put on the impact of excess heat on the district heating sector and the energy system as a whole, highlighting that it reduces the utilisation of fossil fuels in the system and consequently its environmental impact. It has to be pointed out that the availability of excess heat in the majority of research articles is considered constant, leading to its complete utilisation in district heating in the analysed scenarios. However, this is very often not the case since the industrial facilities do not operate constantly but rather work in shifts, as shown in Ref. [46]. Therefore, the excess heat availability can range from the full capacity during the working days to lower capacity during the night and weekends. This intermittency that can occur in certain cases requires the use of thermal storage to increase its utilisation rate. Also, as already mentioned, integrating daily, weekly, and seasonal thermal storage units with the district heating systems is one of the prerequisites of the 4th generation systems due to the intermittency of the renewable sources, but also to increase the flexibility of the existing production units, mainly cogeneration and power to heat options. This is a well researched topic and numerous studies have confirmed the significance of thermal storage integration. For example, authors in Ref. [47] develop a model for optimal sizing of thermal storage, conventional sources and solar thermal capacity for optimal system operation, while in Ref. [48] authors elaborate the necessity of thermal storage when power to heat technologies are integrated in the smart energy system. Moreover, seasonal storage options are reviewed in detail in Ref. [49], while indirect systems using phase change material have been discussed in Ref. [50] in order to address the size issue of thermal storage units. However, not much attention is given in the existing literature to integrating thermal storage with excess heat, despite the obvious requirement for such a combination.

An additional issue with excess heat is that the main producers of excess heat, like various industrial facilities and thermal power plants are often not located in the vicinity of the existing demand and the district heating distribution network. This was shown for example in Ref. [51], where authors analyse potential excess heat sources for heat pumps in Denmark and debate that further research is required on the topic of their feasibility in terms of their distance. Furthermore, such conclusions are also made for the case of Great Britain in Ref. [52] due to the fact that remote excess heat sources have not shown feasible results in the preliminary analyses. Especially the heat transport costs have been analysed in Ref [53] for the case of long distances between the excess heat source and the demand. The results showed the proportionality of the maximum distance and the square root of the heat quantity.

To evaluate the economic feasibility of a certain energy production technology, especially in terms of comparing it to the other energy production technologies, levelized cost of energy is an often used criterion. It considers all the costs during the lifetime of the project in order to provide a depreciated unit cost of energy produced from the specific technology, which shows the minimum price of energy that this technology needs to achieve on the market to break even. As an investment criterion, it has been used frequently to compare different electricity production technologies. For example, recently it was used to compare nuclear and gas power plants, while also including additional parameters like uncertainties and endogeneities to the standard cost categories [11]. It was also recently used to compare a solar chimney technology to other renewable power production technologies [13]. However, in the heat sector this criterion is not used that often since the majority of the calculations focus on providing the total cost of the system and the effect of certain technology on this parameter, as shown for a building in Ref. [54]. Despite that, levelized cost of heat has been used in certain heat sector focused research, for example in Ref. [14] where authors use it to analyse the feasible level of heat savings and heat production in the EU. Also, it has been used to calculate the feasibility of Fresnel solar collectors [15] and different fuel options for a heat only boiler, including co-firing of solid, liquid and gaseous fuel [55]. Nevertheless, none of these focus on excess heat utilisation and using levelized cost of heat as a criterion for its utilisation in district heating. Using levelized cost of heat is especially relevant for analysing different options for the new district heating system, where the infrastructure did not exist previously. It must be noted that one of the reasons it has not been frequently used as a criterion for excess heat utilisation is the fact that most of the reviewed papers focus on integrating excess heat into the already existing district heating infrastructure, therefore neglecting potentials of excess heat integration in areas where no district heating networks exist at the moment.

In order to integrate various excess heat sources into the district heating network, third party access needs to be granted. This has been discussed in Ref. [9], where authors provided basic comments on the benefits of and the need for such a heat market to foster industrial excess heat integration in district heating. However, in the majority of cases district heating is still regulated as a monopolistic activity. From this perspective it implies that one company is responsible for all the services, i.e. heat production, distribution and supply [56]. Naturally, this prevents competition and with it the potential for decreasing the costs and the environmental effect in such a system. Through the last decades, the majority of European countries underwent a theoretical transformation of their heating sector in terms of its deregulation, but in practice the situation did not change much, and monopolies still exist throughout Europe. Some examples of practical deregulation of the heating sector include Germany [57], Sweden [58] and Denmark

[59] among others. A particularly interesting example is Lithuania, which allows independent heat producers to supply heat to the distribution network leading to the decreased costs for the end users [10]. This is permitted in cases when these producers exhibit lower prices compared to the production costs of other units. However, there is no real day ahead heat market in Europe and the research in the field of heat market integration is still scarce. No papers have been found to provide a detailed model of the wholesale heat market, which is a prerequisite for facilitating excess heat exploitation. Only few researches tackle this topic, for example Ref. [60] which uses the already existing Plexos model for wholesale heat market simulation and Ref. [61] where authors design the heat merit order to make the heat production costs transparent. An especially interesting topic when considering the day ahead heat market is bidding price formation. Since such a market draws many characteristics from the day ahead electricity market, the conclusion would point towards marginal cost biding as a standard biding strategy. This is expected because most of the research dealing with electricity markets uses marginal cost biding, as shown e.g. in Ref. [62], Ref. [63] and Ref. [64], which all use this biding strategy in their electricity market simulations. Nevertheless, despite being considered generally the only biding strategy for energy markets, it is not necessarily the case in real life market conditions. This has been discussed in Ref. [65], where authors simulate different biding strategies for the electricity sector, mainly marginal cost biding, total cost biding, next cluster biding and oligopoly biding in order to analyse their effect on the feasibility of different market actors. They argue that in real life market conditions, the strategic biding is observed. This means that biding prices are not necessarily calculated by using marginal costs. Similar observations can also be made for the heating sector, but no papers have tackled different biding strategies in the day ahead heat market until now.

1.3 Objective and hypotheses of research

The objectives of this research can be summed up as follows:

1. To define the decision making criteria regarding the investment into the excess heat utilisation equipment, by using the levelized cost of excess heat method

2. To demonstrate the feasibility of excess heat utilisation in district heating systems consisting of different layouts, by implementing previously developed method

3. To evaluate the functionality of local deregulated heat market

The hypothesis of this research is that the levelized cost of excess heat method should be used as a criterion for excess heat utilisation from industrial and service sectors in district heating systems, providing the minimum price which would enable various excess heat producers to participate in the local deregulated heat market.

1.4 Scientific contribution

The scientific contribution of this research is:

1. Levelized cost of excess heat method for the assessment of its utilisation in district heating systems, taking into account different layouts of the system.

2. Method for the evaluation of local deregulated heat markets' functionality.

2 A BRIEF OVERVIEW OF METHODS

2.1 Heat demand mapping

The first step of the analysis included calculating the heat demand and the potentials for district heating in a certain area, where such information is not already accessible. The tool, which was used for these calculations was qGIS [66], which also enabled the graphical presentation of the heat demand density over a certain area and the district heating potentials. This tool is a Graphical Information System (GIS) tool, which enables processing of spatial information and its graphical presentation. It integrates data on the location of a certain feature, with all the other types of descriptive data for that feature, therefore making it suitable for this step in the analysis [67].

The developed method is especially suitable for small cities or villages, where no official published energy data exists. However, due to the specifics of the method shown in the following paragraph, it wouldn't be suitable for larger cities, when the time commitment is taken into account.

First a survey was conducted with the citizens of the city of Ozalj [68], a small rural city in central Croatia, which served as a case study for the analyses performed in PAPER 1, PAPER 2 and PAPER 3. The questionnaire was developed as a part of the CoolHeating project [4], with questions being specifically designed in such a way that good quality energy data is collected from the citizens. The main types of collected data included information on building stock (e.g. age, insulation, net heating area, heating system in use, etc.), as well as their annual fuel consumption. By combining these data and visually inspecting the buildings in the city it was possible to categorize and associate them with the calculated specific heat demands. These can be seen in Table 1. Here it must be noted that the survey was implemented only with the households and therefore only the specific heat demands for the first four categories were calculated from the survey results, while for the last four the data were taken from the city's Sustainable Energy Action Plan [69]. The survey was carried out on the sample of 391 households, which is 17% of the overall number of households in the city and its results accurately display the current situation of the building stock in continental Croatia.

Table 1 Building categories and associated specific heat demands used for heat demand mapping

Category	Number of buildings analysed in the survey	Specific heat demand (kWh/m^2)
Old house	241	177.75
New house	12	112.5
House without the facade	28	262.5
Apartment building	21 apartments	161.25
Office building	-	135
Public building	-	270
Historic building	-	78.75
Industry	-	110

The other steps of heat demand mapping can be summarised graphically and are shown in Figure 3. After performing several calculations, the final heat demand of each building was calculated by multiplying the total heated gross area with the specific heat demand, depending on the category. Details of the method can be found in PAPER 1.

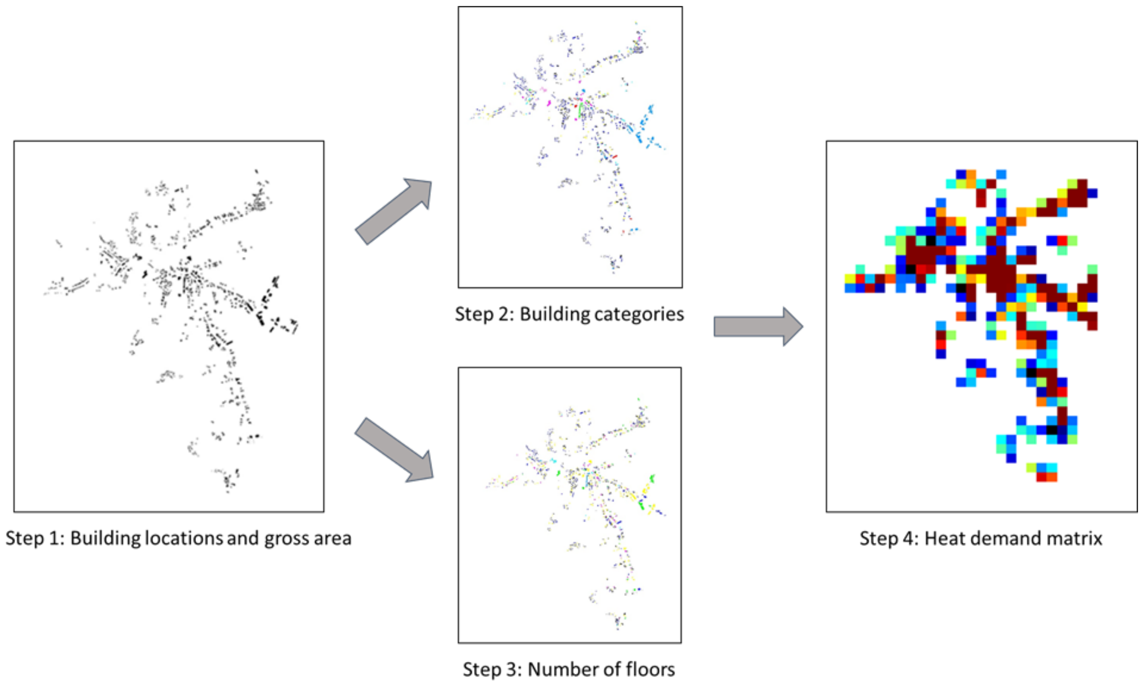


Figure 3 Graphical representation of the four main steps in the heat demand mapping method

2.2 Levelized cost of excess heat

As already mentioned in the Introduction section, levelized cost of energy is an often used criterion for evaluating the feasibility of energy technology implementation. It sums up all the costs during the technology lifetime and expresses a specific cost of producing one unit of energy. For the technology to be feasible, the average price that it receives for its produced energy during the project lifetime must be higher than levelized cost of energy. In its general form, levelized cost of energy constitutes of three parts: capital cost, operation and maintenance cost and fuel cost. For a conventional heating technology, it can be expressed as:

$$\text{LCOH} = \frac{I_c \cdot CRF \cdot (1 - TD_{pv})}{8760 \cdot i \cdot (1 - T)} + \frac{O_{total}}{8760 \cdot i} + c_{fuel}\ \ [€/kWh] \tag{1}$$

Where I_c is the capital cost of the production facility [€/kW], CRF is capital recovery factor which discounts the investment, T is tax rate, D_{pv} is the present value of depreciation taken from [70], i is the capacity factor of the production facility, O_{total} are total operation and maintenance costs [€/kW] and c_{fuel} is the cost of fuel being used [€/kWh]. Here it must be noted that the cost of CO_2 emissions from the EU ETS has not been considered due to the very low carbon prices at the time of the writing of the first paper, as well as due to the fact that as a part of this thesis mostly smaller systems have been analysed (which would not be covered by EU ETS). However, the implications will be discussed in the Results and Conclusion sections.

In this form, LCOH has first been used to calculate the feasibility of district heating in cities where no district heating infrastructure exists. This was done by integrating the equation (2) in qGIS software.

$$R = Q \cdot c_h - Q \cdot LCOH - 10000 \cdot l_s \cdot c_p\ [€] \tag{2}$$

Where $\boldsymbol{R}$ is potential revenue for a district heating system in a single 100x100 m area [€], $\boldsymbol{Q}$ is heat demand of a single 100x100 m area [kWh], $\boldsymbol{c_h}$is the price of heat [€/kWh], $\boldsymbol{l_s}$ is the average specific distribution network length [m/m2], while $\boldsymbol{c_p}$ is the cost of distribution network installation [€/m].

When R>0, this means that district heating can operate with positive revenue in that 100x100 m area and therefore it is feasible. Integrated with qGIS, this results in a map of areas where district heating is feasible. The reasoning behind calculating the potential revenue for 100x100 m areas is in the chosen resolution of the heat demand map. The above equation would need to be adjusted if used for different resolutions, by changing the number before the last term in the right side of the equation.

In the Introduction section, it was highlighted that excess heat sources, whose significant benefits have already been shown, are often located outside of the cities and therefore further away from the consumers and the associated distribution network. To consider this issue, LCOH was further adapted and used to define the maximum feasible distance of a certain excess heat source from the demand. First, this analysis is done for the high temperature excess heat source (usually industrial), which only requires the heat exchanger to transfer the heat to the district heating system. Also, the analysis is first done from the perspective of the district heating system operator, resulting in additional excess heat procurement costs, as seen in equation (3).

$$\mathrm{LCOEH} = \frac{I_{HE} \cdot CRF \cdot (1 - TD_{pv})}{8760 \cdot i \cdot (1 - T)} + \frac{O_{HE,total}}{8760 \cdot i} + c_{excess\,heat} \quad [€/kWh] \qquad (3)$$

Where I_{HE} is the investment cost for the heat exchangers [€/kW], $O_{HE,total}$ are the operation and maintenance costs for the heat exchangers [€/kW] and $c_{excess\,heat}$is the cost of excess heat [€/kWh].

The additional revenue is then calculated by using the equation (4). The resulting value is divided by the discounted cost of pipes in order to determine the maximum distance of the excess heat source from the heat demand

$$\mathrm{R}_{EH} = E_{total} \cdot r_{heat} - (E_{EH} \cdot LCOEH + E_{DH} \cdot LCOH) - l \cdot n \cdot c_{pipes} \quad [€] \qquad (4)$$

where $\mathrm{R}_{EH}$is extra revenue, E_{total} is the total heat demand of the area for which it would be feasible to connect to a natural gas district heating system [kWh], r_{heat} is revenue from heat, i.e. the price of heat [€/kWh], E_{EH} is available excess heat [kWh], $LCOEH$ is levelized cost of excess heat [€/kWh], E_{DH} is the remaining heat demand being covered by the natural gas based production facility of the district heating system [kWh], $LCOH$ is levelized cost of heat for the district heating system [€/kWh], l is the average length of distribution network in a 100x100 m area [m], n is the number of 100x100 m areas and $c_{pipes}$is the discounted cost of pipes [€/m]. It has to be emphasized one more time that these equations are applicable for the analysis of excess heat integration into the new district heating system, as a replacement for other planned production units, e.g. natural gas boilers.

On the other hand, equation (3) would change if the temperature of the excess heat source would decrease below the required temperature of the district heating network, which is usually the case with urban excess heat sources like the one from supermarkets, hospitals, power substations, etc. Under those circumstances, having a heat exchanger would not be enough and the heat pump would be required to increase the temperature of the excess heat source to the desired level, as presented in equation (5).

$$\text{LCOEH} = \frac{I_{HP} \cdot CRF \cdot (1 - TD_{pv})}{8760 \cdot i \cdot (1 - T)} + \frac{O_{HP,total}}{8760 \cdot i} + c_{excess\ heat} + c_{el,th}\ [€/kWh] \quad (5)$$

Where I_{HP} is the investment cost of the heat pump (including the cost of heat exchangers) [€/kW], $O_{HP,total}$ are total operation and maintenance costs of the heat pump [€/kW] and $c_{el,th}$ are the costs for the required electricity consumption of the heat pump [€/kWh]. The most obvious difference between the two equations for LCOEH is in the addition of $c_{el,th}$ when heat pumps need to be used. However, this parameter does not represent the electricity costs per se since it needs to be expressed per unit of heat. Therefore, it is calculated by using the equation (6).

$$c_{el,th} = \frac{c_{el}}{COP}\ [€/kWh_{th}] \quad (6)$$

Where c_{el} is the cost of electricity [€/kWh] and COP is the coefficient of performance of the heat pump. More details of the method can be found in PAPER1 and PAPER 2. The above-mentioned formulae are the backbone of this thesis and will be used in different forms throughout the text.

2.3 Energy system modelling

One important parameter in the equations (3) and (6), which significantly affects the outcomes of the analysis, and the overall feasibility of excess heat is the capacity factor of excess heat. While most of the previous research assumes it to be 100%, this number depends on the configuration of the system in which excess heat is to be integrated. Therefore, this factor can be significantly lower than 100%, when certain low-cost technologies are also used in the same system. Even if it is the lowest cost technology, its capacity factor can still be much lower than 100% due to the potential mismatch between the heat demand and its availability. In order to get the realistic capacity factor of excess heat in different configurations of the system, it is necessary to model the system and simulate its operation. For that purpose, energyPRO model was used [71].

EnergyPRO is an analytical optimization model which provides optimal system operation for the given heat demand. The time frame for the analysis is one year. Different time steps can be selected, but for the purpose of heat system modelling, one hour has been used. Different types of data are needed for modelling, including data on technology operation costs, fuel costs, as well as revenues from heat and electricity sales. The model does not, however, simulate the heat production capacity of each technology, which therefore needs to be predetermined, alongside the specific technical and economic data and the technical constraints of each unit. A brief overview of the optimisation procedure can be summed up as follows: the priority number is first allocated to each modelled technology in each time step, based on their costs and revenues. The lowest priority number gives the highest priority technology, which means that the unit with the lowest priority number is put in operation first. Then the model continues with the second lowest unit and all the others until the demand is met. The overview of the model, i.e. the block diagram of energyPRO (used to model scenarios in PAPER 2) is shown in Figure 4.

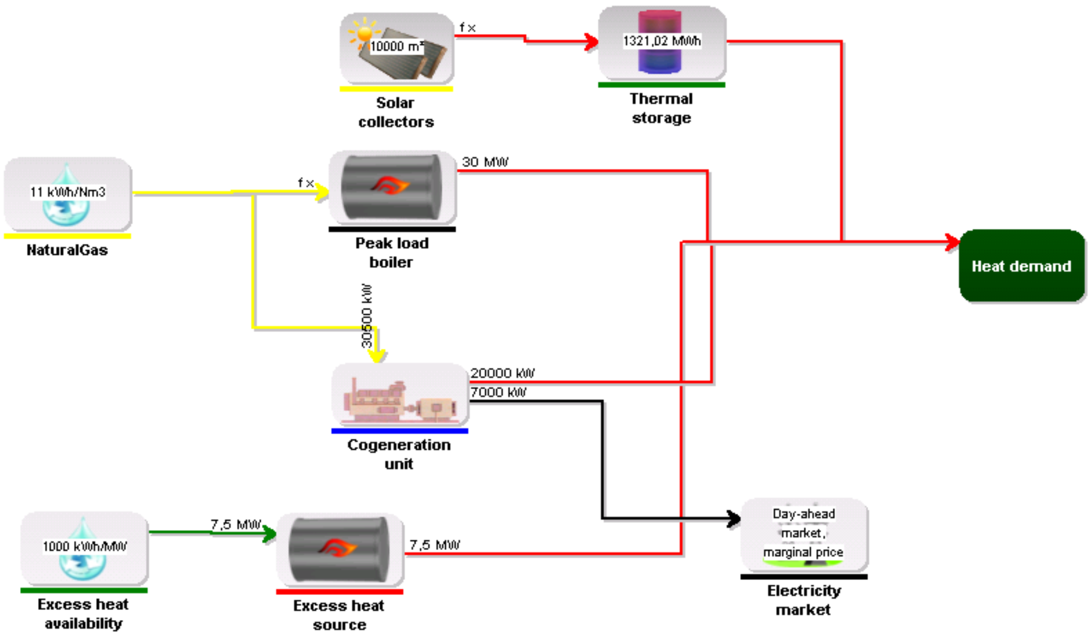


Figure 4 The interface of the energyPRO model used for heat system modelling

The energyPRO model has been selected for the energy modelling purposes in this thesis since it has already been proven as a useful energy modelling tool in various other research articles focused on the heat sector. For example, it was used to analyse the economic and environmental benefits of integrating solar thermal with heat pumps in the district heating system of Helsinki [34], evaluate the means of integrating booster heat pumps in the low temperature district heating networks [72], analyse the integration of the heating sector with electricity and transport sectors [73], investigating different technology combinations in a flexible district heating system in Baltics [74], optimize the heat production from cogeneration and renewables in Bosnia and Herzegovina [75] and many other.

2.4 Day ahead heat market modelling

For the purpose of heat market modelling, the Day Ahead Market Model (DARKO) has been used [76]. Despite being a general, advanced open source [77] energy market model, it has been specifically adjusted to include the heat market characteristics. It includes different types of market orders on both the supply and the demand side of the chain. This includes simple and complex orders, although only the simple orders have been used for heat market modelling, due to its characteristics.

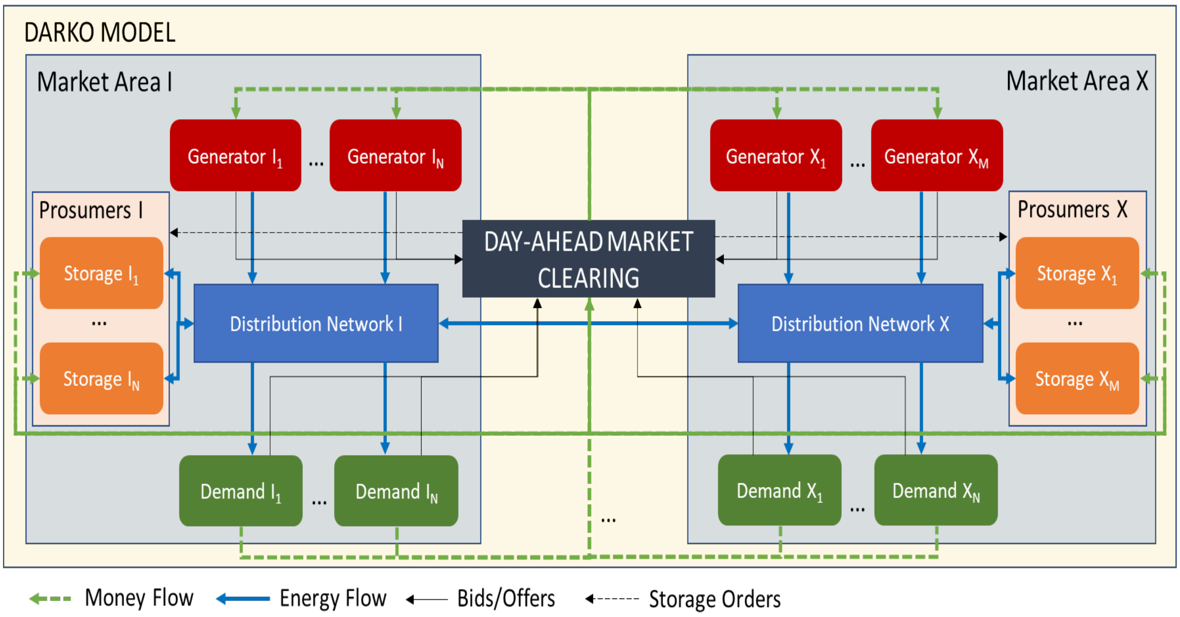


Figure 5 The schematic of the DARKO model used for day ahead heat market modelling

The hierarchical structure of the model is as follows: A single distribution network (in this case, a district heating network) exists in each market area, which acts as a link between all the market participants in that market area, including producers, demands and storages/prosumers. Different market areas can be interconnected through a set of transmission lines, in this case transmission pipes, which can have a positive impact on the market clearing prices of the market areas by pushing the merit order supply curves in the right direction when additional cheap orders are available, and the interconnection capacity is high enough to enable this. The official documentation of the model can be found in [78], while the graphical representation of the model is shown in Figure 5.

In general, in the day ahead energy markets, the market is cleared by solving the Social Welfare Maximization Problem. Its aim is to maximize the social welfare in terms of maximizing the economic benefits from both the production and demand side, while ensuring the obeying of the operational and storage constraints at every time period of the optimization horizon. For that reason, the same clearing model has been selected for modelling the day ahead heat market, with the addition of some specifics relevant for the heat sector. From that perspective, the most relevant addition are the storage orders which are currently not incorporated in any energy markets. However, in the heating sector these can be fully utilized due to the presence of the thermal inertia in the distribution networks which leads to non-instantaneous energy flows between the producers and the consumers. In order to fully address thermal inertia in the distribution networks, each part of the network has been modelled as a small but expensive (low efficiency) thermal storage unit which can shift a portion of the excess supply to the next time period.

The objective function of the model is formulated as a MILP problem, which aims at maximizing the social welfare w_{tot}

$$\max w_{tot} = c^{do} - c^{so} \tag{7}$$

The social welfare is comprised of two functions. The first one represents the overall cost function of hourly demand orders:

$$c^{do} = \sum_{d \in D} \sum_{o \in O} \sum_{i \in I} \left(P_{do}^{i} Q_{do}^{i} x_{do}^{i} \right) \tag{8}$$

where, P_{do}^{i}, Q_{do}^{i} represent price quantity pairs of various demand orders in the trading period i. These are expressed in €/MWh and MWh, respectively. Furthermore, x_{do}^{i} represents the demand orders acceptance ratio in trading period i (%). Second function is the overall cost function of simple hourly orders:

$$c^{so} = \sum_{s \in S} \sum_{o \in O} \sum_{i \in I} \left(P_{so}^{i} Q_{so}^{i} x_{so}^{i} \right) \tag{9}$$

where, P_{so}^{i}, Q_{so}^{i} represent price quantity pairs of various simple orders in the trading period i. These are expressed in €/MWh and MWh, respectively. Furthermore, x_{so}^{i} represents the simple orders acceptance ratio in trading period i (%). Here it has to be noted that the demand quantities are always presented as negative values and the supply quantities as positive values, due to Social Welfare Maximisation Problem.

One of the most important parameters in heat market modelling is the bidding price, which is calculated by considering the relevant techno-economic data for each technology. Different bidding strategies can be used for bidding price formation, as explained in the introduction section. Especially due to the specifics of the heating sector, which affect the profitability of the heat producers in the market, marginal cost bidding might not be the ideal solution. Overall, it can be discussed that the participants of the heat markets do not have broad opportunities for the additional income streams since they lack reserve markets where these producers could offer ancillary services, a common concept in the electricity markets. Furthermore, district heating are usually isolated, local systems supplying heat to separate cities or neighbourhoods, leading to the lack of opportunities for heat exchange between different regions and/or countries.

Hence, it was necessary to consider and compare the two possible bidding strategies: marginal cost bidding and total cost bidding. Marginal cost bids are usually used in energy market models and the related analyses. They were calculated by considering only the variable costs, which usually consist of fuel costs and variable operation and maintenance costs. However, strategic bidding is often observed in the real energy markets [65], which can include increasing the bids to cover the total costs of a certain technology. These were calculated by considering all the costs related to the certain technology, including the discounted investment, variable and fixed operation and maintenance costs and the costs for fuel. Offering prices, on the other hand, have been assumed as being slightly higher than the bidding price of the most expensive technology in the system. This is done to make sure that the demand will be satisfied in every hour of the year, which is a prerequisite in the model.

Finally, as different sources of excess heat are in the focus of the heat market analysis, their feasibility has been assessed by using the levelized cost of excess heat. For each excess heat source participating on the heat market, levelized cost of excess heat is calculated and then compared to the average achieved price for that source on the day ahead market. From that perspective, levelized cost of excess heat provides a minimum price at which excess heat and other market actors can feasibly participate on the day ahead heat market. More details on this method can be found in PAPER 4 and PAPER 5.

3 SELECTED RESULTS AND DISCUSSION

3.1 Determining the feasibility of district heating through the use of LCOH

As mentioned in the Methods section, the first step of the analysis was to determine the heat demand in the selected case study. The case study, which was analysed in the first 3 papers was the city of Ozalj, a small rural city in central Croatia for which no energy data was available and which only uses individual heating solutions at the moment, meaning that no district heating system is available in the area. For that reason, heat demand mapping was implemented by using the method described in 2.1. The results showed that the overall heating demand of the city amounts to 90.92 GWh. The full heat demand map can be seen in PAPER 1. However, not all the heat demand could be feasibly connected to the district heating system, since the remote, low building-density areas would not have a high enough heat demand density and would therefore need to use the individual heating solutions like heat pumps. Hence, it was necessary to determine which part of the demand could be feasibly covered by district heating, which is done by integrating equations 1 and 2 into the qGIS. The result, i.e. the 100x100 m feasible areas are shown in Figure 6.

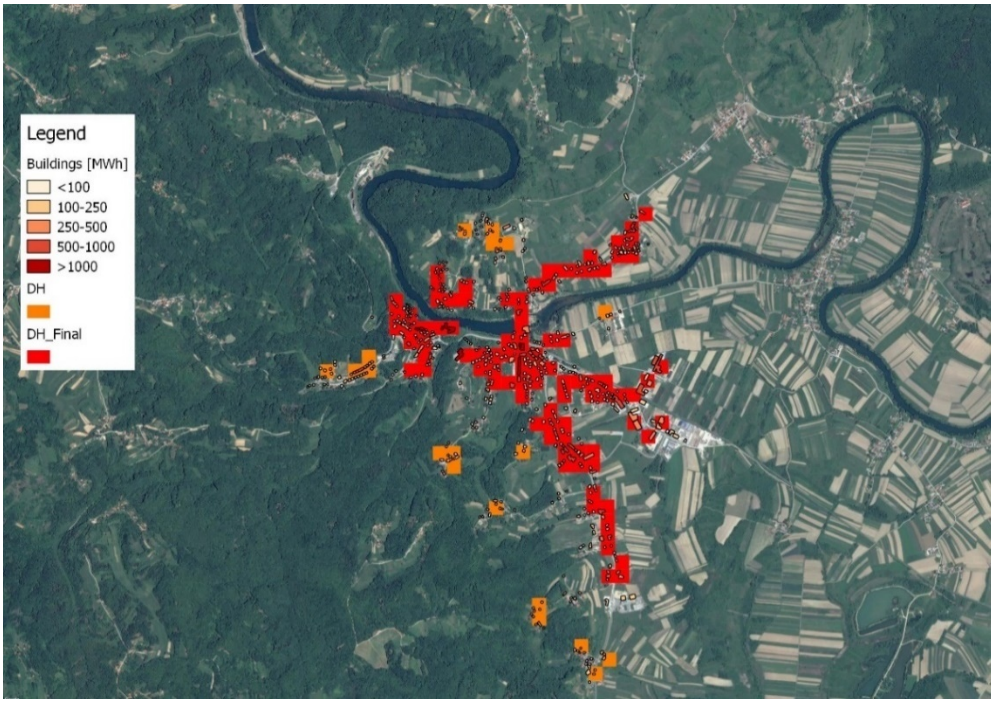


Figure 6 Parts of the city in which it is feasible to connect to a district heating system (orange) and final selection used in the further analyses (red)

It has to be noted that actual areas where it would be feasible to connect to district heating are coloured in red, while the orange-coloured areas have been excluded from the analysis due to their remote location from the grouped (i.e. red) areas and therefore the higher piping costs which make them infeasible in the end. Overall, 83.3 % of the heating demand, or 75.4 GWh could be connected to district heating, showing the high feasibility of this technology even in the rural small cities which constitute mostly of individual houses and just a few apartment buildings in the city centre. These results serve as a good introduction to the main part of this thesis, focusing on the excess heat utilisation in newly built and existing district heating systems.

The following sections, focusing on the case study of the city of Ozalj have been divided into the following parts. In the first step, the analysis was done on the annual level, taking into account only the annual aggregated values of energy data to provide a first level analysis of the excess heat feasibility. In the second step, this was supplemented with the hourly level analysis on the time scale of one year, taking into account the hourly variability of excess heat and heat demand in different configurations of the system. In the third step, the effect of different temperature levels of the excess heat source on LCOEH and overall feasibility of excess heat have been considered. In the fourth step, a more detailed analysis of the necessity of thermal storage for increasing the utilisation rate of excess heat has been studied.

3.2 Spatial analysis of excess heat feasibility

After determining the heat demand which could be covered by district heating on an annual level, the next step included calculating the potential of replacing the part of production from the conventional district heating units with high temperature excess heat, by using equation (4). Since certain parameters in this equation can vary depending on different conditions, the result is presented in the form of the sensitivity analysis, considering different values for the excess heat price, cost of distribution pipes and the available excess heat in the area, as seen in Table 2.

Table 2 Different excess heat prices, costs of pipes and available excess heat supply used in the analysis of excess heat utilization

Excess heat price [€/MWh]	Cost of distribution pipes [€/m]	Available excess heat supply [GWh]
1	200	10
2	400	20
3	600	30
4	800	40

Especially the cost of distribution pipes presents a relevant parameter in this analysis since it is the most capital-intensive part of the investment, when utilizing excess heat source. This can be seen in Figure 7, where the maximum distance of the excess heat source from the demand is presented for different variations of the aforementioned parameters. By using this method, both the investment in the heat exchangers and the distribution network is considered, giving a more detailed insight into the feasibility of excess heat. The analysis is done from the perspective of the district heating operator, as an investor into the excess heat utilisation equipment.

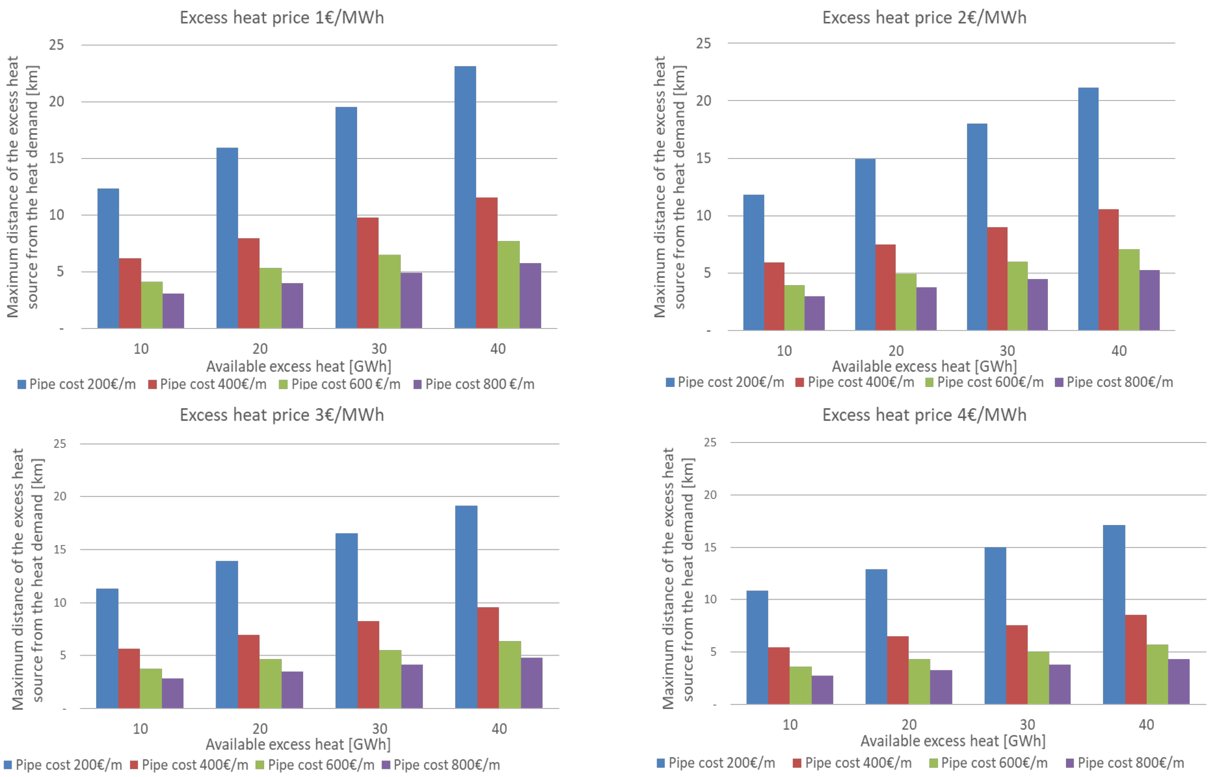


Figure 7 Maximum distance of the excess heat source from the heat demand for different values of available excess supply, excess heat price and costs of pipes

First, it can be argued that high temperature excess heat proves to be a feasible solution in every case, regardless of the pipe cost, excess heat price or the available amount of excess heat. That is, in every case the maximum distance of the excess heat source was positive meaning that excess heat could be feasibly utilised if it was located inside the resulting radius. This shows the high potential of this source, especially in terms of it being a more feasible solution then the conventional natural gas district heating production units. However, the limitations, in terms of the excess heat location should also be pointed out. While the maximum difference of the excess heat source from the demand equals to 23.11 km in the case of 40 GWh available excess heat supply, its price of 1 €/MWh and the pipe cost of 200 €/m, this reduces to as low as 2.7 km when 10 GWh of excess heat is available, the pipe costs are of 800 €/m and the excess heat price is 4€/MWh. To summarise, in case of high available excess heat amounts and low pipe costs, this source could be utilised from various locations outside of the analysed city and even from the nearby larger cities with higher industrial activities. Overall, it can be concluded that the levelized cost of excess heat method can and should be used as an efficient way of analysing excess heat feasibility. From this perspective, it serves as a good quality decision making criterion for the investment into the excess heat utilization equipment in the new district heating systems by providing the maximum feasible distance of the excess heat source.

3.3 Environmental benefit of using excess heat

An additional benefit of replacing conventional district heating production with excess heat is the reduction of environmental effect since excess heat utilisation does not produce any additional pollutant emissions. This is shown in Figure 8. The calculations were done according to IPCC EMEP CORINAIR methodology [79].

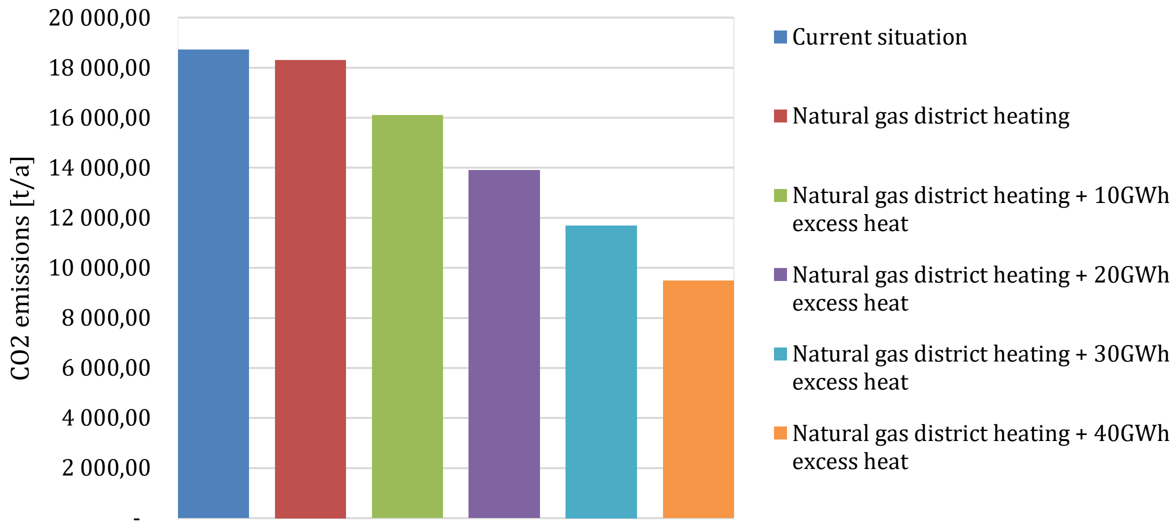


Figure 8 Results of CO_2 emission analysis for different excess heat availabilities

When conventional natural gas district heating is installed, replacing the individual heating solutions, a small decrease of CO_2 emissions can already be observed. This is due to the high efficiency of the district heating boilers and the strict regulations imposed to them, concerning pollutant emissions. To provide some context, it has to be mentioned that more than 70% of the existing buildings in the city of Ozalj currently use biomass in the individual stoves, which results in lower CO_2 emissions in the current situation. However, the old and inefficient furnaces do not use any filtering systems, resulting in high emissions of local pollutants, such as NO_x, particulate matter and CO, as seen in Table 3. The high accumulation of these pollutants can result in significant health problems of the local population. Therefore, by replacing individual boilers with a conventional district heating system the particulate matter emissions get almost completely eliminated, while NO_x emissions are reduced by 87% and the CO emissions are reduced by 97%.

Furthermore, when conventional district heating production unit is replaced by excess heat, significantly higher CO_2 emissions reduction can be observed, as seen in Figure 8. The emissions from excess heat production facilities are already calculated in the sector where they are produced (industry or service sector) and therefore are not considered in the heating sector, leading to a significantly lower overall environmental impact of the system and the heating sector in general. The same conclusion can be made for the local pollutant emissions, which decrease even further when excess heat is used. This could prove to be an additional benefit when excess heat is integrated in larger systems (where fossil fuel boilers>20 MW are present) which would be subject to the EU ETS and therefore would have to pay for their emissions. Since the emissions from excess heat source would already be accounted for in the source of origin, their costs would not increase, which would increase their feasibility when compared to other (fossil fuel) production technologies in the system.

Table 3 NOx, PM and CO emissions for different cases

	Current situation	Natural gas district heating	Natural gas district heating + 40 GWh excess heat
NO_x emissions (kg/a)	25,783.24	3,292.07	1,707.62
PM emissions (kg/a)	1,331,938.62	29.93	15.52
CO emissions (kg/a)	2,153,771.65	70,013.02	36,316.36

3.4 Excess heat capacity factor variations

In the previous step, the analysis was done on the annual level, not taking into account the hourly variations of different parameters, e.g. heat demand and excess heat availability. In other words, the capacity factor was assumed to be 100%, i.e. it was assumed that all the available excess heat is completely utilised in district heating. However, this is not the case with many industrial and service sector excess heat sources. The availability of excess heat can vary significantly throughout the day, the week and even the year, depending on the original industrial process or service sector activity, e.g. due to different shifts of the industrial facility as shown in Ref. [46]. Furthermore, heat demand also varies on the hourly, weekly and seasonal level, which can lead to significant mismatches between the available excess heat and the heat demand in the system and reduce the capacity factor of excess heat considerably. In order to take this into account, an hourly variation of excess heat availability has been approximated, based on Ref. [46] and shown in Figure 9 on a weekly basis. This variation repeats throughout the year and has been used to consider the industrial excess heat variability in PAPER 2, PAPER 3, PAPER 4 and PAPER 5. The hourly distribution of heat demand has been done by using the degree hour method [80].

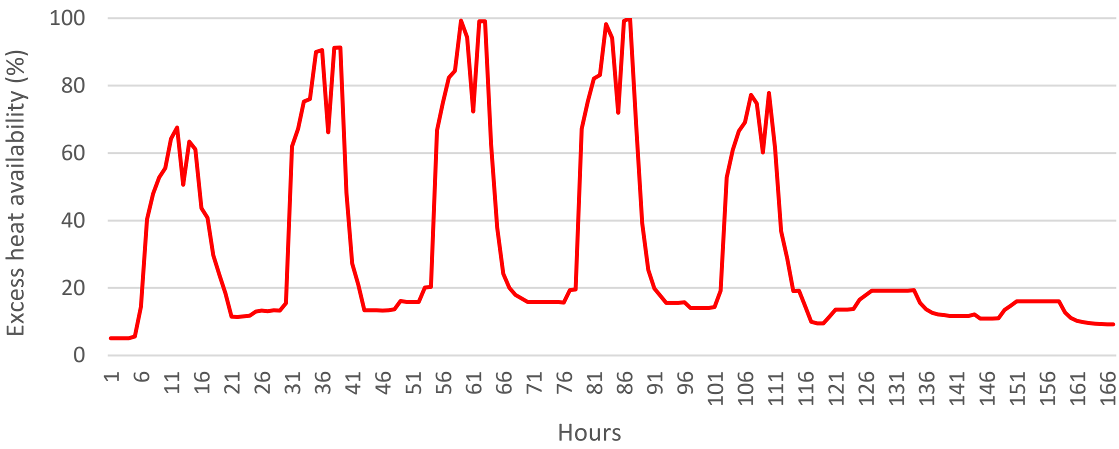


Figure 9 Hourly variation of excess heat availability through the time horizon of one week

To have a more detailed insight into the capacity factor of excess heat in different district heating layouts, hourly simulation of the system operation has been performed by using energyPRO tool, as explained in further detail in 2.3. For that reason, a scenario analysis has been performed taking into account different combinations of the following production units: natural gas boiler, natural gas cogeneration, solar collectors, seasonal thermal storage (exclusively for solar thermal), excess heat, dedicated thermal storage for excess heat and heat pumps, as seen in Table 4.

The Reference scenario presents a technical concept that was developed for the city of Ozalj as a part of the CoolHeating project [81] and which included the combination of a peak load boiler, cogeneration unit, solar thermal collectors and thermal storage system. The sizing of these units was done in such a way that the cogeneration operates as the baseload unit, peak load boilers are used for covering the peak demands during the winter, while the area of solar collectors was designed by considering the available land area owned by the municipality. Since this configuration is expected to be built in the future, it has been used as a Reference scenario.

Table 4 Different district heating layouts analysed in the scenario analysis

	Reference	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Natural gas boiler	✓	✓	✓	✓	✓	✓
Natural gas cogeneration	✓	✓	✓	✓	✓	✓
Solar collectors	✓	✓	✓	-	-	-
Seasonal thermal storage	✓	✓	✓	-	-	-
Excess heat	-	✓	✓	✓	✓	✓
Thermal storage for excess heat	-	-	✓	-	✓	✓
Heat pump	-	-	-	-	-	✓

Moreover, certain industrial facilities have been detected in the nearby areas of the city, mainly manufacturing industry and ceramic industry. Especially the ceramic industry shows high potential as shown in literature [82], due to the high temperatures used in its processes. However, no real time data could be obtained on the hourly availability of excess heat in the area and therefore the variation from Figure 9 has been used. Taking into account the results from 3.2, the availability of excess heat has been assumed at 20 GWh, which could cover approximately 29% of the heat demand in the city. The sizing of all the technologies used throughout scenarios has been done in such a way that the heat demand of the city is always fully covered. More detail on the capacities of each analysed technology and the reasoning behind their sizing is provided in PAPER 2.

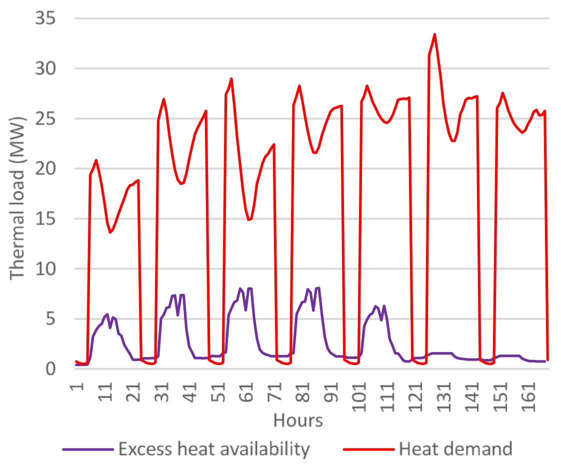
Table 5 Capacity factor of excess heat in different scenarios

	Reference	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Capacity factor of excess heat	-	53%	64.8%	64.5%	85%	85%

Since the focus of this section is on the capacity factor of excess heat in different system configurations, only this parameter will be discussed, as shown in Table 5. The full results, i.e., production from each technology in different scenarios is presented in PAPER 2.

It can be immediately seen that the capacity factor of excess heat is significantly below 100% in all the cases. This happens for multiple reasons. The first one is the mismatch between heat demand and excess heat availability both on the daily and seasonal level. During the night, the heat demand usually decreases significantly resulting in excess heat availability being higher than the heat demand, and therefore being wasted. During the summer, the same thing happens throughout the day since the heat demand constitutes only of the domestic hot water demand, which is significantly lower compared to excess heat availability. This can be easily seen in Figure 10, which shows the high oscillations between heat demand and the assumed excess heat availability during the night period in winter, and especially during the summer period.

Therefore, even if no other competing low-cost technologies are used in the system, the capacity factor of excess heat couldn't be higher than 64.5%, as seen in Scenario 3. This leads to a conclusion that a dedicated thermal storage is necessary in order to utilise a higher share of available excess heat.



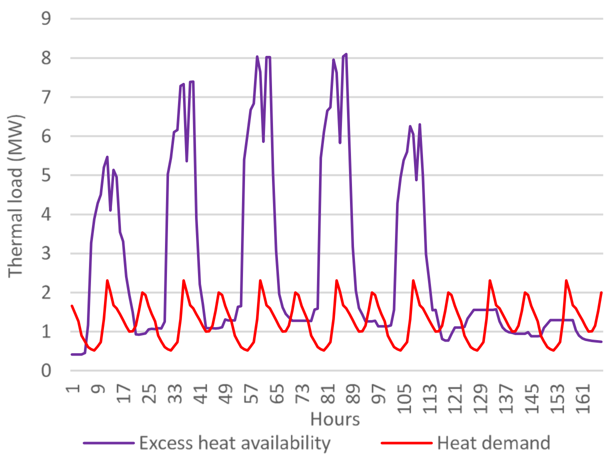


Figure 10 Mismatch between excess heat availability and heat demand during winter (left) and summer (right)

The second reason is competition with other low-cost technologies, in this case solar thermal. The operating costs of solar thermal are lower than the high temperature excess heat operating costs, which decreases the use of excess heat, especially during the summer. This results in the capacity factor as low as 53%, as seen in Scenario 1.

The capacity factor increases when a dedicated steel tank thermal storage for excess heat is added. In this step, the idea was to analyse the implementation of a short-term storage alongside excess heat, while larger, seasonal storage solutions will be analysed in 3.5. Adding thermal storage to a system configuration with solar thermal increases the capacity factor of excess heat to 64.8%, while in the configuration without solar thermal it increases to 85%, showing the significant benefit of using thermal storage in combination with excess heat. However, storage technologies increase the investment costs of excess heat. For that reason, LCOEH needs to be calculated for every scenario to provide a fair economic comparison of excess heat utilisation in all the scenarios. This is seen in Figure 11.

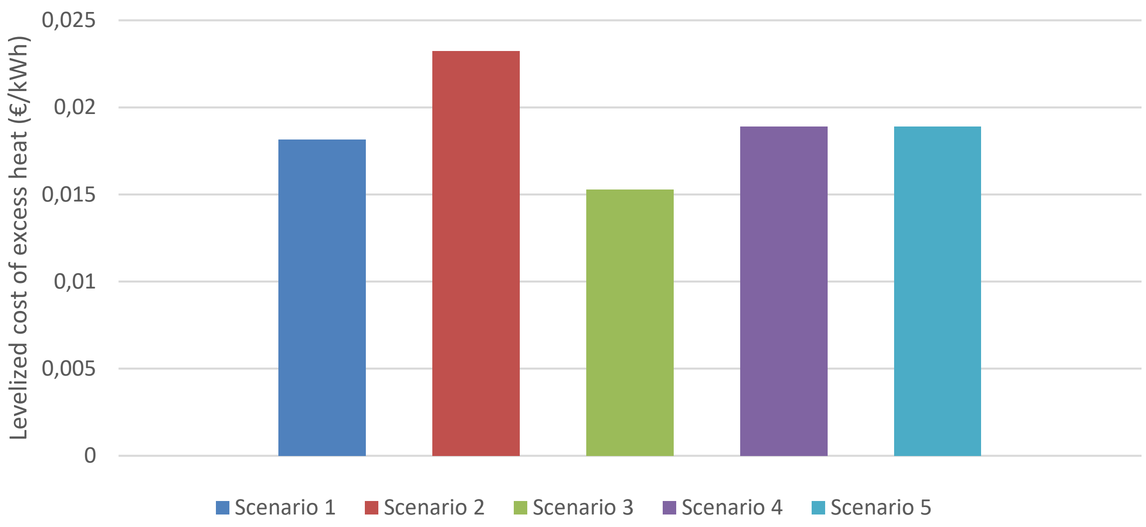


Figure 11 Levelized cost of excess heat for each of the scenarios

It can be seen that LCOEH is the lowest for Scenario 3 which provides the highest capacity factor without using thermal storage. When thermal storage costs are considered, LCOEH is increased by 53% for Scenario 2 since the capacity factor of excess heat is still rather low in this configuration. However, in Scenarios 4 and 5, when no solar thermal is available, LCOEH becomes lower and is similar to the one in Scenario 1, being only 26% higher compared to Scenario 3. These results show that using larger buffer tanks for increased excess heat utilisation is not a feasible solution, since the capacity factor increase is not high enough to counter the high costs of this configuration. Different storage options, i.e., sizes will be further analysed in the next section.

3.5 Thermal storage options for excess heat

It was shown in the previous section that using thermal storage is a prerequisite for the higher capacity factor of excess heat. To determine whether it should be a short term or long term, i.e., seasonal storage, a series of simulations have been carried out in energyPRO considering various thermal storage capacities ranging from 2,000 m^3 to 220,000 m^3. Then, the levelized cost of heat has been calculated for the whole system, considering the results from these simulations. This way, the best solution for the analysed case study was determined, while considering the economics of the overall system. Lower capacity thermal storage units were modelled as steel tanks, with the top to bottom temperature difference of 40°C, and 95% utilisation rate. Thermal losses of these units were modelled by considering the height of steel tanks, thermal conductivity and thickness of the insulation material (polyurethane foam), as well as the ambient temperature. Larger storage units on the other hand were modelled as large underground pit units, usually constructed to serve as a seasonal storage.

Here it should be pointed out that while the case study remained the same in this analysis, the maximum available excess heat amount increased slightly compared to the analysis done in the previous section. This is because a more detailed evaluation of the existing excess heat sources in the area has been performed based on the excess heat source potential map [83] and the availability of ceramic industry in the vicinity of the city. The overall availability of high temperature excess heat was therefore assumed at 23 GWh annually. On the other hand, the Reference scenario remained the same as in 3.4, due to the aforementioned reasons. Hence, the Reference scenario consisted of natural gas cogeneration, natural gas peak load boiler, solar thermal and dedicated thermal storage for solar thermal.

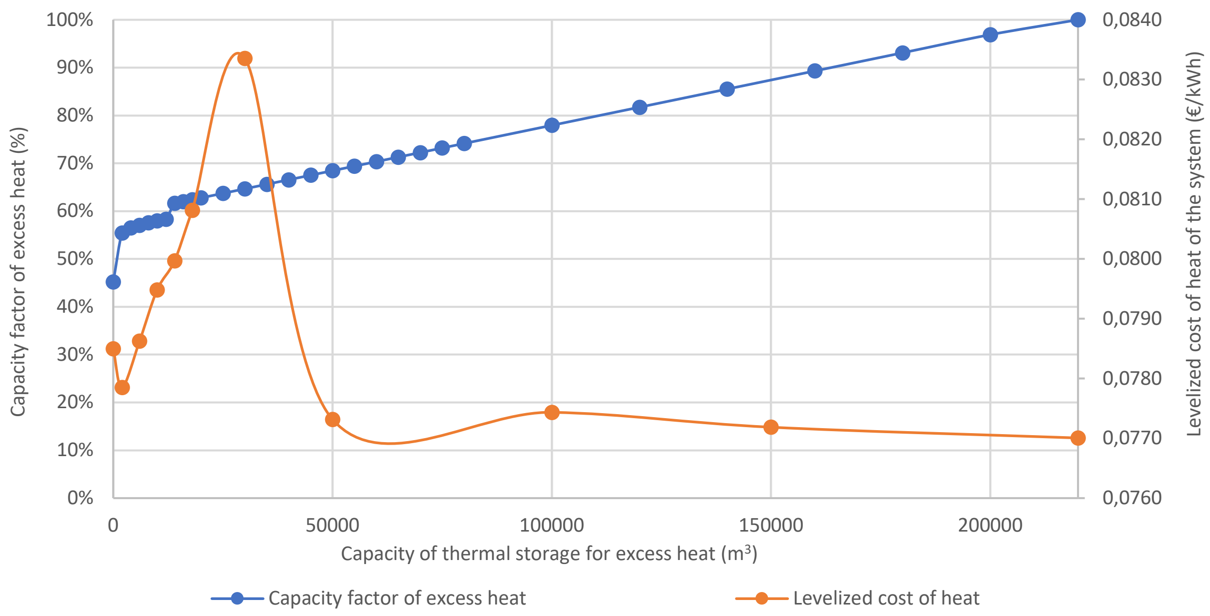


Figure 12 Overall utilization of excess heat source and the economics of the whole system for different capacities of thermal storage

The results can be seen in Figure 12. It shows that it is possible to utilise all of the available excess heat even when the low-cost solar thermal is used, if a large enough dedicated thermal storage system is used. This means that a large, seasonal thermal storage is required for excess heat in such configurations when a technology like solar thermal exists in the system. However, the situation would be similar even in cases when there is no solar thermal in the system (i.e. excess heat is the lowest cost technology) due to the already shown (Figure 10) high mismatch between excess heat availability and heat demand during the summer. In the analysed case, the thermal storage capacity which achieved 100% utilisation of excess heat was 220,000 m^3, which equals to 9,690 MWh. Nevertheless, if such high capacities cannot be built due to space restrictions, implementing a smaller buffer tank can still achieve relatively high capacity factors. The reason behind this is that the highest capacity factor increases happen at smaller capacities due to the largest difference from the reference situation, i.e., no thermal storage. Nonetheless, the results show that seasonal storage is a much more economical solution due to the significantly lower specific investment costs when compared to buffer tanks. When high capacity buffer tanks are used, the overall cost of the system increases significantly regardless of the increased capacity factor of excess heat. Therefore, it can be concluded that either a seasonal thermal storage should be used, or a smaller buffer tank. However, only seasonal thermal storage can enable a complete utilisation of excess heat, as shown in Figure 12. More detailed results on system dynamics of utilising thermal storage units with excess heat can be seen in PAPER 3.

3.6 LCOEH of low temperature excess heat sources

The analyses performed in the previous sections were all focused on high temperature excess heat sources, which are usually produced as a by-product of high temperature industrial processes. However, numerous urban excess heat sources [84] exist throughout modern-day cities. These include excess heat from supermarkets, metro stations, data centres, power substations, hospitals, etc. One major difference between most of industrial excess heat and urban excess heat is the temperature level. Urban excess heat sources usually have low temperatures [85], [86] and therefore require the use of heat pumps to achieve the temperature level of district heating supply line [87], which inevitably reduces the feasibility of such solutions.

In order to analyse the effect of using a lower temperature excess heat source on its feasibility, LCOEH has been calculated for different excess heat temperature levels by using equation (5) and plotted in a diagram, as seen in Figure 13. It should be emphasized that the excess heat capacity factor has been recalculated for each temperature level in energyPRO, hence taking into account the decrease of excess heat utilisation when lower COP is achieved. The district heating supply temperature has been assumed at 90°C, in order to consider a standard 3rd generation district heating system with relatively high supply temperatures. Such temperature levels can be anticipated in the South-east European countries, which have an old and inefficient building stock which requires high temperature heating. In such cases, it can be seen that with decreasing excess heat temperatures the LCOEH increases rapidly. The most feasible solution is to utilise high temperature excess heat, which is marked as Direct utilisation in Figure 13 and has the lowest LCOEH. As soon as heat pumps are needed, the feasibility of this source decreases. However, as long as the excess heat temperature is above 66°C in this case, this source is still more feasible than the natural gas boiler. After this point, the temperature is too low for the service sector or industrial excess heat to be a competitive heat source for district heating.

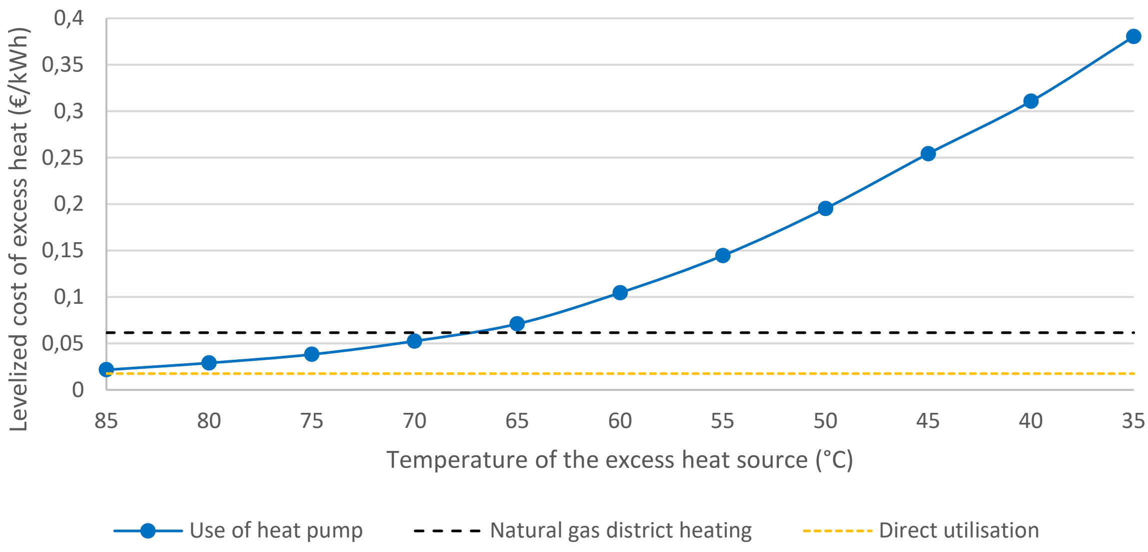


Figure 13 The effect of the temperature level of excess heat source on the LCOEH

Still, it is expected that future district heating systems will have lower supply temperatures since the EU legislation fosters the implementation of energy efficiency measures in buildings to decrease their energy consumption and consequently the required temperatures of the heating system. Therefore, lower temperatures of end users have also been considered and the results are presented in Figure 14.

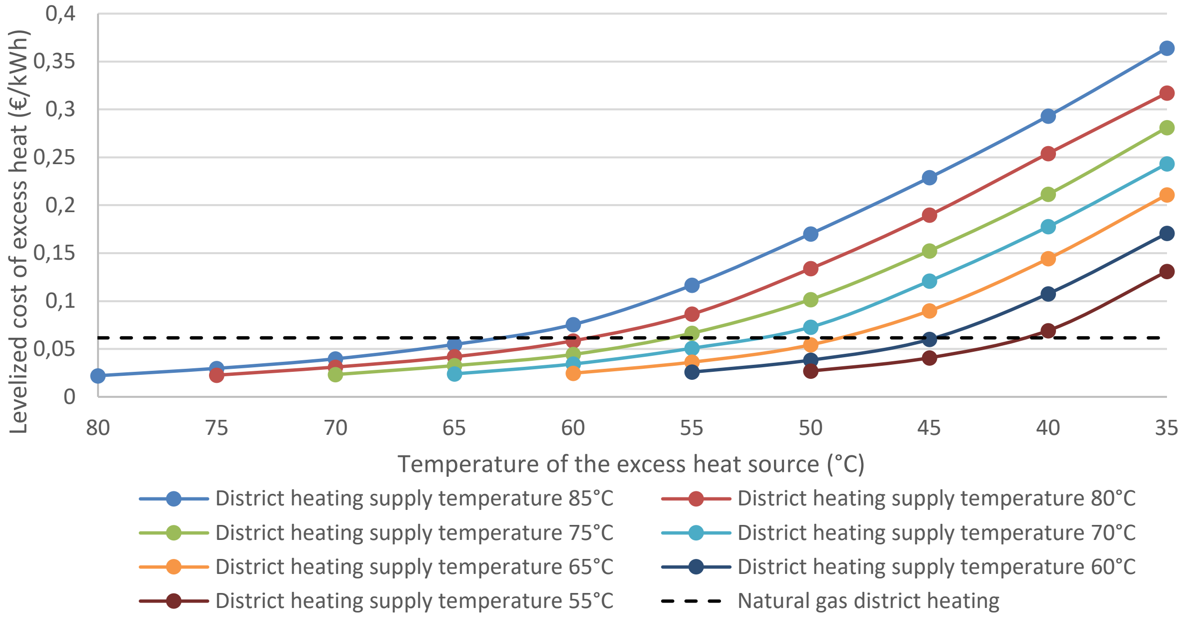


Figure 14 The effect of lowering the needed supply temperature in a district heating system on LCOEH of excess heat sources on different temperature levels

It can be seen that with decreasing district heating supply temperatures, the feasibility of low temperature excess heat sources increases significantly. For example, if the district heating supply temperature in the analysed case decreases to 55°C, the LCOEH of the excess heat source with the temperature of 41°C would still be lower than the LCOH of the natural gas boiler. Similarly, for the same temperature of excess heat source, the LCOEH decreases significantly with lower supply temperatures.

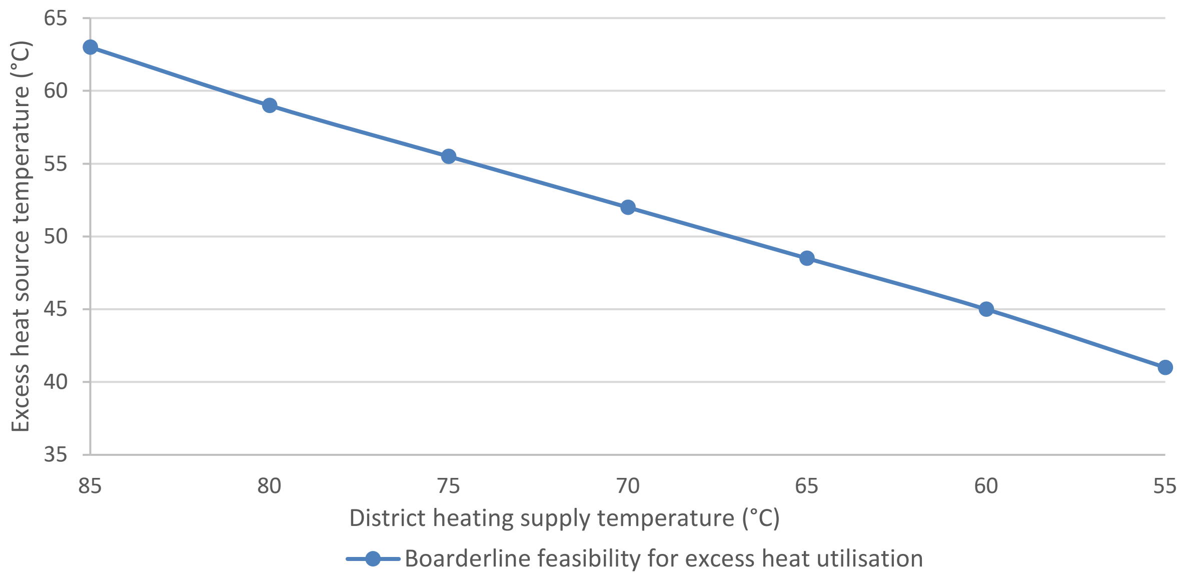


Figure 15 Decrease of the borderline feasibility excess heat source temperature with the district heating supply temperature

To visualise the increased feasibility of low temperature excess heat sources with lower district heating supply temperatures, the borderline feasibility excess heat source temperature has been plotted alongside the district heating supply temperature in Figure 15, which shows the decreasing trend with lower district heating supply temperatures.

These results lead to two major conclusions. First, they point out the necessity of energy efficiency increase in the buildings sector leading to the subsequent reduction of the temperatures, both on the end user and the district heating network side. Second, it is certain that district heating systems will gradually move towards the 4th generation in the next decades, which will include low supply temperatures and therefore significantly increase the feasibility of low temperature excess heat utilization.

To supplement these results, the analysis of maximum feasible distance of the potential excess heat source has been performed, based on equations (4) and (5) and considering different temperature levels of both the excess heat source and the end user, i.e., the supply temperature of the district heating system. The results are shown in Figure 16.

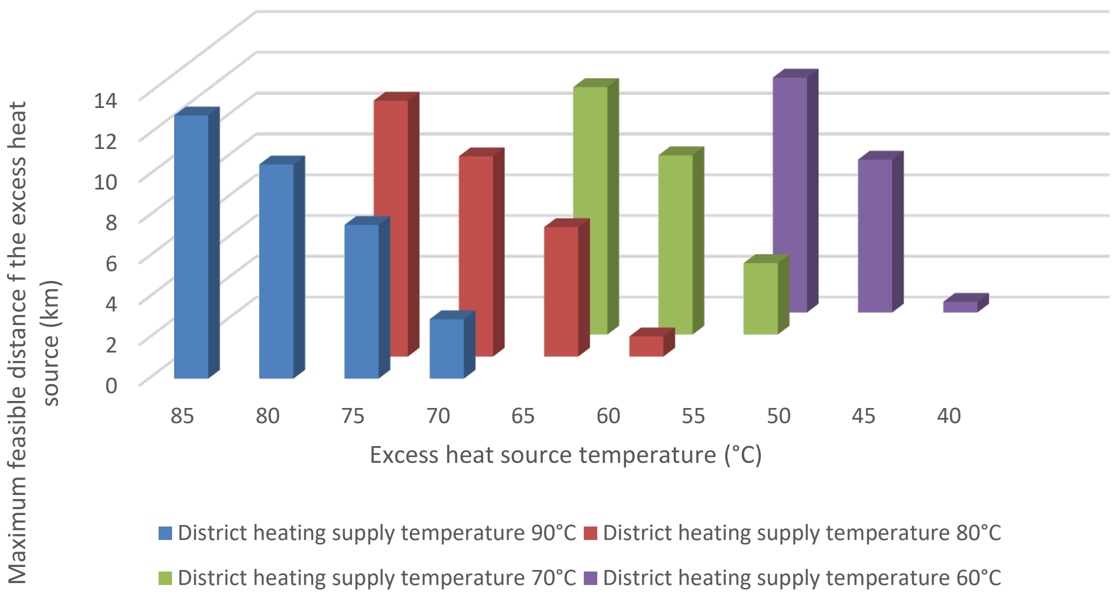


Figure 16 Variations of maximum feasible distance of the potential excess heat source with the temperature of the excess heat source and the district heating supply temperature

It can be seen that the maximum feasible distance of the excess heat source decreases with lower excess heat temperatures, but this decrease is lower if the low temperature district heating system is used, as expected based on the previous results. For example, in the analysed case, the results show that at the excess heat source temperature of 70°C and the district heating supply temperature of 90°C, the source would need to be located in the close proximity of the district heating network, i.e. within the city itself in order to be feasibly utilised. However, in the case of district heating supply temperature of 60°C, excess heat source with the temperature of 40°C could be utilized if located in the close proximity of the distribution network. Also, if the supply temperature is 90°C, the maximum excess heat source distance is 12.9 km if its temperature is 85°C. Nonetheless, when the supply temperature is lowered, similar distances can be achieved with excess heat source temperature of 55°C.

3.7 High and low temperature excess heat utilisation on a day ahead heat market

The previously shown results all focused on the case study of the city of Ozalj, from that point of view presenting a case where no district heating exists in the city at the moment. Therefore, all the analyses were done from the perspective of planning a new district heating system and determining which sources should be used, with the focus on high temperature and low temperature excess heat. Hence, it was assumed that all the investments are done by a single district heating company, which would operate the system in this city. To broaden the scope of the analysis, the next subsections will be focused on another case study, the city of Sisak, which already has an operating district heating system. From that perspective, excess heat owners would need to have the third-party access to the district heating network, and they would bear the costs of utilising this source. In order to do that, a day ahead heat market needs to be implemented in the city, as already discussed in 2.4

3.7.1 A brief overview of the case study and scenarios

As already mentioned, the case study for the heat market analysis is the city of Sisak. In the scope of this study, the analysed production technologies included the existing biomass cogeneration and natural gas heat only boilers, but also industrial and service sector excess heat sources and solar thermal, which proved to be the main competitor of excess heat throughout the previously shown results. It must be pointed out that the analysis was performed with the real heat demand data, real data on the existing production units, but also the assumed data on excess heat potentials from various actors, as well as assumed data on the solar thermal plant, since no detailed information on these actors currently exists. Additionally, since the extension of the district heating system in Sisak is planned [88], the analysis also included the additional heat demand and the natural gas boiler in the old town, which currently operates as a separate smaller district heating system

Therefore, three different zones have been specified to consider different heat transfer media being used (steam and hot water), as well as different temperature levels of different categories of heat demand (industrial and household). Z1 included the existing production units together with the industrial heat demand, based on the heat carrier being used in this zone (steam) and the physical location of these units. Furthermore, Z2 included the existing heat demand connected to the main district heating system of Sisak, while Z3 included the heat demand and the production unit of the old town currently operating as a separate district heating system. The heat transfer medium in Z2 and Z3 is hot water. A representation of the analysed zones is shown in Figure 17. More details on the zones and the case study itself can be found in PAPER 4.

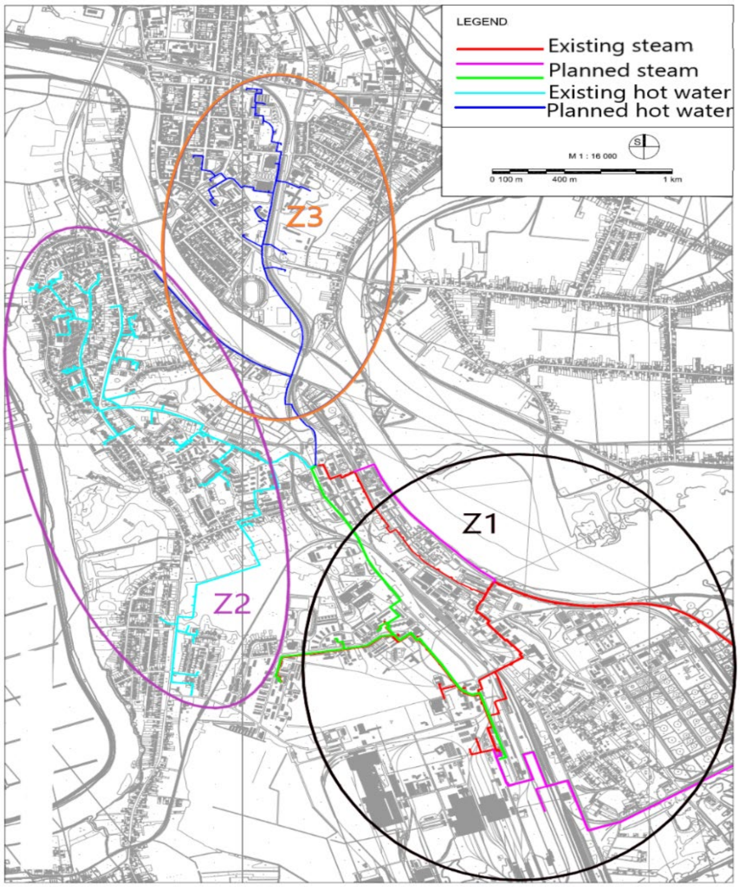


Figure 17 The location of the main zones considered in the heat market, map based on Ref. [88]

To analyse the benefits of heat market implementation, as well as utilisation of various excess heat actors on such a market in different configurations, a scenario analysis has been performed. That way, different combinations of heat production technologies, including the existing units, as well as planned low cost units can be studied and the overall economics of different excess heat actors in these configurations can be calculated, based on the method presented in 2.4. Different combinations of technologies, based also on the results from previous chapters, are shown in Table 6. In Scenario 1, only the existing heat production technologies are participating on the market, i.e. natural gas heat only boilers (HOBO_GAS) and biomass cogeneration (CHP_BIO). In Scenario 2, additional three excess heat sources have the possibility to participate on the heat market. These include high temperature excess heat from the nearby refinery (EH_IND) and low temperature excess heat from the supermarket (EH_SMARK) and the hospital (EH_HOSP). The industrial excess heat potential has been calculated by combining the Heat Roadmap Europe method presented in Ref. [5] and the excess heat potentials map for Croatia [89]. On the other hand, the potential of the excess heat from supermarket and hospital and their temperature levels have been assumed based on the literature [90], [91], [92]. Scenario 3 adds a solar thermal plant with its dedicated thermal storage unit since this technology showed to be the main competitor to excess heat. It has been modelled in such a way that its maximum production equals to the maximum availability of all the excess heat sources combined. Finally, Scenarios 4 and 5 combine all the previous scenarios and include all the available technologies, with the addition of a dedicated seasonal thermal storage for excess heat sources in Scenario 5. More details on the sizing of different technologies and scenarios in general can be found in PAPER 4.

Table 6 Different combinations of technologies considered in the heat market analysis

	Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
HOBO_GAS_1	✓	✓	✓	✓	✓
HOBO_GAS_2	✓	✓	✓	✓	✓
HOBO_GAS_3	✓	✓	✓	✓	✓
CHP_BIO	✓	✓	✓	✓	✓
EH_IND	-	✓	-	✓	✓
EH_SMARK	-	✓	-	✓	✓
EH_HOSP	-	✓	-	✓	✓
SOLAR	-	-	✓	✓	✓
TS_SOLAR	-	-	✓	✓	✓
TS_EH	-	-	-	-	✓

3.7.2 Capacity factor variations of different excess heat producers on the heat market

After inserting all the required technical and economic data into the DARKO model, optimisation of all the scenarios has been performed, providing the optimal production from different technologies on a day ahead heat market. These results can be seen in Figure 18. It can be seen that CHP_BIO acts as a base technology in all the scenarios, providing the majority of heat on the heat market. This is expected since it is built as a base unit and has a much higher capacity then excess heat and solar thermal. In Scenario 1 it covers more than 70% of the heat demand since its bidding price is lower than the one for HOBO_GAS, while HOBO_GAS covers the peaks. When the three aforementioned excess heat sources are added in Scenario 2, the production from both CHP_BIO and HOBO_GAS decreases, mostly due to the low-cost industrial excess heat which also has the highest available amount among the analysed excess heat sources. However, low temperature excess heat sources are not utilised to their full potential due to the high bidding prices of these sources, which are a result of their high total costs, as already shown in Figure 13 and Figure 14. This will be discussed in more detail in the next paragraphs.

Furthermore, if solar thermal is used instead of excess heat in Scenario 3, the production from CHP_BIO and HOBO_GAS decreases even further since the bidding prices of solar thermal are constantly lower than those of these two technologies. This also leads to a complete utilisation of all the available heat from solar thermal.

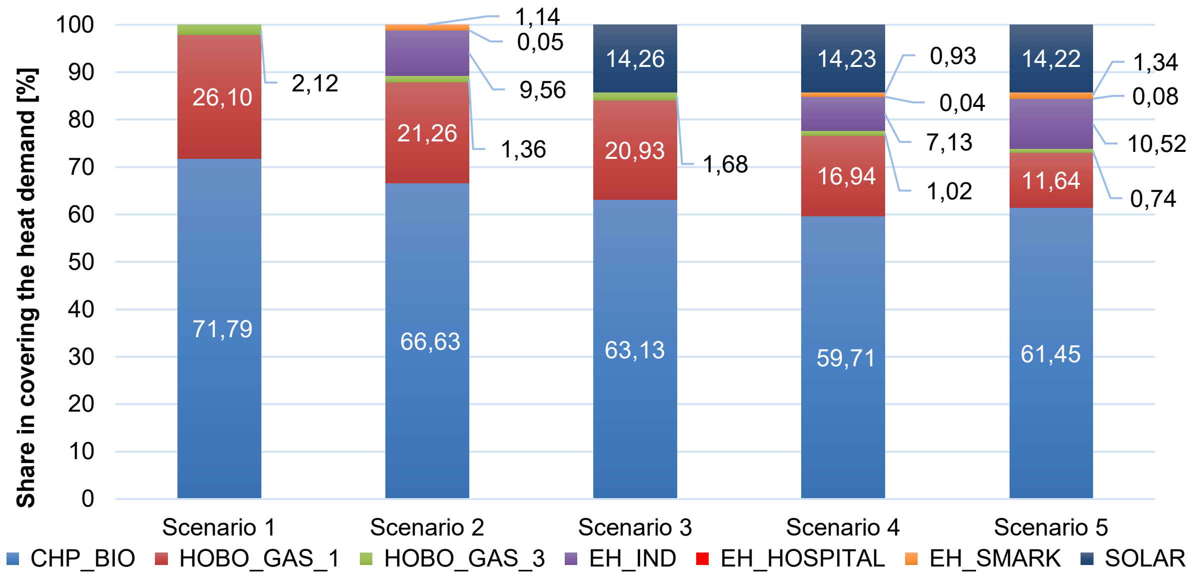


Figure 18 Cleared bids from different heat production technologies in five scenarios, expressed through the share in covering the heat demand

In Scenario 4, when all the available technologies can participate on the heat market, the production from HOBO_GAS and CHP_BIO naturally decreases even further. However, due to the low bidding prices of solar thermal, the production from excess heat sources decreases, compared to Scenario 2. For that reason, a dedicated seasonal thermal storage is added in Scenario 5, which only excess heat sources can use. This increases the cleared bids, i.e. production from all the three excess heat sources and decreases the production from HOBO_GAS and CHP_BIO even further. To have a better overview of the overall utilisation of excess heat sources in different scenarios, Table 7 presents their capacity factors.

It can be seen that due to the high costs, the capacity factor of EH_HOSP in Scenario 2 is at just 10.85%. Because of its low temperature, the operating costs required to achieve the necessary temperature level make it the unit with highest bidding prices in the majority of hours during the year. On the other hand, the capacity factor of EH_SMARK is not much higher at 31.9% despite its assumed higher temperature which results in lower bidding price. The reason behind it is that the cheapest units (CHP_BIO and EH_IND) cover all the heat demand in certain hours of the year, making EH_SMARK unnecessary despite the fact that it is cheaper than the fossil fuel boilers in a number of hours. Also, it can be noticed that even EH_IND did not achieve complete utilisation in this scenario regardless of being the unit with lowest bidding prices, due to its variability, as already shown in previous results.

Table 7 The capacity factor of different excess heat sources participating on a heat market in [%] for Scenario 2, 4 and 5

	EH_SMARK	EH_IND	EH_HOSP
Scenario 2	31.96	90.22	10.85
Scenario 4	26.20	67.51	9.03
Scenario 5	37.70	99.94	17.80

The capacity factor of all the excess heat sources decreases even further in Scenario 4, when both excess heat and solar thermal have access to the heat market. It again clearly shows that solar thermal is a direct competitor to excess heat, as it reduces the capacity factor of EH_IND to 67.5%, EH_SMARK to 26.2% and EH_HOSP to 9%.

In the end, adding a seasonal thermal storage for excess heat in Scenario 5 results in almost complete utilisation of EH_IND but doesn’t change the situation for EH_SMARK and

EH_HOSP much, since their bidding prices remain much higher compared to EH_IND, solar thermal, but also CHP_BIO in the majority of time. These results support the findings presented in 3.6 and bring in question the overall feasibility of such low temperature sources on the heat market, which will be further discussed in the next sections.

3.7.3 Market clearing price on the heat market

When it comes to the economics of the heat market, the most important parameter is the market clearing price (MCP), which shows the price at which the market was cleared in each hour, i.e. where the demand cost curve crosses the supply cost curve. From the demand side, it can be used to show the total demand costs in a year by multiplying the MCP in every hour with the cleared demand and summing up the values on the annual level. The results for the five presented scenarios are shown in Figure 19.

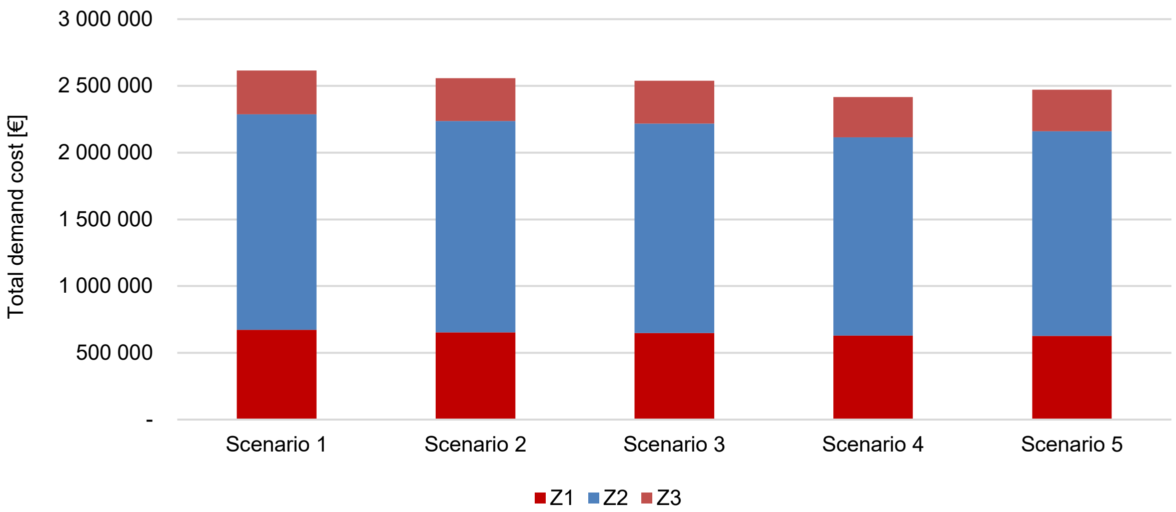


Figure 19 The total costs of the demand side divided per zones for each of the scenarios

First of all, it can be seen that the highest costs for the demand side are in Scenario 1, in which excess heat and solar thermal do not have access to the heat market. It must be pointed out that these results do not represent the total cost of end users, but instead the wholesale costs which need to be marked up with supplier costs and the distribution costs in order to get the real end user cost, excluding tax. By allowing industrial and service sector excess heat sources to bid on the market, the total demand costs decrease by 2.2% in Scenario 2 and even further when solar thermal is also integrated in Scenario 4, by 7.6%. An interesting point of discussion are the costs for Scenario 5, which increase slightly when compared to Scenario 4. The reason behind it is the implementation of thermal storage unit which enables higher acceptance of bids from low temperature excess heat sources, which have the higher bidding prices and therefore increase MCP in certain hours. This naturally leads to the increased total demand costs on the annual level. Nonetheless, the demand costs of Scenario 5 are still the second lowest among all the scenarios. Therefore, when the environmental effect of Scenario 5 is considered from the perspective of having the lowest fossil fuel technology production, its benefits prove to be the highest. These results show the advantages of the wholesale heat market for the end users due to the decreased costs, which especially applies when low bidding price technologies are used, such as solar thermal and high temperature excess heat.

To get a more detailed overview of the economics of each scenario, MCP has been plotted in a box & whiskers diagram in Figure 20 for all three zones. The diagram can be read as follows: the whiskers show the minimum and the maximum value that occurs in the selected period, the x shows the mean value, and the middle line shows the median value. The bottom line of the box represents the first quartile, while the top line of the box represents the third quartile.

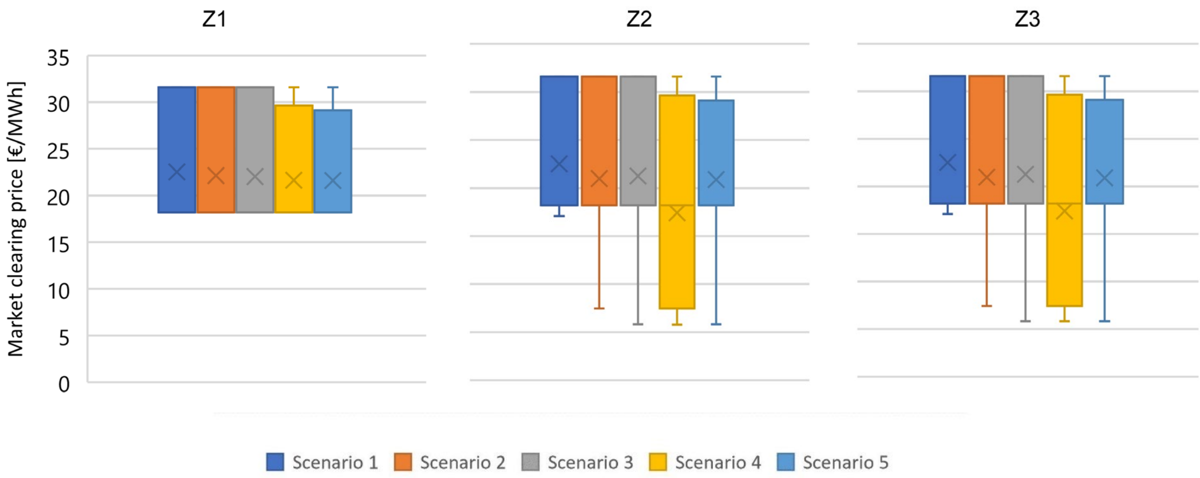


Figure 20 Market clearing price for each zone and scenario on the heat market

First, it can be seen that the changes of MCP in Z1 are rather small through different scenarios since excess heat sources and solar thermal are not allowed to bid in that zone. This is because the demand of Z1 only consists of the industrial heat demand and the temperatures have therefore been assumed too high for the utilisation of these sources. Nevertheless, it can be seen that utilising excess heat and solar thermal does affect the mean MCP slightly, especially in Scenario 4 and Scenario 5. This effect is indirect, and it happens because these sources reduce the need for HOBO_GAS units in other zones, that way enabling the increased production of lower cost CHP_BIO in covering the demand of Z1.

When the results for the other two zones are considered, much higher variations of MCP between different scenarios can be noticed since both excess heat and solar thermal are allowed to place bids in these zones. Hence, the minimum achieved MCP is reduced significantly in Scenario 2, where excess heat is allowed to place bids. This subsequently decreases the mean value of MCP in Z2 by 7% when compared to Scenario 1, i.e. to 20.96 €/MWh. The system configuration of Scenario 3 results in slightly higher mean MCP, at 21.27 €/MWh. This is due to the variability of solar thermal, which is unavailable in most winter hours, all the while the excess heat availability remains constant throughout the year.

The highest variations of MCP, as well as the lowest mean MCP can be seen in Scenario 4 for both Z2 and Z3. The reasoning behind it is that the excess heat bids are accepted only in those hours when their bidding prices are the lowest since there is no dedicated thermal storage unit for this source. This has a considerable effect on the overall cost but also on the utilisation of excess heat, as shown in Figure 18. On the other hand, when a dedicated thermal storage for excess heat is added in Scenario 5, this results in the second lowest mean MCP. An interesting result can be noticed for Z1, where the lowest mean MCP is achieved for Scenario 5. This happens because of the increased share of utilized excess heat, which leads to the reduced need for the expensive fossil fuel boilers and subsequently to covering a higher share of demand in Z1 by a lower cost CHP_BIO. Finally, it can be seen that the differences between Z2 and Z3 prices are practically negligible, hence the focus will be put on Z1 and Z2 results in the following paragraphs, which focus on MCP duration curves.

Figure 21 and Figure 22 show the load duration curves for MCP in Z1 and Z2 respectively. It can be seen that MCP does not fall below 18.21 €/MWh in Z1, since excess heat and solar thermal affect this zone only indirectly, through lowering the production from peak load HOBO_GAS. Therefore, the lowest MCP corresponds to the bidding price of CHP_BIO. Furthermore, it is obvious that the longest duration of the low MCP in Z1 is achieved in Scenario 5, due to the reasons explained in the above paragraphs, while the shortest is in Scenario 1.

On the other hand, much lower MCPs can be achieved in Z2 as excess heat and solar thermal are allowed to place bids in this zone. For example, MCP remains below 8 €/MWh for 3233 hours annually in Scenario 4. The low MCP is also achieved in Scenario 2 and Scenario 3, however the duration is much shorter, i.e. 919 hours for Scenario 2 and 475 for Scenario 3. An interesting result can be noticed for Scenario 5, where the MCP equals to the bidding price of CHP_BIO in the most hours of the year. The reason behind it is the thermal storage unit which enables storing excess heat in hours when it would otherwise be used directly on the market. This means that CHP_BIO is a marginal technology in those hours and its production therefore increases, as seen in both Figure 18 and Figure 22.

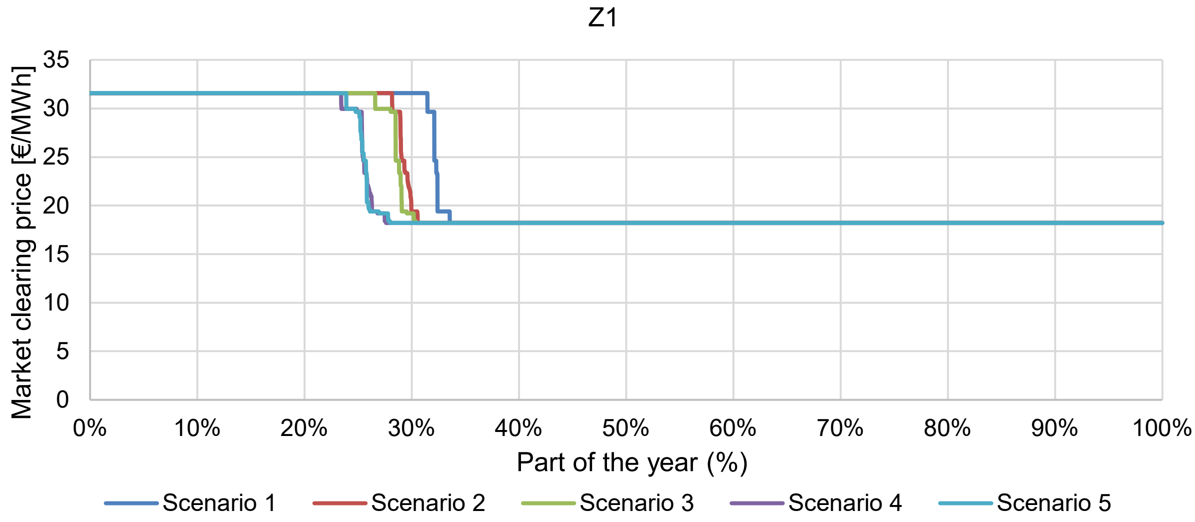


Figure 21 Load duration curve of the market clearing price for Z1

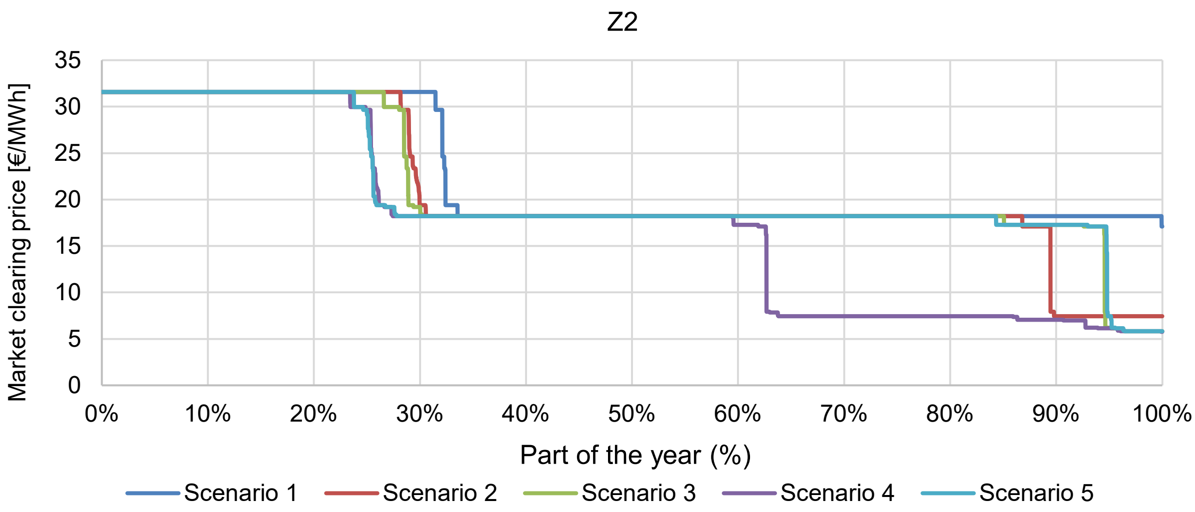


Figure 22 Load duration curve of the market clearing price for Z2

Since Scenario 4 and Scenario 5 show the most interesting results from the perspective of allowing high and low temperature excess heat and solar thermal to participate on the market, a more detailed comparison between the two scenarios will be provided, based on Figure 23. It shows the hourly MCPs throughout the year for both scenarios, plotted on the same graph. Since excess heat and solar thermal provide a direct effect only on Z2 and Z3, the results are plotted only for Z2. The most evident differences can be observed outside of the heating season. The MCP of Scenario 5 remains below the HOBO_GAS bidding price for a much longer time period in autumn, i.e. until mid-November, while in Scenario 4 the MCP increases approximately 1.5 months before. This happens because of the dedicated excess heat thermal storage unit. The same can be observed in the spring, when HOBO_GAS units turn off approximately half a month before in Scenario 5, resulting in the decreased MCP. However, in the summer period, Scenario 5 results in a much higher average MCP since CHP_BIO needs to operate in times when thermal storage unit is being charged, which clearly shows its effect on MCP. Therefore, Scenario 4 results in lower MCPs in the summer period, when the demand is mostly covered by industrial excess heat and solar thermal, while Scenario 5 allows the higher utilisation of excess heat and subsequently reduced number of high MCP periods enabling the decrease of HOBO_GAS production.

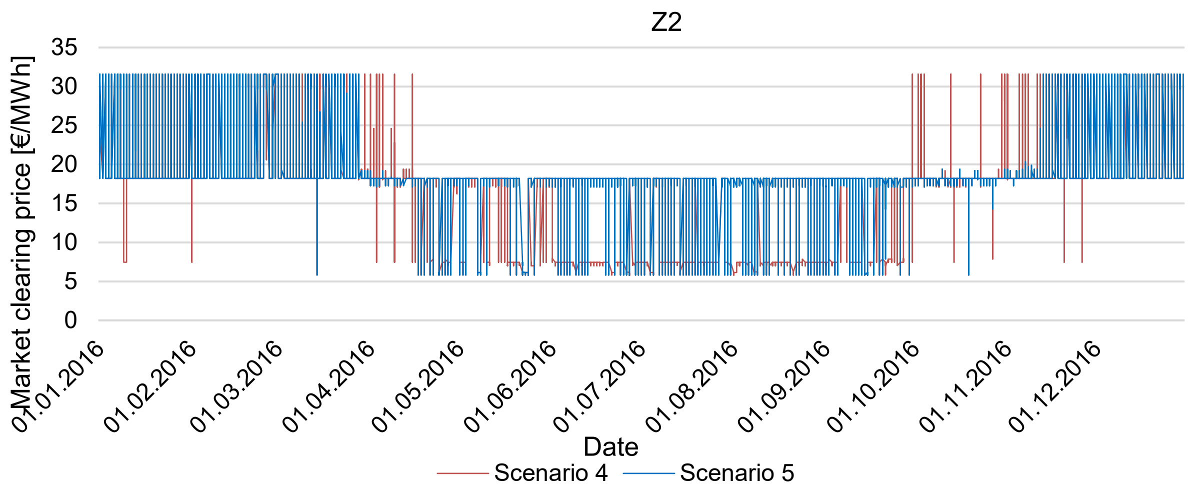


Figure 23 Hourly market clearing price of Scenario 4 and Scenario 5 in Z2

The final economic parameter which will be discussed in this subsection is the total welfare, which is maximised through the objective function of the heat market. It is shown for each of the scenarios on an annual level in Table 8.

First of all, it shows that the total welfare is positive in all of the scenarios and therefore the benefits of the heat market implementation are considerable. Furthermore, total welfare increases in each scenario and is maximal in Scenario 5 since most excess heat and solar thermal bids are accepted in the market. Considering the benefits on both the demand and production side, the most optimal solution is the combination of technologies in Scenario 5, even when environmental effect is not considered.

Table 8 Total welfare of all the scenarios, on an annual level

Scenario	Total Welfare [€]
Scenario 1	3,681,941
Scenario 2	4,022,894
Scenario 3	4,175,062
Scenario 4	4,444,681
Scenario 5	4,604,915

3.7.4 Feasibility of excess heat sources participating on a heat market

To determine the feasibility of high and low temperature excess heat sources participating on the heat market, levelized cost of heat was calculated by using the adapted versions of the equations (3) and (5). However, this value by itself does not determine if the utilisation of a certain excess heat source on the market was feasible or not. Hence, the achieved average price on the heat market was also calculated for these sources, as elaborated in more detail in 2.4. Since HOBO_GAS and CHP_BIO units are already built and in operation, the focus of this analysis was on excess heat sources and solar thermal. LCOH of these sources in different scenarios is shown in Table 9.

Table 9 Levelized cost of heat in [€/MWh] for excess heat sources and solar thermal in different scenarios

	Scenario 2	Scenario 3	Scenario 4	Scenario 5
EH_IND	9.42	-	12.59	8.50
EH_SMARK	60.40	-	72.05	48.46
EH_HOSP	184.00	-	218.50	103.80
SOLAR	-	6.39	6.42	6.23

The lowest LCOH in all the scenarios is achieved for solar thermal, due to its high capacity factor and low operating costs. For excess heat on the other hand, LCOH value differs significantly depending on the source in question. While industrial high temperature excess heat provides rather low LCOH in all the scenarios, the LCOH of low temperature excess heat sources is significantly higher. This happens both because of the high operation costs and the low capacity factor of these sources on the heat market.

Furthermore, the resulting average prices on the annual level, achieved on the heat market for these 4 sources are presented in Table 10. Solar thermal unit achieves lowest average prices on the heat market since it reduces the MCP throughout the year. Furthermore, EH_IND also achieves relatively low average prices on the market. These are however increased for low temperature excess heat sources since their bids are accepted during a much shorter time period and only when they are lower than the bids of HOBO_GAS units. This results in a relatively high achieved price on the market. Nonetheless, when compared to the LCOH of these sources it can be seen that despite these high values, they are still not higher than the LCOH, which means they are not feasibly utilised on the heat market.

Finally, it can be concluded that both solar thermal and high temperature excess heat sources are highly feasible in such heat markets since their achieved prices overcome their LCOH by a large margin. Low temperature excess heat, on the other hand, cannot be feasibly utilised in such markets since they have high operation costs due to the use of heat pumps. This conclusion is valid for traditional high temperature district heating systems. This calls for the 4^{th} generation low temperature district heating, which would enable much higher utilisation of low temperature excess heat sources and foster their participation on heat markets.

Table 10 Achieved average price in [€/MWh] of the excess heat sources and solar thermal on the heat market in various scenarios

	Scenario 2	Scenario 3	Scenario 4	Scenario 5
EH_IND	22.49	-	23.45	23.18
EH_SMARK	30.32	-	30.93	31.16
EH_HOSP	31.18	-	31.16	31.33
SOLAR	-	19.81	15.42	18.37

3.8 Bidding strategies on the heat market

In the previous section, the bids for different heat market players have been defined by using total cost bidding, as an alternative to marginal cost bidding. The reasoning behind it were the specifics of the heat sector, where usually no additional revenues can be achieved, e.g., on reserve markets. Furthermore, the idea was to simulate bidding as realistically as possible, since marginal costs are not necessarily used on the real markets, i.e., the real bidding prices remain unknown. Also, from the perspective of low temperature excess heat, including total costs results in higher bidding prices of these sources, ergo higher achieved prices on the market and higher feasibility. However, by using marginal cost bidding the merit order of the heat market could change, leading to the higher utilisation of low temperature excess heat. For that reason, this section focuses on the merit order of different technologies when different bidding strategies are used, as well as on the economics of excess heat sources.

3.8.1 Merit order under different bidding strategies

The bidding prices in total cost bidding and marginal cost bidding were calculated as explained in 2.4 and the results have been plotted on the annual level in Figure 24 and Figure 25. More detail on the calculation method and the specifics of the two analysed bidding strategies can be found in PAPER 5.

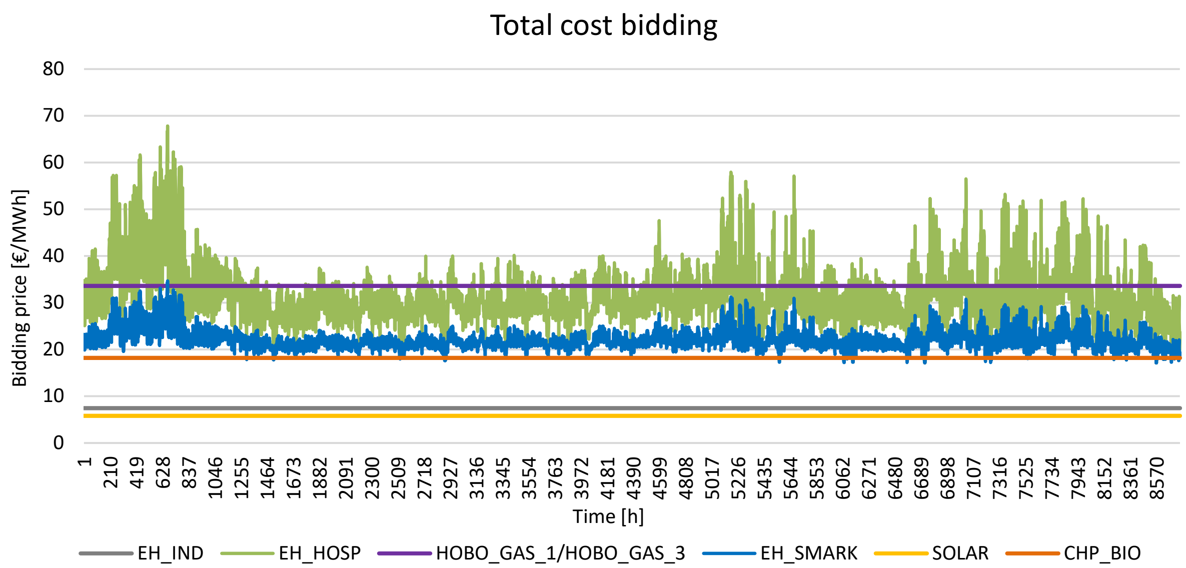


Figure 24 Bidding prices of different heat production technologies when using total cost bidding

When total cost bidding is used, solar thermal has the lowest bidding prices due to the lowest overall costs. Industrial high temperature excess heat has slightly higher bidding price than solar thermal, but it is still rather low when compared to other analysed technologies. These two technologies have constant prices throughout the year since no component of their total cost is hourly variable. The same is for the biomass cogeneration plant, which is the next technology in the merit order. However, during some hours of the year, excess heat from the supermarket has a lower bidding price than cogeneration. This is because of the variability of its bidding prices. The variability is the result of low temperature excess heat sources having the additional electricity price component since they need electricity to power the heat pump and achieve the required temperature level. Nevertheless, during most of the hours, the bidding price of supermarket excess heat is above that of cogeneration, making it the next technology in the merit order. Hospital excess heat bidding prices are also variable and proportionally higher than the ones for the supermarket excess heat due to the lower assumed temperature level and therefore lower COP. In most hours of the year, this is the last technology in the merit order, with the bidding prices even higher than the ones for the natural gas heat only boilers.

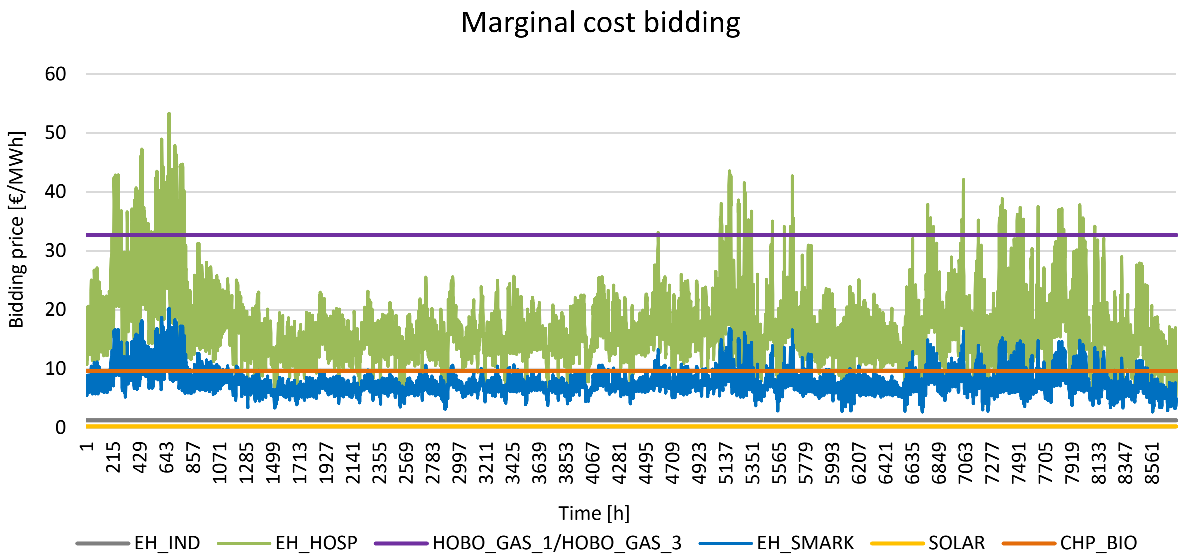


Figure 25 Bidding prices of different heat production technologies when using marginal cost bidding

When marginal cost bidding is used, certain changes in the merit order occur, as seen in Figure 25. While solar thermal and industrial excess heat remain the cheapest and their merit order does not change, the same cannot be said for the other technologies on the heat market. Using marginal cost bidding affects the bidding prices of the low temperature excess heat sources significantly. This also effects the merit order of cogeneration and heat only boilers on the heat market, but only in correlation with low temperature excess heat. The bidding price of supermarket excess heat decreases below that of the cogeneration unit in most hours, improving its position on the merit order substantially. Bidding prices of hospital excess heat also decrease proportionally and are lower than the ones of heat only boilers in most hours of the year. This is expected to considerably increase the utilisation rate of the low temperature excess heat. However, it can be discussed that the highest absolute decrease of bidding prices incurred for technologies with no fuel, or other intensive variable costs (in this case solar thermal and industrial excess heat), which amounted to more than 80%. All the other technologies showed much lower bidding price decreases despite their significant effect on the merit order.

3.8.2 Capacity factor of excess heat sources under different bidding strategies

In order to determine the effect of different bidding strategies on the heat market results, two scenarios were simulated: total cost bidding scenario and marginal cost bidding scenario. The system configuration was used from Scenario 5 explained in 3.7.1. Heat production, i.e. cleared bids from different available technologies are shown in Figure 26. It can immediately be seen that production from solar thermal and industrial excess heat remains the same, regardless of the bidding strategy used. Both of these technologies are utilised to the maximum of their availability when marginal cost or total cost bidding is used, and their merit order does not change.

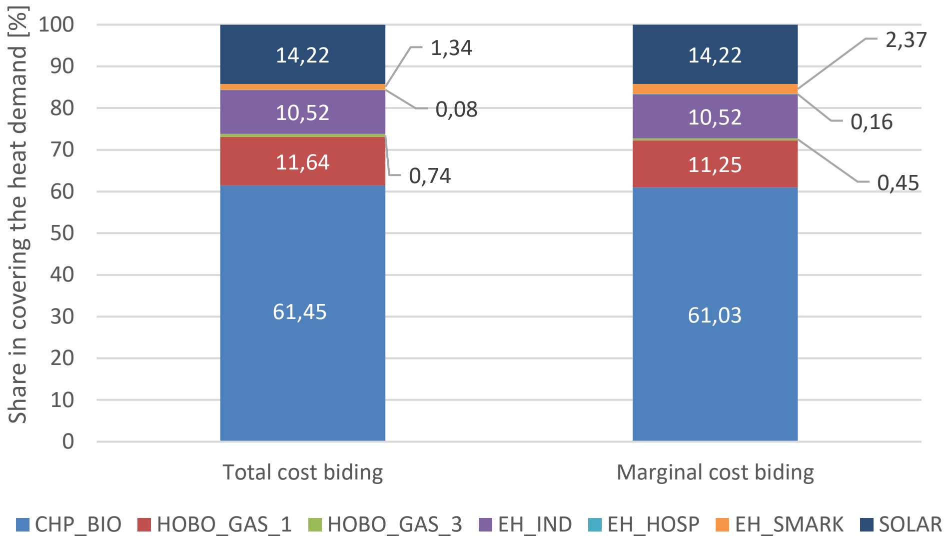


Figure 26 Cleared bids for two biding strategies, presented as the share in supplying the overall heat demand

On the other hand, the number of cleared bids from both low temperature excess heat sources almost doubles. Due to that, the production from the cogeneration unit decreases slightly, but as it operates as the base unit, this reduction is not significant. Overall, it can be argued that the highest effect of using different bidding strategies is on low temperature excess heat sources, as can be also seen from Table 11. Using marginal cost bidding enables much higher utilisation of low temperature excess heat due to the change of their position in the merit order. However, when the overall capacity factor of these two sources is presented, their utilisation still remains rather low, despite using marginal cost bidding.

Table 11 Capacity factor of low temperature excess heat sources in [%] when different biding strategies are applied

	EH_SMARK	EH_HOSP
Total cost biding	37.70	17.80
Marginal cost biding	66.84	36.19

3.8.3 Market clearing price under different bidding strategies

When market clearing price is analysed for both bidding strategies in Figure 27, it shows that substantially lower mean MCPs, as well as their minimum values are achieved for marginal cost bidding, as expected. On the other hand, the maximum MCP remains rather similar in both cases, due to the use of natural gas heat only boiler whose bidding price does not change significantly regardless of the bidding strategy used. It can also be seen that the decrease of the mean MCP is the lowest for Z1 since excess heat and solar thermal are not allowed to bid in that zone. However, it is still decreased by 30.2% due to the high number of accepted bids from the cogeneration plant, whose marginal costs vary considerably when compared to its total costs. It can be concluded that total cost bidding is a more attractive solution for the heat producers since it results in fairly higher MCPs and consequently higher revenues. On the other hand, marginal cost bidding allows higher capacity factors of low temperature excess heat but also results in lower revenues for these sources, as seen in Figure 27. This brings in question the improved feasibility of low temperature excess heat sources when marginal cost bidding is used.

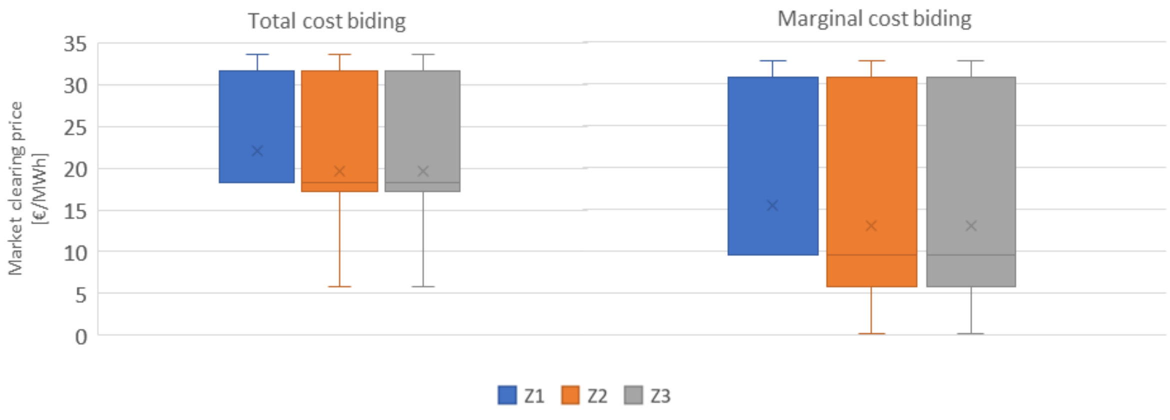


Figure 27 Market clearing prices for different zones when total cost and marginal cost biding are applied

On a further note, Table 12 shows that the demand costs decrease in all the zones when marginal cost bidding is used, leading to a conclusion that this is a more beneficial bidding strategy from the perspective of end users. However, this difference amounts to 15%, which is not significant, especially when it is considered that these are not the final end user costs. Since the end users cannot participate directly on the wholesale heat market, these costs actually represent the supplier costs, which means that the final costs for the end users would be higher depending on the business model of the supplier. Hence, it can be concluded that the effect of using different biding strategies is higher on the production side than the demand side.

Table 12 Overall cost in [€] for the demand side for different biding strategies in each zone

	Total cost biding	Marginal cost biding
Z1 demand cost	626,356	471,064
Z2 demand cost	1,533,077	1,354,200
Z3 demand cost	312,293	275,855
Overall demand cost	2,471,727	2,101,119

3.8.4 Excess heat feasibility under different bidding strategies

As elaborated in 3.7.4, the feasibility of excess heat sources on the wholesale heat market can be determined by calculating both the LCOEH and the average achieved price on the market and comparing them. In cases when the average achieved market price for a certain source is higher than its LCOH, it can be concluded that its utilisation is feasible. The comparison of these two values for marginal cost and total cost bidding is provided in Figure 28.

It can be seen that the LCOEH decreases significantly for low temperature excess heat sources when marginal cost bidding is used, i.e. 36.2% for the supermarket excess heat and 41.6% for the hospital excess heat. However, the figure also shows that despite the higher utilisation and subsequently lower LCOEH, the production costs still remain much higher than the achieved price on the heat market, therefore making these sources infeasible when utilised in standard 3rd generation district heating systems with higher supply temperatures.

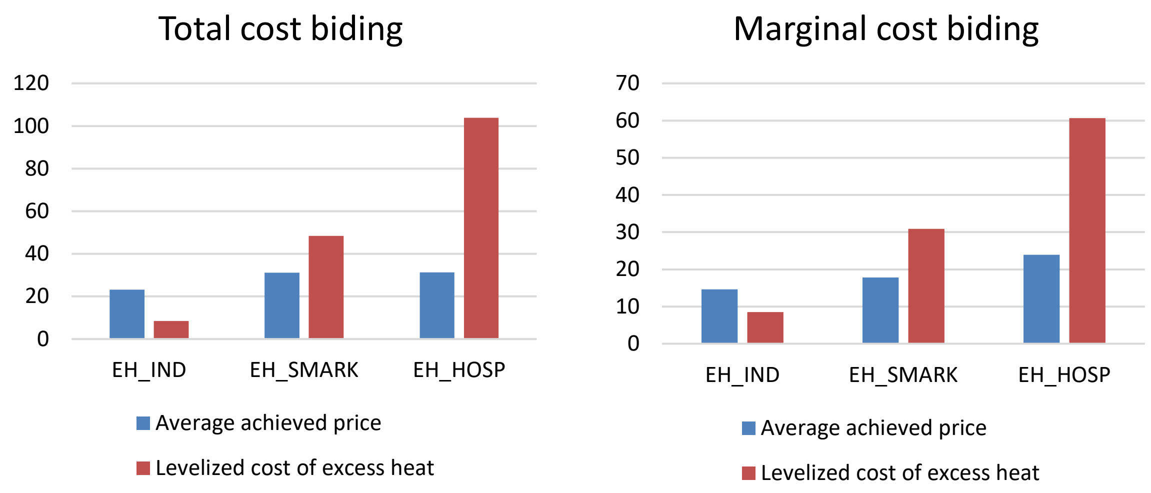


Figure 28 Average achieved price and levelized cost of excess heat for two biding strategies

3.9 The effect of power market prices on the utilisation of low temperature excess heat

In the previous subchapters it was shown that low temperature excess heat is not a feasible solution when integrated alongside conventional heating units and renewables. Here it has to be pointed out that all the analyses were done assuming the integration of excess heat into the 3rd generation district heating systems, which have higher supply temperatures and are still a predominant generation in many countries of Europe [93]. This results in high variable costs of low temperature excess heat and subsequently the low utilisation rate and low feasibility. These variable costs mostly consist of electricity costs for heat pumps, which have been calculated by using the prices from Croatian Power Exchange (CROPEX) for 2017 [94]. However, the prices on the power market can differ considerably on a year-to-year basis, because of various factors including meteorological conditions, development of the power sector, economic situation, etc. For that reason, an analysis of bidding prices has been performed for the low temperature excess heat sources, considering electricity prices from four consecutive years, i.e. 2017 until 2020.

The results are shown in Figure 29 for marginal cost bidding, but the conclusions can be applied to both marginal and total cost bidding due to the reciprocal change in bidding prices. This figure shows the bids for hospital excess heat in 2017 with the quartiles and median value of bids in the period 2017-2020. The visualisation has been performed for a typical winter week (1st January- 7th January) and a typical summer week (1st August – 7th August). The results show that electricity prices and subsequently excess heat bids are much higher in 2017, when compared to the standard values in the analysed period. In the visualized period, the bids of hospital excess heat are higher than the median value and are located in the 4th quartile, being among the 25% of the most expensive bids. This shows that the yearly variations of power market prices have a great effect on the bids of low temperature excess heat sources. The results for the supermarket excess heat are not presented since the qualitative effect is the same.

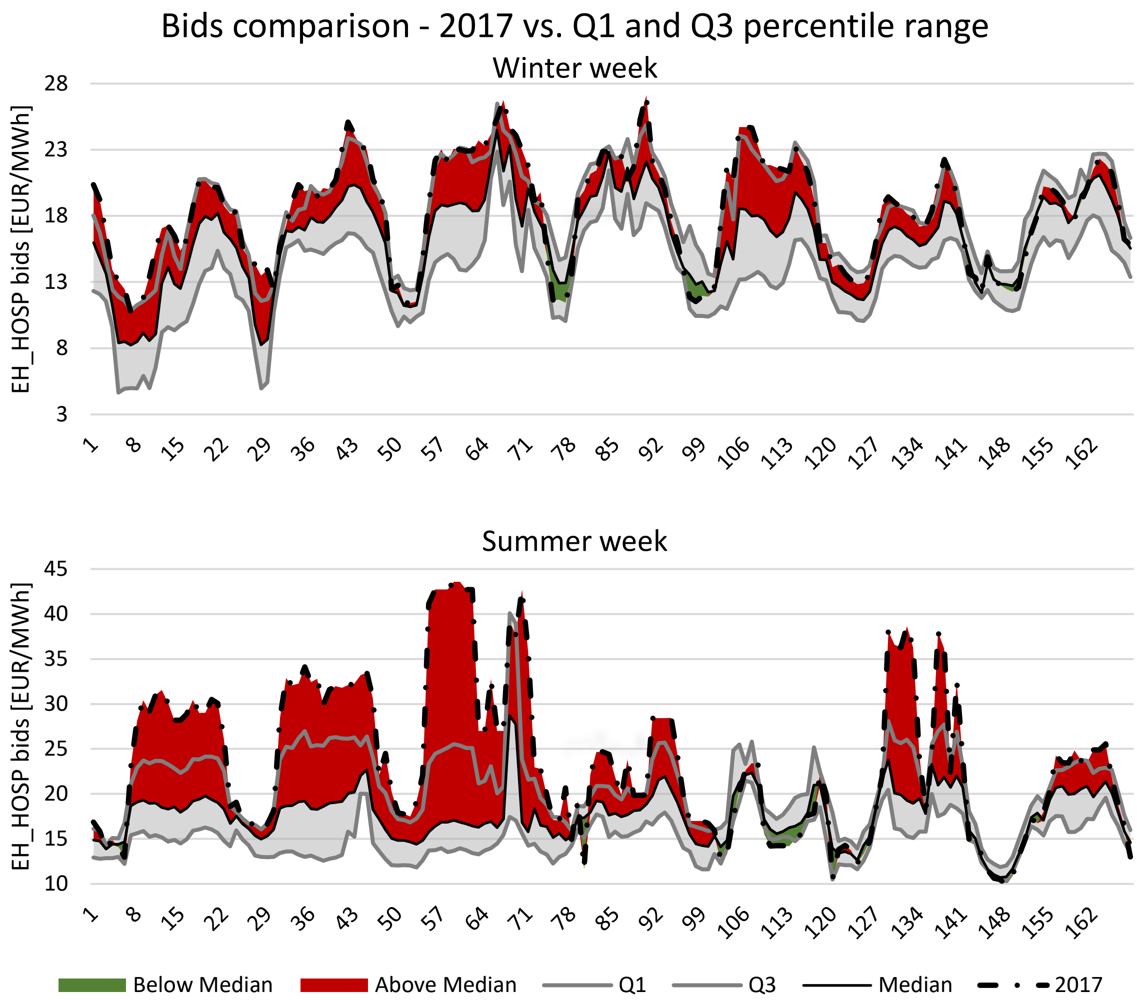


Figure 29 Comparison of EH_HOSP bids for 2017 with the quartile and median values for the period 2017-2020, for a typical winter week (up) and a typical summer week (down)

Table 13 Capacity factor of low temperature excess heat sources in [%] for different years

	EH_SMARK	EH_HOSP
2017	66.84	36.19
2018	64.33	38.66
2019	66.38	37.36
2020	69.42	43.71

In order to fully understand the effect of the yearly power market price variability on the utilisation of low temperature excess heat sources, heat market simulations were performed considering power market prices from 2017 until 2020.

The results, in the form of low temperature excess heat capacity factors are shown in Table 13. The decreased power market prices lead to increased capacity factors of both analysed low temperature excess heat sources, with the highest changes appearing in 2020. However, these are still not high enough to achieve the low LCOEH, which would make them feasible on the heat market. For example, the LCOEH of supermarket EH in reduced by 7.2% in 2020 compared to 2017, while for hospital excess heat it reduced by 18.9%. These numbers are relatively high, but the average achieved prices on the heat market also decrease which means that these sources remain infeasible.

Nevertheless, it can be concluded that power market prices affect the utilisation rates of low temperature excess heat sources and that their reduction could foster the feasibility and utilisation of this source. This is particularly important from the perspective of integrating higher amounts of renewable energy on the power markets which has shown to reduce the power market prices [95]. Hence, the increased renewable energy utilisation in the electricity sector could also foster the low temperature excess heat utilisation, enabling the increased efficiency and sustainability of the heating sector.

4 CONCLUSIONS AND FUTURE WORK

In this section, the main conclusions from this thesis will be presented, covering its main objectives and the hypothesis. First of all, it can be concluded that levelized cost of excess heat method should be used as a criterion for analysing excess heat utilisation. This was proven throughout the papers published as a part of this thesis. By using levelized cost of excess heat one can demonstrate the maximum feasible distance of the excess heat source from the demand, which is a useful feature, especially when considering the fact that the majority of available excess heat is located far from the high demand density areas. When applied on the case study of the city of Ozalj in Croatia, it showed that high temperature excess heat could be feasibly utilised even if located more than 23 km away from the demand, in case of high excess heat availability and low distribution pipe costs. In case these parameters are unfavourable, high temperature excess heat still proves to be a feasible solution but needs to be located in the close vicinity of the demand. Furthermore, it was also shown how levelized cost of heat integrated with GIS mapping procedures can be a good criterion and a planning tool for district heating in general, enabling one to pinpoint the feasible city areas which should be connected to a district heating system.

From the perspective of the environmental effect, it was shown that already conventional district heating solutions have an environmental benefit over individual heating solutions, which grows substantially when excess heat sources are used. The main reason behind it is that their emissions are already accounted for in the sector of their primary use, meaning that they can be considered a zero-emission source for heating. The highest impact is on the local pollutants, including NO_x, CO and particulate matter which decrease by more than 90% when district heating replaces individual heating solutions in cities. This is especially relevant for the smaller rural cities which tend to use biomass stoves for heating, leading to high local pollutant emissions and subsequently severe health problems of the population.

As already indicated, levelized cost of excess heat, and therefore the feasibility of excess heat can vary considerably depending on different factors. Capacity factor and the temperature level of the excess heat source both have the profound effect on the levelized cost of excess heat. First, different system configurations and variability of excess heat availability influence the capacity factor of high temperature excess heat. The results of the scenario analysis lead to a conclusion that the biggest competitor to the high temperature excess heat is solar thermal, which has lower operating costs and therefore higher priority, reducing the amount of utilised excess heat. Other analysed production technologies have shown to not compete with excess heat directly. However, even if no solar thermal is available in the system, the mismatch between the excess heat availability and heat demand results in low capacity factors and therefore higher levelized cost of excess heat. This means that the dedicated thermal storage unit is a prerequisite for a feasible utilisation of available excess heat sources and their high capacity factors. Based on the presented results, it can also be concluded that in most cases, seasonal thermal storage units need to be implemented in order to utilise 100% of excess heat. From the economic point of view, this has also resulted in the lowest levelized cost of heat for the whole system.

On the other hand, the previously listed conclusions were all made for the high temperature excess heat sources utilised in high temperature district heating systems. However, there is a high potential for low temperature urban excess heat which is usually located inside the high heat density areas. By adapting the levelized cost of excess heat method, it was shown how the lower temperatures of the excess heat source effect it. It can be concluded that in the 3rd generation of district heating systems with higher supply temperatures (>85°C), low temperature excess heat sources are not feasible. Nevertheless, by transferring towards the 4th generation of district heating with lower supply temperatures, the feasibility of low temperature excess heat increases significantly, which emphasizes the necessity for such a transition.

All these results and conclusions were considered and provided the input for the final part of the thesis, focusing on the utilisation of excess heat sources on the wholesale heat market. This option was analysed as a way of granting third party access for the excess heat producers to supply their heat to the district heating systems. The focus was on both high temperature industrial excess heat and low temperature service sector excess heat and their integration into the heat market with other competing producers. The results showed the benefits of a wholesale heat market in general, which proved to facilitate the increase of the total social welfare, especially when excess heat sources were allowed access to the market. However, despite their positive effect on the total welfare from the demand side (by reducing the market clearing prices in certain hours), low temperature excess heat sources once again proved to be infeasible when utilised on a high temperature heat market. This was shown by calculating their levelized cost of excess heat and comparing it to the average achieved prices on the heat market, which were significantly lower in all the analysed cases. However, it must be noted that the CO_2 prices for natural gas peak load boilers were not considered in this thesis when formulating its bidding prices due to the reasons mentioned in the Method section. The rising CO_2 prices in the EU ETS [96] and the fact that most peak load boilers are above 20 MW capacity (being required to participate in the EU ETS) could result in the change of merit order between low temperature excess heat and peak load boilers, leading to a higher feasibility of low temperature excess heat. High temperature excess heat and solar thermal on the other hand proved to be feasible in all the cases, due to their low cost and subsequently low bidding prices. Also, this way the hypothesis of this thesis was proved, showing that levelized cost of excess heat provides the minimum price which would enable various excess heat producers to feasibly participate in the local deregulated heat market.

Finally, it can be concluded that changing bidding strategies (total cost and marginal cost bidding) results in the change of merit order of low temperature excess heat sources in most hours of the year. This subsequently increases their capacity factor when marginal cost bidding is used. Nonetheless, due to the high marginal costs of these sources, their overall feasibility doesn't change since the average achieved price on the heat market still remains significantly lower than their levelized cost of excess heat. As the main factor in their marginal price calculation is the electricity price for powering the heat pumps, further analysis focused on determining the effect of power market prices on the overall feasibility of these sources. It was shown how the variations of these prices on the year-to-year basis influence the capacity factor of low temperature excess heat sources through decreasing their marginal prices, which still proved insufficient to change their feasibility in the analysed case study. However, it can be concluded that the reduction of power market prices, influenced by the increased share of renewables on such a market could foster the feasibility and utilisation of low temperature excess heat, enabling the increased efficiency and sustainability of the heating sector.

The considerable potentials of this research topic have been proven in Section 1 and throughout the thesis. Therefore, some ideas on the future research will be listed in this paragraph. As the combination of levelized cost of heat method and GIS mapping has been shown as a good planning tool for district heating systems, further research should be done to define the feasible district heating connections when high temperature excess heat is also used in the system. It can be assumed that this would lead to increased number of feasible city areas which should be connected to a district heating system. Further analysis could also be done on the topic of heat market utilisation in 4th generation district heating systems, to prove the expected higher feasibility of low temperature excess heat in such systems. Also, since the carbon prices have not been considered in this thesis, further research on feasibility of low temperature excess heat should be done, taking into account EU ETS prices. A special focus should be given to the plan of the European Commission to include the emissions from individual boilers into the EU ETS, which would further increase the feasibility of low carbon district heating solutions, such as excess heat. Finally, from the perspective of the integration of power and heat markets through low temperature excess heat, the effect that renewables have on the power market price decrease and subsequently on low temperature excess heat feasibility should also be studied in more detail.

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6 CURRICULUM VITAE

BORNA DORAČIĆ mag.ing.mech. was born on the 13th of March 1992 in Zagreb, Croatia. After finishing the high school "II. Gimnazija" in Zagreb in 2010 with highest grades, he received the right to the direct enrolment at the Faculty of Mechanical Engineering and Naval Architecture (FMENA), University of Zagreb, where he finished the undergraduate studies in mechanical engineering in 2014, and the graduate studies (with honours – Magna Cum Laude) in 2016. Immediately after finishing his studies, he got employed at the Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, at the Department of Power, Energy and Environmental Engineering as a research assistant and a PhD student. In this position, he has worked on several EU funded projects, namely CoolHeating, UpgradeDH, DHswitch and PROSEU focusing on facilitating renewable and sustainable solutions for the district heating sector. He also worked as a team member on the RESFLEX project, funded by the Croatian Science Foundation, focusing on modelling the energy demand and the measures for its reduction until 2050 for the Republic of Croatia. Apart from research, he was also a part of the team providing consulting services for private companies and public bodies in the topic of sustainable energy solutions. Since June 2021, he is working as an EU project manager at the University of Vienna in Vienna, Austria.

He attended 17 international scientific conferences and numerous national, project related conferences. He has been a part of the Local Organizing Committee of the international SDEWES Conference in 2017 and 2019 and acts as a Steering Committee Member of Fondacija SDEWES. He is an author of 28 scientific papers, out of which 10 are published in renowned (CC/SCI indexed) journals. His current Scopus *h*-index is 6. He serves as a Reviewer for Renewable and Sustainable Energy Reports, Energy Conversion and Management, Energy and Buildings, Applied Thermal Engineering, Cleaner Engineering and Technology, Energy and JSDEWES journals and has been awarded Recognized Reviewer Status by Elsevier.

List of published scientific journal papers:

- Doračić, B.; Pavičević, M.; Pukšec, T.; Duić, N. Bidding strategies for excess heat producers participating in a local wholesale heat market. Energy Reports 2022; 8: 3692-3703. https://doi.org/10.1016/j.egyr.2022.02.307
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prosumer ecosystems in Europe. Energy Res Soc Sci 2022;86:102425. https://doi.org/10.1016/j.erss.2021.102425.

- Ferrari L, Morgione S, Rutz D, Mergner R, Doračić B, Hummelshøj RM, et al. *A comprehensive framework for District Energy systems upgrade*. Energy Reports 2021;7:359–67. https://doi.org/10.1016/j.egyr.2021.08.095.
- Doračić, B., Pavičević, M., Pukšec, T., Quoilin, S., Duić, N., *Utilizing excess heat through a wholesale day ahead heat market – The DARKO model*. Energy Convers. Manag 2021; 235: 114025. https://doi.org/10.1016/j.enconman.2021.114025
- Doračić B, Grozdek M, Pukšec T, Duić N. *Excess heat utilization combined with thermal storage integration in district heating systems using renewables.* Therm Sci 2020;24 (6 Part A):3673–84. https://doi.org/10.2298/TSCI200409286D
- Doračić B, Pukšec T, Schneider DR, Duić N. *The effect of different parameters of the excess heat source on the levelized cost of excess heat.* Energy 2020;201:117686. https://doi.org/10.1016/j.energy.2020.117686
- Rutz D, Worm J, Doczekal C, Kazagic A, Duić N, Markovska N, et al. *Transition towards a sustainable heating and cooling sector - case study of southeast European countries.* Therm Sci 2019; 23:3293–306. https://doi.org/https://doi.org/10.2298/TSCI190107269R.
- Dorotić H, Doračić B, Dobravec V, Pukšec T, Krajačić G, Duić N. *Integration of transport and energy sectors in island communities with 100% intermittent renewable energy sources.* Renew Sustain Energy Rev 2019;99. https://doi.org/10.1016/j.rser.2018.09.033.
- Doračić B, Novosel T, Pukšec T, Duić N. *Evaluation of excess heat utilization in district heating systems by implementing levelized cost of excess heat.* Energies 2018;11. https://doi.org/10.3390/en11030575
- Čulig-Tokić D, Krajačić G, Doračić B, Mathiesen BV, Krklec R, Larsen JM. *Comparative analysis of the district heating systems of two towns in Croatia and Denmark*. Energy 2015;92:435–43. https://doi.org/10.1016/j.energy.2015.05.096

7 SUMMARY OF PAPERS

PAPER 1

Doračić B, Novosel T, Pukšec T, Duić N. *Evaluation of excess heat utilization in district heating systems by implementing levelized cost of excess heat.* Energies 2018; 11. https://doi.org/10.3390/en11030575.

District heating plays a key role in achieving high primary energy savings and the reduction of the overall environmental impact of the energy sector. This was recently recognized by the European Commission, which emphasizes the importance of these systems, especially when integrated with renewable energy sources, like solar, biomass, geothermal, etc. On the other hand, high amounts of heat are currently being wasted in the industry sector, which causes low energy efficiency of these processes. This excess heat can be utilized and transported to the final customer by a distribution network.

The main goal of this work was to calculate the potential for excess heat utilization in district heating systems by implementing the levelized cost of excess heat method. Additionally, the paper provided the economic and environmental benefit of switching from the individual heating solutions to a district heating system. This was done by using the qGIS software. The variation of different relevant parameters was taken into account in the sensitivity analysis. Therefore, the final result was the maximum potential distance of the excess heat source from the demand for different available heat supplies, costs of pipes and excess heat prices.

In this paper, Doračić was responsible for data collection, method development, calculations and graphical representation of the results. Novosel was responsible for performing qGIS calculations. The paper was written by Doračić and reviewed by Pukšec and Duić.

PAPER 2

Doračić B, Pukšec T, Schneider DR, Duić N. *The effect of different parameters of the excess heat source on the levelized cost of excess heat.* Energy 2020; 201:117686. https://doi.org/10.1016/j.energy.2020.117686

In areas with higher heat demand densities, district heating is the most logical way of achieving heat sector decarbonisation aims, especially when renewable energy or highly efficient cogeneration is used. However, excess heat from industry is also recognized as a valuable source with the high potential for utilization. It increases the economic and environmental viability of the system due to the low operation, investment and conventional energy costs. The main goal of this work was to define the effect of the main factors influencing the levelized cost of excess heat. The paper provided the feasibility of excess heat utilisation in different district heating configurations, including solar collectors, cogeneration, peak load boilers, heat pumps and heat storages, showing that its overall utilisation can be much lower than the expected 100% of the overall availability depending on the configuration. Furthermore, temperature levels of the excess heat source have been considered in the analysis to show changes in levelized cost of excess heat with different temperatures and the necessary preconditions for its utilisation. It has been concluded that it is necessary to reduce the supply temperature of district heating in order to make the low temperature excess heat sources feasible.

In this paper, Doračić was responsible for data collection, modelling, method development, calculations and graphical representation of the results. The paper was written by Doračić and reviewed by Schneider, Pukšec and Duić.

PAPER 3

Doračić B, Grozdek M, Pukšec T, Duić N. *Excess heat utilization combined with thermal storage integration in district heating systems using renewables.* Therm Sci 2020;24 (6 Part A):3673–3684. https://doi.org/10.2298/TSCI200409286D

District heating systems already play an important role in increasing the sustainability of the heating sector and decreasing its environmental impact. However, a high share of these systems is old and inefficient and therefore needs to change towards the 4th generation district heating, which will incorporate various energy sources, including renewables and excess heat of different origins. Especially excess heat from industrial and service sector facilities is an interesting source since its potential has already been proven to be highly significant, with some researches showing that it could cover the heat demand of the entire residential and service sector in Europe. However, most analysis of its utilization in district heating are not done on the hourly level, therefore not taking into account the variability of its availability. For that reason, the main goal of this work was to analyse the integration of industrial excess heat into the district heating system consisting of different configurations, including the zero fuel cost technologies like solar thermal. Furthermore, cogeneration units were a part of every simulated configuration, providing the link to the power sector. Excess heat was shown to decrease the operation of peak load boiler and cogeneration, that way decreasing the costs and environmental effect of the system. However, since its hourly availability differs from the heat demand, thermal storage needs to be implemented in order to increase the utilization of this source. The analysis was performed on the hourly level in the energyPRO software.

In this paper, Doračić was responsible for data collection, modelling, method development, calculations and graphical representation of the results. The paper was written by Doračić and reviewed by Grozdek, Pukšec and Duić.

PAPER 4

Doračić, B., Pavičević, M., Pukšec, T., Quoilin, S., Duić, N., *Utilizing excess heat through a wholesale day ahead heat market – The DARKO model*. Energy Convers. Manag 2021; 235: 114025. https://doi.org/10.1016/j.enconman.2021.114025

District heating has already proven to be a suitable solution for the decarbonisation of the most energy intensive energy sector in Europe, heating and cooling. However, to achieve this, it needs to incorporate renewable and sustainable energy sources into the generation mix which is still dominated by fossil fuels in many countries. Alongside traditional renewables like solar thermal, geothermal and biomass, excess heat from the industrial and service sector has a high untapped potential. Nonetheless, to utilize it in district heating, third party access must be granted. For that reason, a wholesale day ahead heat market has been modelled in this study and validated on a case study in the city of Sisak in Croatia. The idea was twofold: to evaluate the functionality of such a heat market and its effect on the existing system, as well as to analyse the integration of high and low temperature excess heat sources in different conditions, including the use of thermal storage, as well as the competition with low-cost renewables, i.e. solar thermal. The results have shown that the introduction of a wholesale day ahead heat market would ensure the positive total welfare in all the scenarios. The benefit for the demand side and the total welfare would increase even more if excess heat sources are integrated in the system and especially if they are combined with a thermal storage to increase their capacity factor, which would also decrease the competing effect of solar thermal. Finally, it was shown that low temperature excess heat is not feasible in the high temperature district heating and the transfer to the 4th generation district heating is required to feasibly utilise low temperature sources.

In this paper, Doračić was responsible for data collection, performing simulations, method development, calculations and graphical representation of the results. Pavičević was responsible for model development. Doračić provided input and feedback on the model development. The paper was written by Doračić and reviewed by Pavičević, Quoilin, Pukšec and Duić. Pavičević also provided input on the model description.

PAPER 5

Doračić, B.; Pavičević, M.; Pukšec, T.; Duić, N. Bidding strategies for excess heat producers participating in a local wholesale heat market. Energy Reports 2022; 8: 3692-3703. https://doi.org/10.1016/j.egyr.2022.02.307

With district heating shifting towards the 4th generation systems, it will have to use locally available energy sources, like biomass, geothermal, solar thermal, etc. Excess heat sources from various industries and tertiary sector buildings can also be included. Utilizing it in district heating systems has a number of benefits, including the efficiency increase of the industrial process, reducing greenhouse gas emissions of the heating sector and decreasing the heat price due to low capital and operation costs. In order to utilize excess heat in the existing or new district heating system, third party access has to be allowed. This calls for a local wholesale day ahead heat market, which already showed its potential through the authors previous research.

This work consists of analysing two different bidding strategies which can be applied on the heat market: total cost biding and marginal cost biding. The focus here is to research the feasibility of the excess heat sources when different bidding strategies are used, especially when low temperature excess heat is considered, which has variable hourly costs due to the electricity demand for operating a heat pump. The results show that, despite the increased capacity factor of low temperature excess heat when marginal cost biding is used, it remains infeasible when supplying heat to the high temperature district heating networks through a heat market. Therefore, lower temperature 4th generation district heating systems are a necessity for a feasible utilisation of low temperature excess heat. Finally, the effect of the power market prices on the low temperature excess heat feasibility was analysed and it was shown that it is significant, which led to the conclusion that introducing a higher share of renewables into the power market could foster the utilisation of these heat sources

In this paper, Doračić was responsible for data collection, performing simulations, method development, calculations and graphical representation of the results. The paper was written by Doračić and reviewed by Pavičević, Pukšec and Duić. Pavičević also provided input on the model description.

PAPER 1

energies

MDPI

Article

Evaluation of Excess Heat Utilization in District Heating Systems by Implementing Levelized Cost of Excess Heat

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Abstract: District heating plays a key role in achieving high primary energy savings and the reduction of the overall environmental impact of the energy sector. This was recently recognized by the European Commission, which emphasizes the importance of these systems, especially when integrated with renewable energy sources, like solar, biomass, geothermal, etc. On the other hand, high amounts of heat are currently being wasted in the industry sector, which causes low energy efficiency of these processes. This excess heat can be utilized and transported to the final customer by a distribution network. The main goal of this research was to calculate the potential for excess heat utilization in district heating systems by implementing the levelized cost of excess heat method. Additionally, this paper proves the economic and environmental benefits of switching from individual heating solutions to a district heating system. This was done by using the QGIS software. The variation of different relevant parameters was taken into account in the sensitivity analysis. Therefore, the final result was the determination of the maximum potential distance of the excess heat source from the demand, for different available heat supplies, costs of pipes, and excess heat prices.

Keywords: excess heat; levelized cost of excess heat; district heating; CO_2 emissions; heat demand mapping

1. Introduction

Security of energy supply and CO_2 emissions reduction have been recognized by the EU as the key topics that will define the development of its energy systems. For that reason, the utilization of highly efficient cogeneration with district heating systems should increase significantly, since these systems can greatly increase energy efficiency and reduce the CO_2 emissions of the energy sector. Currently, only 13% of the European heat supply is covered by district heating systems, which makes the potential for increasing this share significant, especially in urban areas which are characterised by high heat demand densities [1]. However, some northern countries, e.g., Sweden, already cover more than 50% of the residential and service sector heat demand with district heating [2], showing the way for the rest of the Europe. An analysis was conducted in Denmark as a case study, which examined the role of district heating systems in future renewable energy systems [3]. The primary conclusion was that the expansion of district heating to up to 70% of Danish net heat demand would be optimal. However, this could be limited by the uneven framework as shown in [4]. The expansion would result in significant fuel savings, reduction of CO_2 emissions, reduction of costs, as well as in better utilization of excess heat. Similarly, from the perspective of the consumers, the most important reasons for connecting to district heating are affordability, increased comfort, and the favourable environmental impact [5]. Prosumers, i.e., consumers who are at the same time producers of heat, will also have an important role in future district heating systems, as shown in [6] for Finland. This will facilitate the integration of renewable energy sources with these systems. The environmental benefit of district heating, combined with the implementation of renewables in other sectors, was shown in [7], providing detailed decarbonization scenarios by 2050 for Italy. These future district heating systems will be classified as fourth-generation district heating systems. They will incorporate low distribution temperatures, use of renewable energy sources and excess heat, use of large scale heat pumps and thermal storage, integration of the heat and electricity sectors, etc. [8]. Integrated with information and communication technologies, they will represent sustainable smart district heating systems as a part of the smart cities of the future [9]. The use of renewable energy sources in particular lowers both the environmental impact and the heat production costs in comparison to conventional district heating systems, as shown in [10]. Furthermore, low supply and return temperatures lower the losses in the distribution network, which are currently one of the biggest problems of the existing old systems, especially in Eastern Europe. This was presented in a study [11], which provided a comparative analysis between two district heating systems in Croatia and Denmark. It showed that because of the advanced age and high distribution temperatures in the Croatian system, heat losses are approximately three times higher than in the Danish system. However, the prerequisite for low temperature networks is the availability of adequate low temperature sources and their economic conditions, as shown for four cases in Austria [12]. Another way of reducing heat losses is the refurbishment of distribution pipes. Grid losses significantly influence the overall performance of district heating, as shown by data from several systems in Italy [13]. For that purpose, different designs of pipes can be considered, including twin pipes, asymmetrical insulation of twin pipes, double pipes, and triple pipes, which provide potential for energy savings [14]. Furthermore, an increase of insulation standards on pipes also facilitates heat savings. It was shown that the costs are still too high to implement the highest available standard, although it is expected to be feasible in the near future [15].

An interesting heat source for district heating systems is the excess heat from industrial facilities. A significant amount of energy used in industry is currently being wasted, as shown in the case of China, where these losses amount to at least 50% [16]. Moreover, research has shown that there is enough excess heat in the EU to cover the heat demands of all buildings from the service sector and households [17]. Furthermore, an analysis of these sources has been made for the EU-27 [18]. The main conclusion of this research is that the potential for implementation of excess heat in district heating systems is significant, but it is currently not being used. Similar studies have been carried out for various excess heat sources concerning different frameworks, for example analyses of excess heat utilization from thermal power plants in the EU-28 [19], industrial excess heat utilization in China [20], excess heat utilization from the petrochemical industry on the west coast of Sweden [21], and excess heat utilization in Japan [22]. Based on the methods from [18], authors in [23] made an analysis of various excess heat sources in Denmark. The focus was on their utilization in district heating systems, using heat pumps in order to increase the temperature level. Their results showed that these sources are often located far from potential consumers, i.e., heat demands, and therefore further research is required in this area. A similar conclusion was drawn in [24], where authors analyzed the potential for excess heat utilization in district heating systems in Great Britain. It is concluded that in the case of remote locations of these sources, it is not economically viable to utilize them in a district heating network. Some researchers are trying to tackle this problem. For example, the use of mobile heat storage units is proposed in [25]. These units are charged at the site of excess heat sources, transported by a train or a truck to the location of heat demand, and then discharged. Another concept that is being researched is the novel heat allocator concept, which is a combination of a heat engine, a heat exchanger, and a heat pump [26].

A number of studies regarding the economics of excess heat utilization in district heating have already been performed, showing its benefits. This was the focus of [27], where authors provided a system analysis of this source for a case in Sweden. The study implemented a model for minimizing system costs, and it was shown that excess heat is a feasible solution in all the investigated energy market scenarios. Similarly, other research [28] highlighted the economic and environmental advantages of utilizing excess heat in district heating, which also significantly increased the production of jointly operated cogeneration units. Moreover, the optimal contribution of excess heat from industrial facilities has been studied in [29], where the authors developed a method for determining the investment costs of its utilization from a cluster of industrial facilities. The impact of excess heat utilization in a district heating system on CO_2 emissions and the energy system as a whole has been studied for a region in Sweden [30]. The research showed that introducing excess heat into the energy system would reduce the use of fossil fuels and therefore the environmental impact of the energy system, although this is highly case-dependent.

A good criterion for the economic evaluation of energy production technologies is the levelized cost of energy, which takes into account all the cashflows during the lifetime of a plant. Numerous research studies have already been carried out by implementing the levelized cost of electricity calculations. Recently, it has been used in [31] and supplemented by including uncertainty and endogeneities in input parameters for analyzing the economic feasibility of gas and nuclear power plants, showing much higher feasibility for gas power plants. Furthermore, in [32] it has been used to analyze the feasibility of a solar chimney power plant, proving its competitiveness against other renewable power production technologies. However, a significantly smaller amount of research has been carried out in the heat sector by implementing the levelized cost of heat method, with most papers focusing on the calculation of the total costs, as shown for a building in [33]. The levelized cost of heat has been used for example in [34] for determining the feasible level of heat savings and heat production on the European level, in [35] for the Fresnel solar system, and in [36] for co-firing solid, liquid, and gaseous fuel in a heat-only boiler, but none of these papers include excess heat in the analyses. One of the main parameters in the calculation of the levelized cost of excess heat will be the procurement cost of excess heat, which has been analyzed in [37] for excess heat from data centers, while taking into account a scenario with the possibility of a heat market. The potential for heat market implementation, i.e., third-party access, has also been discussed in [38], giving some basic comments on its benefits for excess heat utilization in district heating systems.

This paper presents the continuation of the research conducted in [39], which provided the analysis of excess heat utilization in a district heating system in a small rural city. The concept proved to be feasible; however, the analysis considered only the potentially available excess heat supply, and no other parameters were taken into account. Therefore, this research has been expanded as described in the next few lines. In this paper, heat demand mapping has been utilized in order to provide the analysis of the feasibility of a natural gas district heating implementation for a small city. This way, both the environmental and economic advantages of this system over individual heating solutions are demonstrated. The analysis further includes potential excess heat utilization, taking into account its distance from the heat demand. The novelty of this study is the utilization of the levelized cost of excess heat method. The method is validated by performing a case study for the city of Ozalj, a small city in Croatia.

2. Materials and Methods

The method consists of two main steps: heat demand mapping and feasibility analysis by implementing the novel levelized cost of excess heat method. In the next sections, a more detailed description of the aforementioned steps will be provided.

2.1. Heat Demand Mapping

In order to assess the heat demand of the city of Ozalj and therefore provide the input for the scenario analysis, heat demand mapping was performed. A similar geographic information system analysis has already been done in [40], providing the potential for district heating expansion. However, mapping is not the focus of this paper but only provides the required input for further analysis.

For that purpose, Matlab [41] and QGIS [42] software were used. The data used in the process of mapping were mostly public in order to facilitate the replication of the method. The method was also complemented with the results from a survey carried out in Ozalj [43]. The questionnaire was developed as a part of the CoolHeating project [44], and the questions were specifically designed to collect good quality data from the citizens, in order to assess their heating needs and gather ideas, suggestions, and doubts for connecting to a district heating system. In order to get more precise energy consumption patterns, information was gathered both on the building stock (i.e., age of buildings, type of windows, insulation, net heating area, heating system, etc.) and on the annual fuel consumption. On the basis of this information, the heat demand of each surveyed household was calculated.

In order to better utilize these data for further analysis, the buildings were divided into eight categories with associated specific heat demands. The categories were determined by visually inspecting surveyed buildings and aggregating data from similar buildings into a specific category. This method is suited for smaller municipalities and can provide very detailed and more accurate heat demand maps, both on the building and on the aggregated level. However, when analyzing heat demands of larger areas, this method would not be appropriate since it would require too much time to carry out the survey. Specific heat demands for eight categories of buildings in the city of Ozalj are shown in Table 1. It has to be pointed out that the values for office building, public building, industry, and historic building have been taken from the city's Sustainable Energy Action Plan [45] because of the insufficient data for these categories. Specific heat demands of some categories deviate significantly from the mean values, as shown in Table 1. This is specifically the case for a house without insulation, since this category includes all the houses without any insulation on the outer walls. Therefore, the heat losses are the highest in this category. The survey was carried out in 391 households, which represents a share of 17% of the overall number of households in Ozalj. The results from Table 1 clearly show the status of energy consumption of building stock in the continental part of Croatia. These can also be applied to the whole region of southeastern Europe, because of the similar characteristics in this sector. Such high heat demands are the result of the relatively old age of buildings and low rates of refurbishment, with more than 50% of the surveyed households having no outer wall and roof insulation at all.

Table 1. Building categories and associated specific heat demands.

Category	Number of Buildings Analyzed in the Survey	Specific Heat Demand (kWh/m^2)	Standard Deviation from the Mean Specific Heat Demand (159.2 kWh/m^2)
Old house	241	177.75	18.56
New house	12	112.5	−46.69
House without insulation	28	262.5	103.31
Apartment building	21 apartments	161.25	2.06
Office building	-	135	−24.19
Public building	-	270	110.81
Historic building	-	78.75	−80.44
Industry	-	110	−49.19

The heat demand mapping conducted for this research consisted of four main steps. These can be divided as follows:

1. The first step was to create a matrix in Matlab that contained information on the total gross area and locations of buildings from the Croatian online building census Geoportal [46].
2. In the second stage, the buildings were classified into eight categories according to their purpose and condition, in order to allocate their specific heat demands.
3. At the same time, data on the number of floors were collected by visually inspecting all the households in the analyzed area. This could be done by using free online tools like Google Earth, etc. Both the categories and the number of floors were added to the initial matrix by color coding.

4. Afterwards, the final heat demand matrix was created by multiplying the total gross areas of the buildings with the associated specific heat demands. This final matrix was then transferred into a geographic information system interface using the QGIS tool.

The main steps are presented graphically in Figure 1, which gives an overview of the building locations map, category map, number of floors map, and, finally, the heat demand map on the 100 × 100 m level for the selected location. The final step, i.e., the GIS map is presented in the results section.

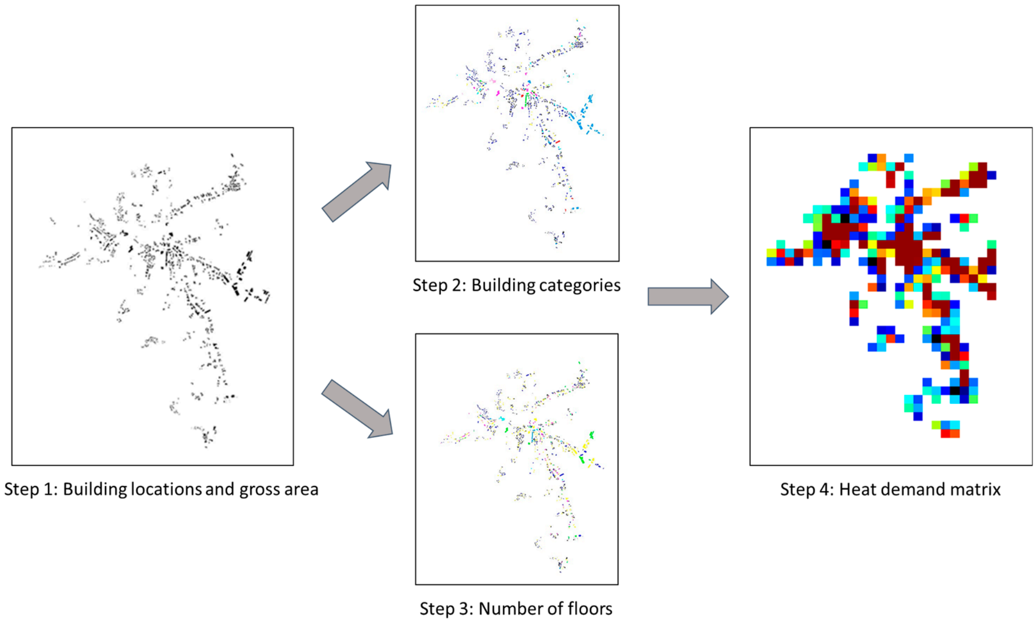

Figure 1. Graphical representation of the four main steps in the heat demand mapping method.

2.2. Scenario Analysis

In order to determine the feasibility and the environmental impact of district heating system implementation in a small rural city, different scenarios were developed. Microsoft Excel and QGIS software were used for the calculations. First, the implementation of a natural gas district heating system was analyzed in order to point out the advantages of such a system over individual heating solutions. The effect of excess heat utilization on the system costs was also researched by implementing the levelized cost of excess heat method, as described in more detail in the following paragraphs. Finally, a sensitivity analysis was implemented, taking into account various relevant parameters.

2.2.1. Implementation of a Natural Gas District Heating System

Feasibility calculations of the proposed scenarios were done on the level of aggregated 100 × 100 m heat demand areas. Furthermore, by using the cost data from [47], the levelized cost of heat was calculated for a potential natural gas district heating system, as shown in (1):

$$\mathrm{LCOH} = \frac{I_c \cdot CRF \cdot (1 - TD_{pv})}{8760 \cdot i \cdot (1 - T)} + \frac{O_{total}}{8760 \cdot i} + c_{fuel} \quad [€/\mathrm{kWh}] \tag{1}$$

where I_c is the capital cost of the production facility [€/kW], CRF is the capital recovery factor which discounts the investment, T is the tax rate, D_{pv} is the present value of depreciation taken from [48], i is the capacity factor of the production facility, O_{total} are the total operation and maintenance costs [€/kW], and c_{fuel} is the cost of the fuel being used [€/kWh].

Besides the heat production facility, the distribution network has also to be taken into account when calculating the feasibility of district heating implementation. The average specific network length could be calculated by dividing the total length of roads by the number of 100 × 100 m areas in the analyzed location. This could be used to calculate the cost of the district heating network installation in every 100 × 100 m area. The technical and cost data of the distribution network and the price of heat were taken from [49]. By integrating these data in the QGIS software (version 2.18.7) and using (2), the feasibility of the district heating system implementation was calculated for every 100 × 100 m heat demand area:

$$R = Q \cdot c_h - Q \cdot LCOH - 10000 \cdot l_s \cdot c_p \ [€] \quad (2)$$

where R is the potential revenue for a district heating system in a single 100 × 100 m area [€], Q is the heat demand of a single 100 × 100 m area [kWh], c_h is the price of heat [€/kWh], l_s is the average specific distribution network length [m/m^2], while c_p is the cost of the distribution network installation [€/m].

The price of heat for the final consumers is a crucial parameter in this kind of analysis since it determines the revenues from the district heating system, thus having a major influence on the feasibility of the whole system. It is accounted for in (2). In Croatia, the heat price for the final consumer is defined by every individual district heating system operator. It is then approved by the Croatian Energy Regulatory Agency. Since the analyzed city of Ozalj currently only uses individual heating systems, the price of the heat was assumed to be the same as for the district heating system in the nearby city of Karlovac, i.e., 66.6 €/MWh. However, this price also includes the connection fee.

Areas where $R > 0$ are feasible for district heating implementation. The calculation in QGIS provided the map with highlighted parts of the city which can be connected to a district heating system. The outputs of this analysis included total heat demand, total area of households, and number of 100 × 100 m areas for which it would be feasible to implement a district heating system.

These data were further used to examine the environmental impact of a natural gas district heating system compared with the existing individual heating systems. The analysis is based on the CO_2 emissions calculation, as well as local particulate matter (PM), CO, and NO_x emissions calculations. The shares of different energy sources, which are currently used in the analyzed city, could be determined by using the data from the survey and the city's Sustainable Energy Action Plan. In the current situation, around 40% of the final heat demand is supplied by individual logwood furnaces, and another 40% by individual fuel oil boilers. The results of the survey showed that these are mostly old and inefficient boilers, causing a high environmental impact on the local level. Taking into account the low efficiency of old boilers and the high efficiency of district heating boilers, the emissions were calculated by multiplying the demand for each fuel with the respective emission factors.

2.2.2. Integrating Excess Heat into the District Heating System

When compared to conventional individual heating solutions, district heating already has significant advantages, both from the economic and the ecological point of view. However, integrating excess heat into a district heating system can provide further benefits, since there are no fuel costs for this source, and the environmental impact is even lower because this heat would otherwise be wasted, and the emissions related to its production would be existent anyway. Therefore, in the second scenario, a part of heat production from natural gas district heating was substituted by excess heat in order to analyze its effect on the overall system. Industrial and other facilities with high amounts of excess heat are often located outside cities, far from the heat demand. Consequently, a significant part of the investment into excess heat utilization is the distribution network which needs to be built in order to transport the heat from the source to the existing demand. The other, less capital-intensive investment is the cost of heat exchangers. It is assumed in this analysis that the temperature level of the available excess heat source is high enough for direct utilization. However, these sources often have low temperatures, especially if the heat is from the service sector. In these cases, heat pumps are needed in order to increase the temperature level of the heat. Low-grade excess heat has a particularly high potential in low-temperature fourth-generation district heating systems and should not be neglected.

In this scenario, the levelized cost of heat method was modified in order to serve as a criterion for investment into the excess heat utilization equipment. As mentioned above, in many cases, these sources are located far from the heat demand, and therefore this scenario includes a calculation of the maximum feasible distance of the potential excess heat source, taking into account different quantities of the available excess heat in the area. This way, both the investment into the heat exchangers and the distribution network are included in the analysis. The modified levelized cost of excess heat was calculated by using (3):

$$\text{LCOEH} = \frac{I_{HE} \cdot CRF \cdot (1 - TD_{pv})}{8760 \cdot i \cdot (1 - T)} + \frac{O_{HE,total}}{8760 \cdot i} + c_{excess\ heat} \quad [\text{€/kWh}] \tag{3}$$

where I_{HE} is the investment cost for the heat exchangers [€/kW], $O_{HE,total}$ are the operation and maintenance costs for the heat exchangers [€/kW], and $c_{excess\ heat}$ is the cost of excess heat [€/kWh].

When calculating the levelized cost of excess heat, the cost for the installation of the distribution network is not included in the equation, since it is accounted for in Equation (4). This is done in order to calculate the maximum potential distance of the heat source from the demand, i.e., the extra revenue which can be used to finance the construction of the distribution network. Therefore, the investment and operation and maintenance costs in (3) only cover the heat exchangers, which are used to extract the excess heat from the source. The cost of excess heat includes the procurement costs, which are defined by the operator of the excess heat facility and agreed with the operator of a district heating system. Different values of excess heat price were analysed in the sensitivity analysis, as shown in Table 3.

Furthermore, the extra revenue was calculated for different values of available excess heat, by using (4). Then, this extra revenue was divided by the discounted cost of pipes in order to determine the maximum distance of the excess heat source from the heat demand:

$$\text{R}_{EH} = E_{total} \cdot r_{heat} - (E_{EH} \cdot LCOEH + E_{DH} \cdot LCOH) - l \cdot n \cdot c_{pipes} \quad [\text{€}] \tag{4}$$

where R_{EH} is extra revenue, E_{total} is the total heat demand of the area for which it would be feasible to establish a connection to a natural gas district heating system [kWh], r_{heat} is the revenue from heat, i.e., the price of heat [€/kWh], E_{EH} is the available excess heat [kWh], $LCOEH$ is the levelized cost of excess heat [€/kWh], E_{DH} is the remaining heat demand being covered by the natural gas-based production facility of the district heating system [kWh], $LCOH$ is the levelized cost of heat for the natural gas district heating system [€/kWh], l is the average length of the distribution network in a 100 × 100 m area [m], n is the number of 100 × 100 m areas, and c_{pipes} is the discounted cost of pipes [€/m].

Since numerous parameters affect the feasibility of excess heat utilization, a sensitivity analysis was made by changing the values of available excess heat, costs of pipes, and cost of excess heat.

3. Results

In this section, the main results of this paper, including heat demand mapping, feasibility analysis of switching from individual systems to natural gas district heating, and feasibility analysis of excess heat utilization in district heating systems, are presented and discussed.

The results of the first step, i.e., the heat demand mapping, can be seen in Figure 2. It shows that the areas with the highest heat demand densities are located around the city centre and the industrial zone, which is expected since most of the public and apartment buildings are situated in that part of the city. The final heat demand of the city amounts to 90.92 GWh. Apart from 100 × 100 m areas, the heat demand was mapped on the building level as well, therefore providing a more detailed insight into the current building stock of the city. This also showed the locations of the biggest heat consumers with the highest potential for connecting to a district heating system, thus providing important information in the planning process.

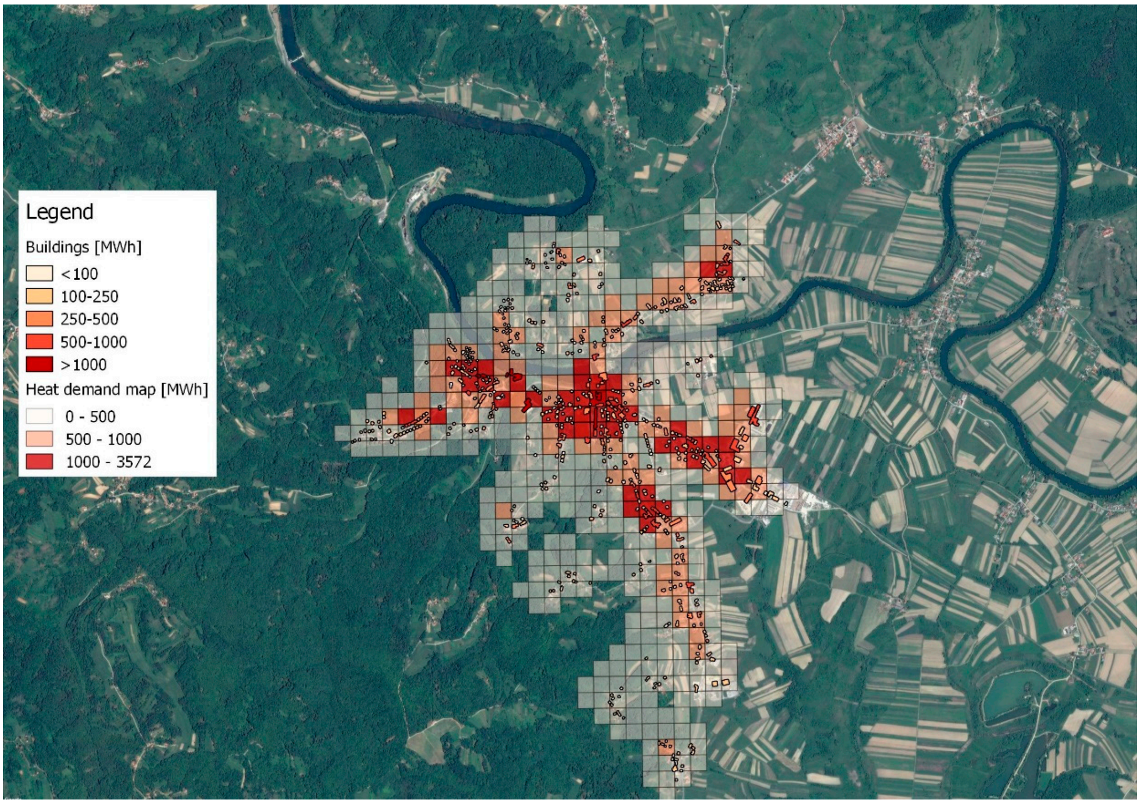

Figure 2. Heat demand map of the city of Ozalj, including the heat demands of each building.

By using the heat demand data from the aggregated 100 × 100 m areas, the share of demand which could be feasibly covered by a district heating system was calculated. Then, all the remote areas were excluded from further analysis, as shown in Figure 3. This was done because the real pipe length in these cases would be much higher, since the average specific distribution network length used in the calculations did not include the distance between the feasible 100 × 100 m areas. However, the average specific distribution network length could be applied in the final selected area from Figure 3, since most of the 100 × 100 m areas are connected or very near each other. The main results of this analysis can be seen in Table 2. They show that it would be feasible to cover 83.3% of the existing heat demand in the city by a natural gas district heating system, providing households with an inexpensive and comfortable way of heating.

On the basis of these results, the potential for excess heat utilization in the analysed system was calculated, as described in the Methods section. The main outcome of this analysis was the maximum distance of the excess heat source from the demand for different excess heat prices and costs of pipes. The latter is an important parameter since it presents the highest investment for a system utilizing a remote excess heat source. This cost also includes digging and the laying of pipes. The different costs of pipes and the prices of excess heat used in the analysis are shown in Table 3. All the variations of these parameters were analysed in the sensitivity analysis and presented in a form of a graph.

Table 2. Main results of the district heating implementation feasibility analysis.

Heat Demand (MWh)	**75,383.00**
Gross household area (m^2)	357,674.00
Number of 100 × 100 m areas	92

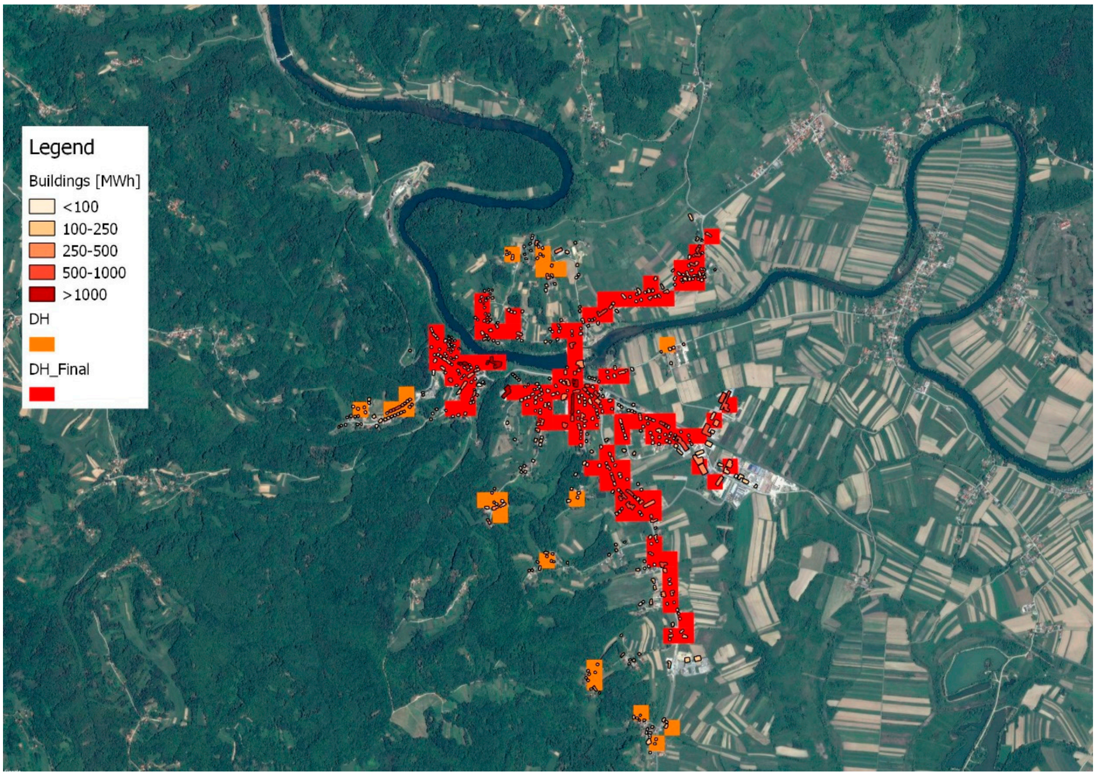

Figure 3. Parts of the city for which it is feasible to establish a connection to a district heating system (orange) and final area selection used in further analyses (red).

Table 3. Different excess heat prices, costs of pipes, and available excess heat supply used in the analysis of excess heat utilization.

Excess Heat Price [€/MWh]	Cost of Distribution Pipes [€/m]	Available Excess Heat Supply (GWh)
1	200	10
2	400	20
3	600	30
4	800	40

The results of the analysis can be seen in Figure 4. This figure shows that the maximum feasible distance of the excess heat source from the heat demand rose with the amount of available excess heat, as expected. However, when the excess heat price was increased, the maximum potential distance of the source decreased. This was also the case with the increasing costs of pipes. Nevertheless, all the variations of the important parameters resulted in a feasible integration of excess heat in a natural gas district heating system. The results showed that the levelized cost of excess heat method can be used as an efficient way of analyzing the feasibility of excess heat utilization in district heating systems, therefore serving as a criterion for the investment into excess heat utilization equipment.

This shows the great potential of this source, but also its limitations regarding the location of the source and its distance to the heat demand. The maximum potential distance varies significantly with different values of the relevant parameters. Therefore, it changed from 23.11 km in the case of 40 GWh available excess heat supply, at the price of 1 €/MWh and pipe cost of 200 €/m, to 2.7 km in the case of 10 GWh available excess heat supply, at the price of 4 €/MWh and pipe cost of 800 €/m. This showed that in the cases in which there is a high availability of excess heat, this excess heat could be utilized from various locations outside the analyzed city and even from larger cities in its vicinity.

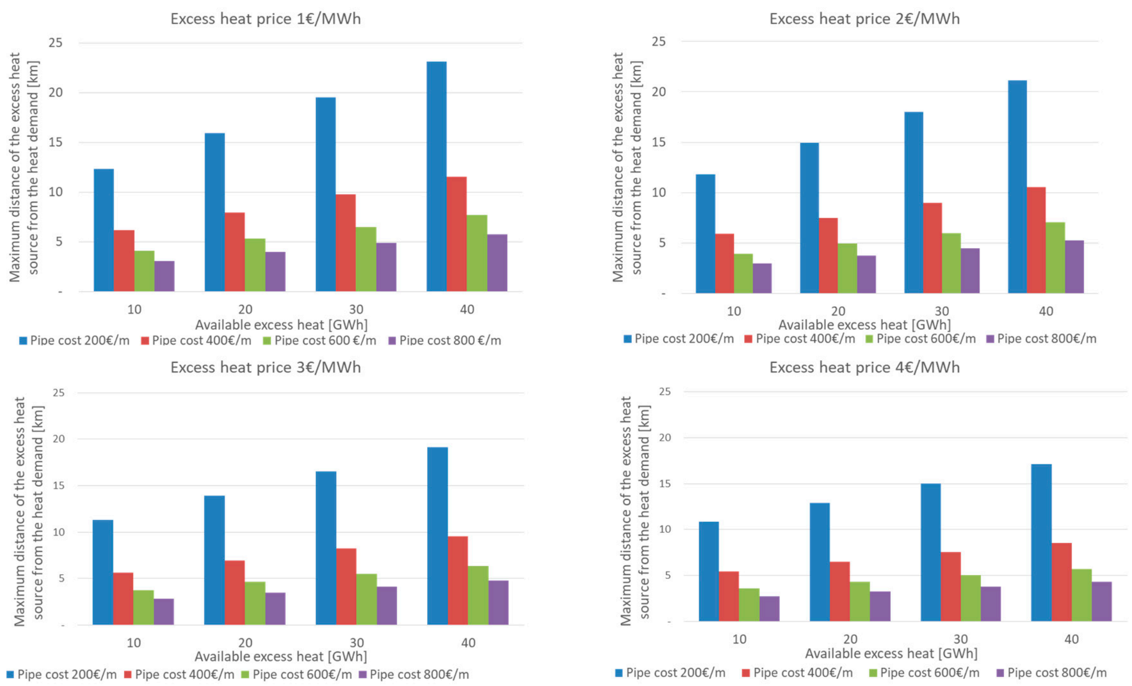

Figure 4. Maximum distance of the excess heat source from the heat demand for different values of available excess supply, excess heat price, and costs of pipes.

Finally, the district heating systems also provide significant environmental benefits due to the high efficiency of boilers and to the strict regulations regarding their pollutant emissions. The results of the CO_2 emissions analysis support this hypothesis by providing the CO_2 emissions savings achieved by switching from individual heating solutions to a natural gas district heating system, as shown in Figure 5. Even though the analysed district heating system uses natural gas as a fuel, its emissions were still lower than in the current situation, because of the aforementioned reasons. However, more significant benefits were achieved by reducing the PM, NO_x, and CO emissions, which are currently substantial because of a high share of old and inefficient logwood boilers without a filtration system. These have a much higher local impact on the environment. Their values were calculated and are presented in Table 4. The highest reductions were achieved for PM emissions, which were almost completely eliminated by introducing a natural gas district heating system. Furthermore, NO_x, and CO emissions were also substantially reduced, by 87% and 97%, respectively.

Additionally, when excess heat is integrated into the system, significantly higher CO_2 emission savings can be achieved. Figure 5 shows that in the case of 40 GWh of excess heat supply, the CO_2 emissions were around 50% of the emissions in the current situation. This is due to the fact that the emissions from the excess heat production facilities are already existent and are calculated in the industrial or service sectors, depending on the origin of excess heat. Therefore, the analysis included only the emissions from the part of the district heating system supplied by the natural gas boiler, significantly lowering the overall environmental impact of the system and the heating sector in general. This was also proven by analysing PM, NO_x, and CO emissions for the case of natural gas district heating plus 40 GWh excess heat, where all the emissions were reduced by more than 93% in comparison to the current situation.

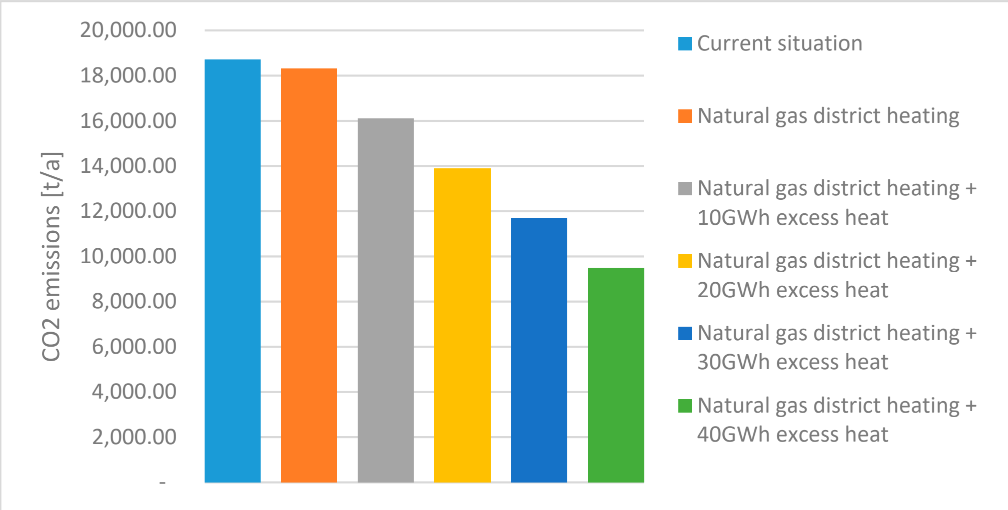

Figure 5. Results of CO_2 emission analysis for different cases.

Table 4. NO_x, PM, and CO emissions for different cases.

	Current Situation	Natural Gas District Heating	Natural Gas District Heating + 40 GWh Excess Heat
NO_x emissions (kg/a)	25,783.24	3292.07	1707.62
PM emissions (kg/a)	1,331,938.62	29.93	15.52
CO emissions (kg/a)	2,153,771.65	70,013.02	36,316.36

4. Discussion and Concluding Remarks

The idea for this paper was twofold. On the one hand, its purpose was to show the economic and environmental benefits of a district heating system implementation in a city which is currently using only individual heating solutions. On the other hand, the novel approach towards analyzing the feasibility of excess heat integration into a district heating system was proposed. The case study was the city of Ozalj, a small city with no existing district heating systems. The prerequisite step in the energy planning of district heating systems is the heat demand mapping of the focus area. This way, parts of the city in which it is feasible to implement a district heating system were determined. In this case, the final heat demand of an area which could be feasibly covered by a natural gas district heating system was 75,383 MWh. These results were then used for further analyses, taking into account the excess heat utilization in a natural gas district heating system.

First, the levelized cost of excess heat was calculated for this source, being significantly lower than for other heat production technologies because of its low investment costs and the lack of fuel costs. It has to be noted that the temperature level of the source was assumed to be high enough, and therefore no heat pumps were needed. Consequently, the only investment cost was for the heat exchangers. However, these sources are rarely located in the vicinity of the potential heat demand, and an investment into additional distribution pipes is necessary. In that case, these are the highest costs related to excess heat utilization. Therefore, by implementing the levelized cost of excess heat method, the maximum distance of the source from the heat demand was calculated, that way taking into account both the investment into heat exchangers and the distribution network. Three different parameters were varied in order to perform the sensitivity analysis: available excess heat supply, costs of pipes, and excess heat price. The maximum feasible distance of the excess heat source from the demand was 23.11 km in the case of 40 GWh available excess heat supply, at the price of 1 €/MWh and pipe cost of 200 €/m. On the other hand, the minimum feasible distance of the heat source from the demand was 2.7 km in the case of 10 GWh available excess heat supply, at the price of 4 €/MWh and pipe cost of 800 €/m. The results showed that excess heat is a feasible solution in all cases, but this is highly dependent on the available excess heat supply and on its distance from the heat demand. Furthermore, it can be concluded that the levelized cost of excess heat method can be used as a criterion for the investment into excess heat utilization equipment.

The final aspect analyzed in this paper was the environmental impact of a district heating system, in relation to individual heating systems. The analysis was conducted both for the CO_2 emissions and the NO_x, PM, and CO emissions, which have a higher influence on the local level. The analysis showed that a natural gas district heating system already has lower CO_2 emissions than individual solutions. Further benefits are achieved as the result of significantly lower local NO_x, PM, and CO emissions from highly efficient district heating boilers, while many individual biomass furnaces are old and do not have the necessary filtration system. Thus, reductions of more than 87% were achieved for all local emissions by switching to a natural gas district heating system. CO_2 emissions were drastically reduced if excess heat was additionally introduced into the system. This heat is already being wasted, and the emissions from its production can be allocated to the industrial or service sectors, depending on its origin. Therefore, when being utilized in a district heating system, this heat does not contribute to the emissions of a heating sector. If 40 GWh of excess heat supply is available, the CO_2 emissions of a district heating system are 50% lower than for individual heating solutions.

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Conflicts of Interest: The authors declare no conflict of interest.

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PAPER 2

The effect of different parameters of the excess heat source on the levelized cost of excess heat

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Abstract

In areas with higher heat demand densities, district heating is the most logical way of achieving heat sector decarbonisation aims, especially when renewable energy or highly efficient cogeneration is used. However, excess heat from industry is also recognized as a valuable source with the high potential for utilization. It increases the economic and environmental viability of the system due to the low operation, investment and conventional energy costs. The main goal of this work was to define the effect of the main factors influencing the levelized cost of excess heat. The paper provided the feasibility of excess heat utilisation in different district heating configurations, including solar collectors, cogeneration, peak load boilers, heat pumps and heat storages, showing that its overall utilisation can be much lower than the expected 100% of the overall availability depending on the configuration. Furthermore, temperature levels of the excess heat source have been considered in the analysis to show changes in levelized cost of excess heat with different temperatures and the necessary preconditions for its utilisation. It has been concluded that it is necessary to reduce the supply temperature of district heating in order to make the low temperature excess heat sources feasible.

Key words: district heating; excess heat; levelized cost of excess heat; feasibility analysis

1. Introduction

Buildings represent a major energy consumer, with around 40% of final energy consumption in Europe. When looking at the source of the consumption in buildings, the heating sector stands out as by far the most energy intensive, with almost 80% of total final energy use [1]. Therefore, one of the most discussed topics in this field lately is the means of producing and supplying this heat to the final consumers. The majority of households and commercial buildings currently use individual heating solutions in the forms of centralized boiler systems on the building level or individual furnaces. These mostly use fossil fuels, e.g. natural gas or fuel oil, and biomass. The negative effects of fossil fuels are well known and while biomass may be considered renewable at certain conditions, its use in individual furnaces, which are often old and inefficient can have a significant negative environmental and health impact on the local level, as discussed in [2]. Therefore, it is necessary to switch to a more sustainable way of heating, and in areas with higher heat demand densities, district heating is an efficient way of supplying heat to the final consumers. On the other hand, in the areas of lower heat demand densities, heat pumps are an ideal solution since they have significantly lower environmental impact than the fossil fuel solutions, as shown in [3]. Currently only 13% of heat supply is covered by these systems on the European level, which makes the potentials for its utilization significant [4].

Various studies have already shown the technical, economic and environmental benefits of increasing the share of district heating, e.g. in [5] where authors concluded that the optimal share for Denmark would be 70% in future energy systems, therefore reducing the CO_2 emissions and costs both directly and indirectly through fuel savings. However, different energy sources can be used for heat production in these systems. Currently, fossil fuels are still broadly used, especially in cogeneration systems as shown in [6]. But in order to comply with the requests of the future energy systems, it is necessary to switch to more sustainable energy sources, as the European Commission recognized in its Strategy on Heating and Cooling [7]. These include renewables, e.g. biomass, solar thermal, geothermal, renewable power-to-heat, as well as excess heat [8]. When compared to the fossil fuel district heating, using renewables results in lower costs and lower environmental impact of the overall system, as shown in [9], which is also one of the main reasons for the consumers to connect to such a system [10]. However, in order to optimize the utilization of variable renewable sources in district heating, thermal storage systems are needed [11], which can have significant space requirements due to their size. This can be solved by using indirect storage systems based on phase change material, which maintain similar performance but reduce the required size by 25% compared to hot water tank storage, as shown in [12].
Even though excess heat might not be renewable at its source, it can be considered as a sustainable option since it would be produced anyway and wasted to the environment. Basically, it presents heat which is produced as a byproduct of some industrial or service sector facility and which would otherwise be wasted into air or water, depending on the cooling system in use. The potential of its utilization is significant, as was shown in [13], where authors debate that the available amount of excess heat on the European level is high enough to cover the demands of buildings in residential and service sector. These results were further complemented with numerous other analyses of potentials on the national or regional level, e.g. industrial excess heat in China [14], Japan [15] or EU-28 [16]. Different tools can be used for such purposes, as was shown in [17] where authors develop a tool for urban excess heat recovery potential. Moreover, the economic benefits of excess heat integration in district heating systems have been shown in numerous studies. In [18], the system analysis of excess heat in Sweden has been implemented, providing the optimization model for system cost minimization and proving the feasibility of such a configuration in the analysed scenarios. Additionally, in [19] the environmental advantages alongside the economic ones have been highlighted for the case of excess heat utilization in district heating, showing also an increase in production of the jointly operated cogeneration units. On the other hand, in [20] the authors have focused on the investment costs of the excess heat utilization from an industrial cluster, providing optimal production from each of the facilities. Furthermore, an analysis on the impact of its utilization on CO_2 emissions and the energy system as a whole has been performed on the case of one region in Sweden [21], showing the reduction of fossil fuel usage and consequently the environmental impact of the energy system.

Regarding the different aspects of the investment into the excess heat utilization equipment, in [22] authors have performed the analysis of its utilization in the new district heating system by using the levelized cost of excess heat method to determine the maximum feasible distances of the potential excess heat source from the demand. Moreover, the heat transport costs in the case of the long distance heat transmission have been analysed in [23], showing that the maximum distances are proportional to the square root of the heat quantity. Other researches have also taken into account the investment costs for connecting the available excess heat sources with the demands, as was shown for the case of Denmark [24] and the temperature level of sources, concluding that in more than 50% of cases heat can be used directly with no need for a heat pump [25].

In order to provide an analysis of the energy system on the hourly level, different tools can be used. One of them is energyPRO, which has already been used in numerous studies and is used in the present study. For example, in [26] it was used to evaluate the effects of integrating new heat pumps and solar collectors into the existing district heating system in Helsinki, in terms of emission reductions and economic benefits. Furthermore, it has also been used to analyse the integration of booster heat pumps in the low temperature district heating systems [27], to develop scenarios for the city of Pecs in terms of electricity, heating and transport sectors [28], as well as analyse different combinations of production technologies in the flexible district heating system in the Baltics in order to calculate the lowest levelized cost of heat [29].The idea of this paper is to complement the research from [22] with the analysis of the effect of different factors of the excess heat source on the levelized cost of excess heat (LCOEH). Levelized cost of heat (LCOH) has been used in various studies, e.g. for analysing the potential for heat production and heat savings in Europe [30], calculating the feasibility of the Fresnel solar system [31] and it was shown in [22] that it is a valid method to analyse the feasibility of excess heat utilization in district heating systems. Therefore, there is a need to define the correlation of its temperature level with the different elements of LCOEH. Another relevant factor which was analysed is the capacity factor of the excess heat utilization, when its variable availability is taken into account.

2. Method

Levelized cost of energy calculates the minimum price at which the unit of energy should be sold in order to break even at the end of the project lifetime. Hence, it takes into account all the cash flows during the lifetime of the production unit. The main parts used for the calculation of LCOH are the discounted capital costs, operation and maintenance costs and fuel costs [22], as can be seen in Equation 1.

$$\text{LCOH} = \frac{I_c \cdot CRF \cdot (1 - TD_{pv})}{8760 \cdot i \cdot (1 - T)} + \frac{O_{total}}{8760 \cdot i} + c_{fuel} \quad [€/kWh] \qquad \text{Equation 1}$$

It must be noted that the presented form of the Equation 1 uses specific values for each of the parameters and not the overall value in order to make it more general, easy to use and applicable to the technology itself and not the specific system. The same form has been used also for the calculations of LCOEH.

The main parameters of the LCOH from Equation 1 are the specific Investment costsI_c $(€/kW)$, the Capital Recovery Factor (CRF) which is used for discounting the investment by taking into account the discount rate and the overall lifetime of the equipment, the capacity factor i, the specific annual operation and maintenance costs O_{total} and the specific fuel costs c_{fuel}. As mentioned, all of these parameters are specific values per unit of heat.

However, the excess heat utilization itself incurs different costs than the usual heat production units. These can vary depending on the temperature level of the source, as well as the overall capacity factor. In case the temperature of the excess heat is high enough for the direct utilization, the LCOH consists of the capital costs for the heat exchanger, its operation and maintenance costs as well as the excess heat procurement costs. Since the temperature is high enough, there is no need for the use of heat pumps. Nonetheless, when the source temperatures are not high enough, it is necessary to increase the temperature level by using the heat pumps, which incurs additional costs. Furthermore, the capacity factor of excess heat can vary significantly due to mismatch between available supply and the demand in different configurations of the system. All these factors have been analysed in this paper in different steps.

First, by using the energyPRO software, different configurations of the system have been modelled in order to determine the capacity factor of excess heat, considering the variability of its availability. LCOEH has then been calculated for each of the scenarios in order to show the effect of different configurations on the feasibility of excess heat integration. Furthermore, the effect of the temperature level of the excess heat source on the LCOEH was analysed, as well as the effect of the temperature of the end users. These were compared with LCOEH of the excess heat source where no heat pump is needed and the LCOH of the standard district heating production unit, i.e. the natural gas boiler. Finally, the change in maximum distance of the available excess heat with the different temperature levels is shown.

2.1. Capacity factor of the excess heat utilization

In most of the previous researches, excess heat has been considered as a source with the constant availability, supplying all of its heat to the district heating network. Yet, most of the time this is not the case. The availability often varies depending on the number of shifts of the industrial facility, as has been shown in [24], ranging from full capacity during the day and lower capacity during the night and the weekends. Due to that, the actual capacity factor of the excess heat utilization, which is a significant factor in the calculation of LCOEH, can be much lower than the expected 100%.

In order to take that into the account and calculate the realistic capacity factor, the hourly simulation of the system operation has to be performed. For that, energyPRO software was used [32]. It optimizes the operation of the heat production units by taking into account the input data on operation costs, revenues and the selected priorities. The output is the production of each unit, CO_2 emissions, number of hours of operation on the annual level, costs, etc. The model uses analytical optimisation in order to calculate the operation of each production unit in the time horizon of one year. This is done by calculating the priority number for each production unit in each time step by taking into account the operation costs and revenues. Then the unit with lowest priority number is put in operation, continuing with second lowest and so on, until the whole demand has been met.

Technical constraints of each unit are also taken into account. An example of the block diagram of the energyPRO model is shown in Figure 1. It presents a model developed for Scenario 1, which will be described in the next subsection. As can be seen, the model has an intuitive and simple graphical interface, where blocks represent energy demands, heat/electricity production units and storage systems. Each of these blocks are modelled by providing input data on the specifics, such as production unit efficiencies, unit specifications, hourly demands, etc. Then the connections between them are modelled by selecting the appropriate operation strategy.

In order to model different scenarios, various technical and economic data needed to be acquired. Since energyPRO optimizes the operation of the system based on the operational costs, the required input data included fixed and variable operation and maintenance (O&M) costs, fuel costs, as well as income from heat and electricity production. O&M costs were taken from [33], while the fuel costs were taken from [34]. The revenues from heat and electricity sales depend on the local framework. Since the numerical example is analysed for the city of Ozalj, as will be elaborated in more detail later, the heat price has been taken the same as for the nearby city of Karlovac at 66.6 €/MWh [22], while the electricity prices have been taken from the Croatian Power Exchange market [35].

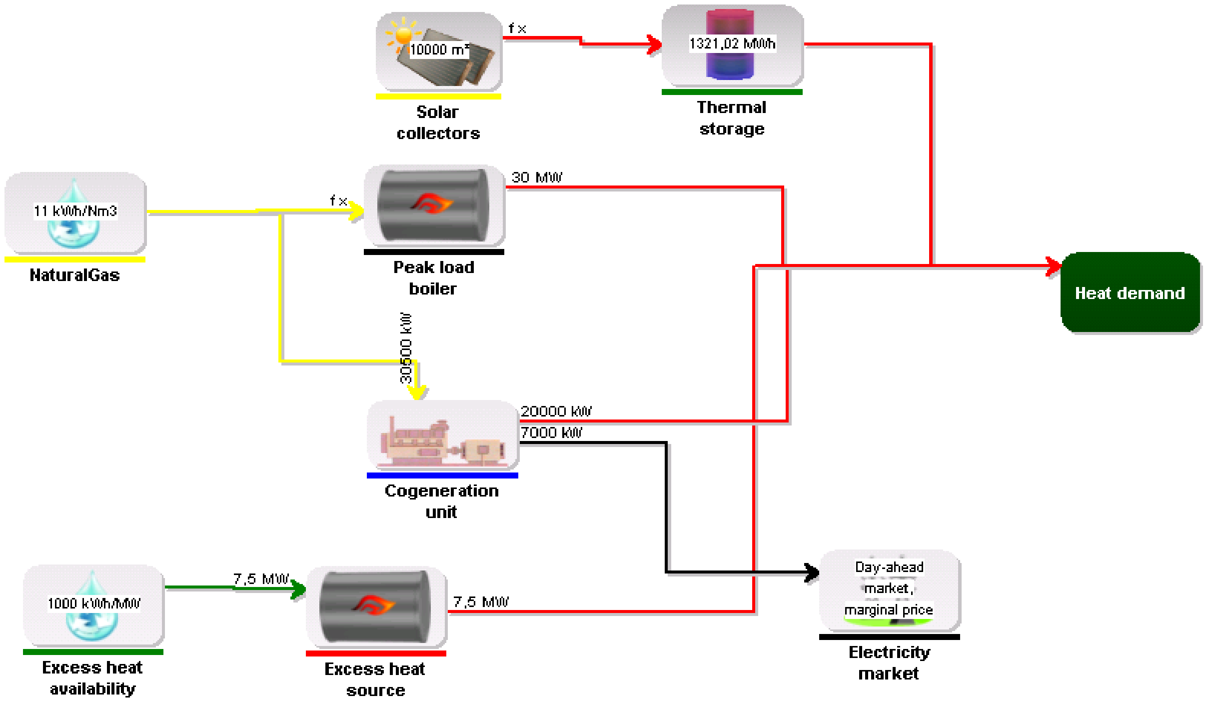

Figure 1. The interface of the model developed for Scenario 1 in energyPRO

For a given maximum excess heat supply its distribution is shown in Figure 2, based on [24]. It reflects well the operation of the manufacturing industry and therefore the availability of excess heat from such a source as well. The distribution is shown for one typical week, which repeats throughout the year. Furthermore, the analysis needs to include the calculation of the hourly heat demand, which is in this case done by the degree-hour method.

The capacity factor will definitely depend on the heat generation mix, i.e. what other technologies supply heat to the district heating network. In cases when e.g. solar thermal supplies heat during the summer months, the capacity factor will be lower due to the inability to supply heat during this time. In order to measure its impact, a scenario analysis has been performed, taking into account different combinations of technologies. Finally, the results from the energyPRO modelling serve as an input for the LCOEH calculation. It must be noted that the results are highly case sensitive, despite considering different heat generation mixes.

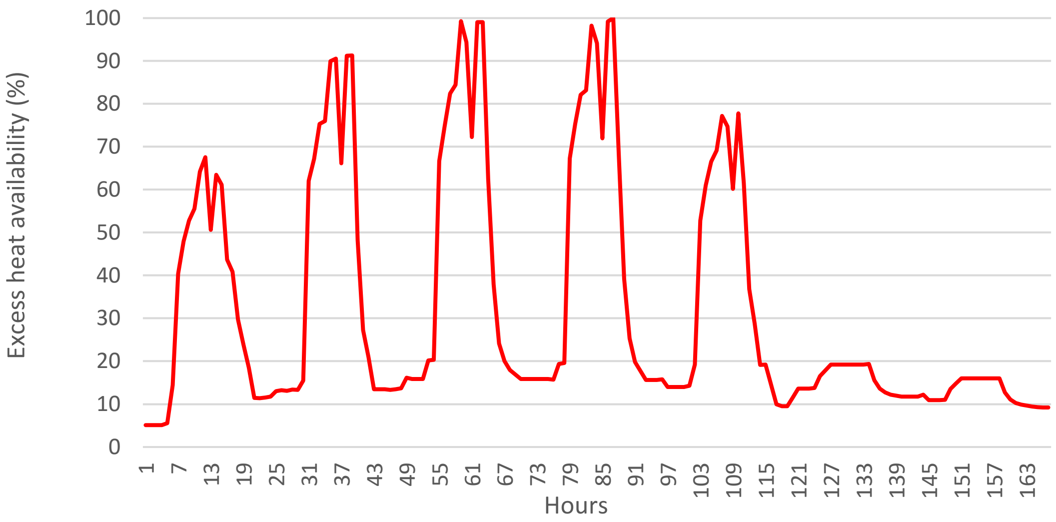

Figure 2 Hourly variation of excess heat availability through the time horizon of one week

2.2.1. Numerical example

In order to model the scenarios, the numerical example has been analysed by using the data for the city of Ozalj, a small rural city in the north-west Croatia, with the population of 1,880. The input data on heat demands and capacities of heat production technologies have been taken from the previous research [22], as well as from the CoolHeating project [36], where the detailed survey of the population has been carried out, providing a comprehensive insight into the energy consumption of the citizens. By using these data, heat demand has been calculated and it amounts to 69.4 GWh. The procedure is explained in more detail in previous research [22]. It has then been elaborated on the hourly level by using the degree hour method. This way, the peak load of the system can be determined, which amounts to 41.5 MW. Here it must be noted that the city completely relies on the individual heating solutions at the moment.

However, as the part of the aforementioned CoolHeating project, a technical concept has been developed for the city, which included the combination of a peak load boiler, cogeneration unit, solar thermal collectors and thermal storage system. These were sized in such a way that the cogeneration units are able to operate as the baseload, peak load boilers cover only the peaks during the winter, while solar collectors area was designed by taking into account the available land area owned by the municipality. This configuration is expected to be built in near future.

On the other hand, certain industrial facilities, mainly manufacturing industry, are present in the relative proximity of the city. By taking into account the data from the excess heat source potentials map [37], it has been concluded that there is significant excess heat potential to be analysed. It must be noted that no real time data on the hourly availability of the excess heat from the mentioned source could be obtained. For that reason, the availability has been approximated by using the variation presented in Figure 2.

Since the method presented in this paper is focused on the LCOH, its use is more suitable for the analysis of the new system implementation. That is why this city, with its newly developed district heating concept has been chosen as the numerical example.

2.2.2. Scenarios

As has been elaborated, technical configurations of the reference system have been selected based on the developed technical concept for the city, as a part of the Horizon2020 project CoolHeating. The available excess heat supply from the manufacturing industry nearby the city has been assumed at 20 GWh annually, considering data from the excess heat source potentials map [37] and the previous results from [22].

List of technologies used in the scenarios and their capacities are shown in Table 1. The basic reference scenario includes a peak load boiler, a cogeneration unit, solar collectors and the thermal storage. As described in the previous subsection, this configuration represents a technical concept developed for the city of Ozalj as a part of the CoolHeating project and it is planned to be built in the city in near future. The capacities in the reference scenario have been selected in order to meet the overall heating demand of the city, taking into account the technical constraints of each technology, as well as land use constraints for solar thermal and thermal storage. Other scenarios included different variations of technologies with the addition of excess heat source in each scenario, in order to utilize its potential from the manufacturing industry in the proximity of the city. Therefore, in Scenario 1, the effect of adding the excess heat to the current technical concept is modelled. In Scenario 2, an additional storage facility for the excess heat is added, based on the results from Scenario 1.

Furthermore, this excess heat configuration is also modelled in Scenario 3, where no solar thermal utilisation exists and no storage is used for excess heat, with the rest of the demand being covered by peak load boiler and the cogeneration unit. In scenario 4, storage for excess heat is added again to the configuration from Scenario 3. Finally, in Scenario 5, a large heat pump is added before the main supply to the already existing configuration to analyse the utilisation of excess heat in such a heat generation mix. The main output of the scenarios are different capacity factors of the excess heat in these configurations, i.e. its overall amount of heat utilised, compared to the maximum available amount. Then, these data were used to calculate the LCOEH of each scenario, by using the formula from [22] in order to compare different configurations. The LCOEH calculations for the scenarios took into account only the direct excess heat utilization and incorporated the costs of the storage system in the method.

Table 1. Capacities of different technologies used in the scenarios

	Reference	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
Natural gas boiler (MW)	31	31	31	31	31	31
Natural gas cogeneration (MW)	20	20	20	20	20	20
Solar collectors (m^2)	10,000	10,000	10,000	-	-	-
Seasonal thermal storage (MWh)	1,320✓	1,320	1,320	-	-	-
Excess heat (MWh)	-	20,000	20,000	20,000	20,000	20,000

Thermal storage for excess heat (MWh)	-	-	1,100	-	1,100	1,100
Heat pump (MW_{th})	-	-	-	-	-	6.2

Since the maximum available excess heat amount can usually cover only a certain share of the overall demand, a peak load boiler and a cogeneration unit have been used in all the scenarios. Maximum availability of the excess heat source has been held constant throughout the scenarios, while the heat pump has been modelled in such a way that it has approximately the same heat output as solar collectors, in order to be able to compare with that scenario. The capacity of the thermal storage unit for the excess heat has been modelled at 1,100 MWh for Scenario 2. Thermal storage units are modelled in energyPRO by selecting the available volume, the temperature difference from top to bottom, which was set to 40°C and the minimum content, which was set at 5% of the capacity. Also, the model requires data to calculate the losses, which include the ambient temperature, insulation thickness and the thermal conductivity of the insulation material. The same capacities have been kept for Scenario 4 and 5 in order to enable an easier comparison of the results. All the heat production units in Scenarios 1-5 have been modelled prior to the supply line of the district heating network and therefore no booster units have been included in the analysis.

2.2. Different temperature levels of excess heat

Many industries and especially service sector facilities produce the low temperature excess heat, which cannot be used directly and therefore requires the use of a heat pump. For the simplification reasons, it is assumed that in case the heat pump is used, there is no need for an additional heat exchanger, i.e. the quality of steam or water is high enough for the direct contact with the evaporator. The threshold for using the heat pump is defined by the needed supply temperature of the district heating system, as well as the temperature level of the excess heat source. Most elements in the LCOH remain the same, however an additional cost is added due to the use of a heat pump, i.e. the cost of electricity for using this device, as can be seen in Equation 2.

$$\text{LCOEH} = \frac{I_{HP} \cdot CRF \cdot (1 - TD_{pv})}{8760 \cdot i \cdot (1 - T)} + \frac{O_{HP,total}}{8760 \cdot i} + c_{excess\ heat} + c_{el,th}\ [€/kWh] \quad \text{Equation 2}$$

Nevertheless, the electricity cost needs to be presented per unit of heat, since the LCOH calculates the production cost for one unit of heat. In order to do that, the coefficient of performance (COP) of the heat pump must be calculated, since it is the correlating factor between the electricity consumption and heat production, as shown in Equation 3. This is introduced in order to take into account the fact that with the decreasing temperature of the excess heat source and thus the increasing temperature difference between the source and the district heating supply, the COP of the heat pump decreases. This leads to higher electricity costs for the operation of the heat pump.

$$c_{el,th} = \frac{c_{el}}{COP}\ [€/kWh_{th}] \quad \text{Equation 3}$$

It is well known that the COP of a heat pump depends significantly on the temperature of the heat source. Therefore, when an ambient source is used (e.g. ambient air, sea water, etc.) it can change drastically throughout the year. However, when excess heat is used, it is assumed that it has a constant temperature during the year and therefore no annual changes of COP occur. Nonetheless, the difference between the required supply and the excess heat source temperature can vary significantly, effecting the COP and consequently the cost of electricity per unit of heat. For the purpose of this research, the COP was calculated by using the Carnot COP and the efficiency of heat pump which was assumed at 60% [38], as shown in Equation 4 and Equation 5.

$$COP_{Carnot} = \frac{T_{DH}}{T_{DH} - T_{EH}} \quad \text{Equation 4}$$

$$COP = \eta \cdot COP_{Carnot} \quad \text{Equation 5}$$

Therefore, by implementing the Equation 2, the correlation between the temperature level of the excess heat source and the LCOEH can be calculated and plotted. However, another parameter influences the results of the calculation significantly, the capacity factor of the excess heat utilization. This will be further elaborated in the next subsection. It needs to be emphasized that all the capital and the operation and maintenance costs have been taken from the same source [33] in order to make the comparison between different cases possible and valid.

2.3. Maximum distance of the excess heat source from the demand

In order to show the effect of the temperature level of the excess heat source on the overall feasibility of its utilization in the district heating system, the maximum distance from the demand is calculated, based on the method described in [22]. That way, the cost of pipes is also considered since it is a significant contributor to the overall costs of the excess heat utilization. This is due to the fact that most of the industrial sources are located further from the demand, and therefore a distribution network needs to be built to the nearest district heating pipe.

The maximum distance is calculated by defining the extra revenue of the system which enables the investment into the distribution pipes. The calculation is shown in Equation 6 and is elaborated in detail in [22].

$$\mathrm{R}_{EH} = E_{total} \cdot r_{heat} - (E_{EH} \cdot LCOEH + E_{DH} \cdot LCOH) - l \cdot n \cdot c_{pipes} \quad [€] \quad \text{Equation 6}$$

By dividing this extra revenue with the discounted cost of pipes, the final result, i.e. the maximum distance can be calculated. This has been calculated for different temperatures of the excess heat source, to show the decrease of the maximum distance with the decrease of the temperature.

3. Results

This section will present the variations of the LCOEH when different configurations of the system, as well as different temperature levels of the excess heat source are taken into account. Furthermore, the effect of variations of the end user temperature levels will be presented and discussed and finally the maximum distance of the source from the demand will be shown for the numerical example.

3.1. Scenario analysis of different system configurations

The production of different units in the scenarios is presented in Table 2. When compared to the Reference scenario, the results of Scenario 1 show that by introducing excess heat into the heat generation mix, the production of the peak load boiler is reduced. The overall benefits of introducing excess heat into the system can be seen in the form of lower natural gas consumption and consequently lower environmental impact of the heating sector. While cogeneration units also produce less heat, the production of solar collectors remains more or less the same, since they have a high priority in the optimization process.

However, this also has a negative effect on the excess heat integration since only around 53% of the available amount has been utilized in this scenario. The problem is not only during the summer when there are excess amounts of solar energy but also during the heating season in the night, when the available amount of excess heat is significantly higher than the heat demand. This leads to the conclusion that storage systems need to be implemented alongside the excess heat facility in order to increase the utilization of excess heat and further reduce the use of fossil fuels in the existing system. For that reason, Scenario 2 analysed the integration of an additional 20 000 m^3 storage system.

Table 2. Production of different units in all the scenarios

	Reference	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
Natural gas boiler	19.48 GWh	12.76 GWh	10.56 GWh	9.41 GWh	6.57 GWh	5.5 GWh
Natural gas cogeneration	40.43 GWh	36.94 GWh	36.81 GWh	47.14 GWh	45.88 GWh	44.99 GWh
Solar collectors	9.53 GWh	9.7 GWh	9.7 GWh	-	-	-
Excess heat	-	10.61 GWh	12.96 GWh	12.89 GWh	17 GWh	17 GWh
Heat pump	-	-	-	-	-	1.88 GWh
Capacity factor of excess heat	-	53%	64.8%	64.5%	85%	85%

The results of Scenario 2 show that by introducing a thermal storage system at the location of the excess heat source, its utilization can increase to 64.8% of the overall availability with the given size of the storage. For that reason, the utilization of the peak load boiler is further reduced to 10.5 GWh/a, while the production of other units remains mostly the same.

However, the results showed that with further increases of the storage size, the utilization doesn’t increase significantly in the given configuration of the system. This is because of the competition with the solar collectors, which have the lowest cost during the summer and are the only used technology for covering the hot water demand in that period, while at the same time filling the seasonal thermal storage for its utilization in the heating season.

Consequently, a configuration without the solar collectors has also been analysed, first without the heat storage for excess heat (Scenario 3), and then with the storage system (Scenario 4). It can be seen that already in Scenario 3 the excess heat utilisation is rather similar to Scenario 2, showing increased feasibility of this source when it is not competing with solar thermal.

However, there is still a need for thermal storage unit if higher utilisation rates are to be achieved. By using the same storage size as in Scenario 2, 85% of the available excess heat can be utilised in Scenario 4, while a 92 000 m^3 seasonal thermal storage has to be used if 100% of available excess heat should be utilised.

Finally, the results from Scenario 5, where the heat pump is added to the configuration from Scenario 4, show that it doesn't affect the excess heat utilisation by a large margin, since its operating costs are higher than for the excess heat most of the times. Therefore, it wouldn't be feasible to implement a heat pump in such a configuration when its high investments are taken into account.

The LCOEH has been calculated for each of the scenarios and the results can be seen in Figure 3. It is the lowest for Scenario 3 since it has the highest excess heat utilisation rate without using the storage system. However, it can be seen that it is not much higher in Scenario 1 when no storage is used. When the costs of storage are taken into account, LCOEH is increased up to 0.023 €/kWh for Scenario 2, but in Scenarios 4 and 5 it is rather similar to Scenario 1, at 0.0189 €/kWh. For further analysis, the configuration of the scenario with lowest LCOEH will be taken into account, i.e. Scenario 3.

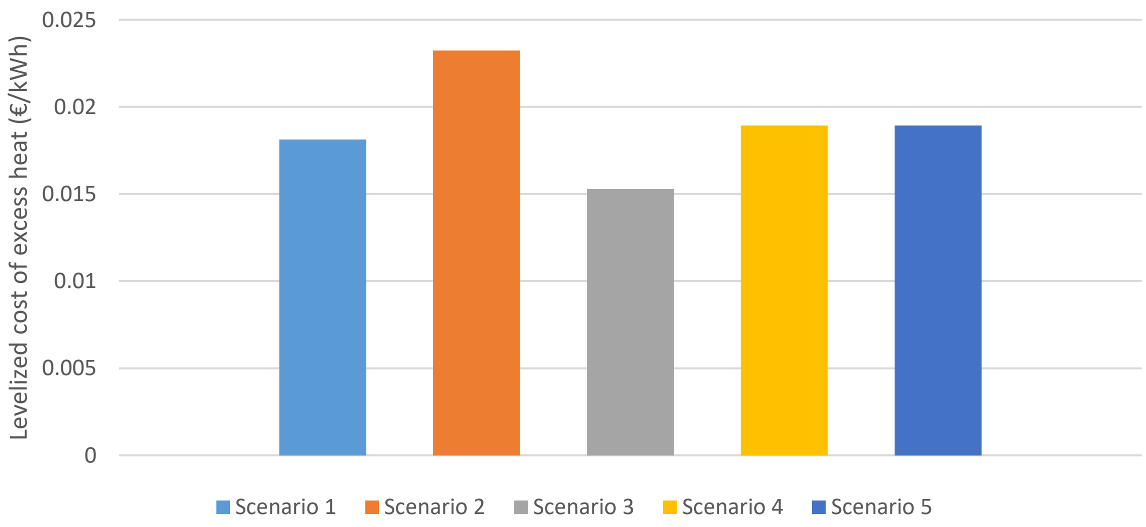

Figure 3 Levelized cost of excess heat for each of the scenarios

3.2. Temperature variations

When all the input data are determined and inserted into the Equation 2, the variation of the LCOEH with the different temperatures of the excess heat source can be calculated. The results are shown in Figure 4. Here it must be noted that the capacity factor has been recalculated in energyPRO for each of the temperature levels, therefore considering the decreasing utilisation of excess heat when lower COP is achieved. The required district heating supply temperature T_{DH} has been selected at 90°C, while the minimum temperature difference between EH source and the district heating supply temperature at 5°C.

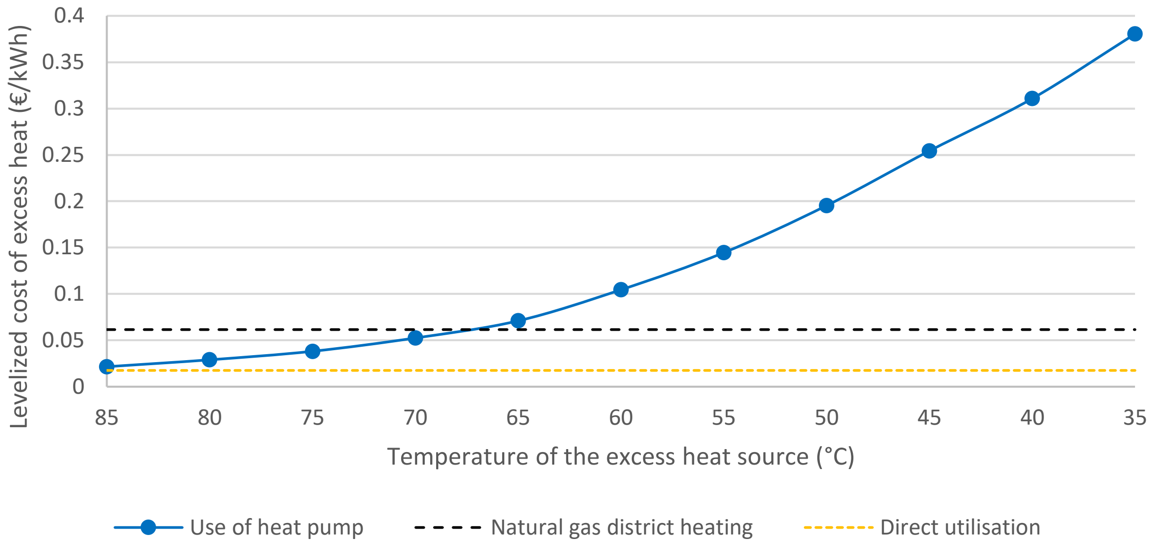

Figure 4 The effect of the temperature level of excess heat source on the LCOEH

As expected, the LCOEH is the lowest in case when no heat pump is used, i.e. that excess heat is used directly, with only the need for a heat exchanger. In Figure 4, this cost is presented as a horizontal line in order to act as a graphical threshold to better read the results. Nonetheless, this value is acquired only for the temperature of the excess heat source above 95°C in order to satisfy the minimum temperature difference between EH source and district heating supply temperature. Furthermore, when the temperature of the excess heat source is lower than the required temperature for direct utilization, heat pump is implemented, and the costs increase. Up until 66°C, the LCOEH is still lower than the LCOH for the natural gas district heating system, which has been taken as a reference system due to its simplicity. After this point, the temperature is too low for the industrial or service sector excess heat to be a competitive heat source for district heating.

Nevertheless, the supply temperature for a district heating network has been selected rather high in this analysis. These temperature levels can be expected in the countries of South-east Europe, where the building stock is old and inefficient and therefore high temperature heating is needed. Still, the legislation of the European Union facilitates the implementation of energy efficiency measures in buildings to lower their consumption and consequently lower the needed temperature of the buildings heating system. These are suitable to connect to a low temperature 4^{th} generation district heating system [39], with supply temperatures as low as 50°C.

Therefore, the needed temperature of the end user has also been taken into account in the analysis. The results are shown in Figure 5.

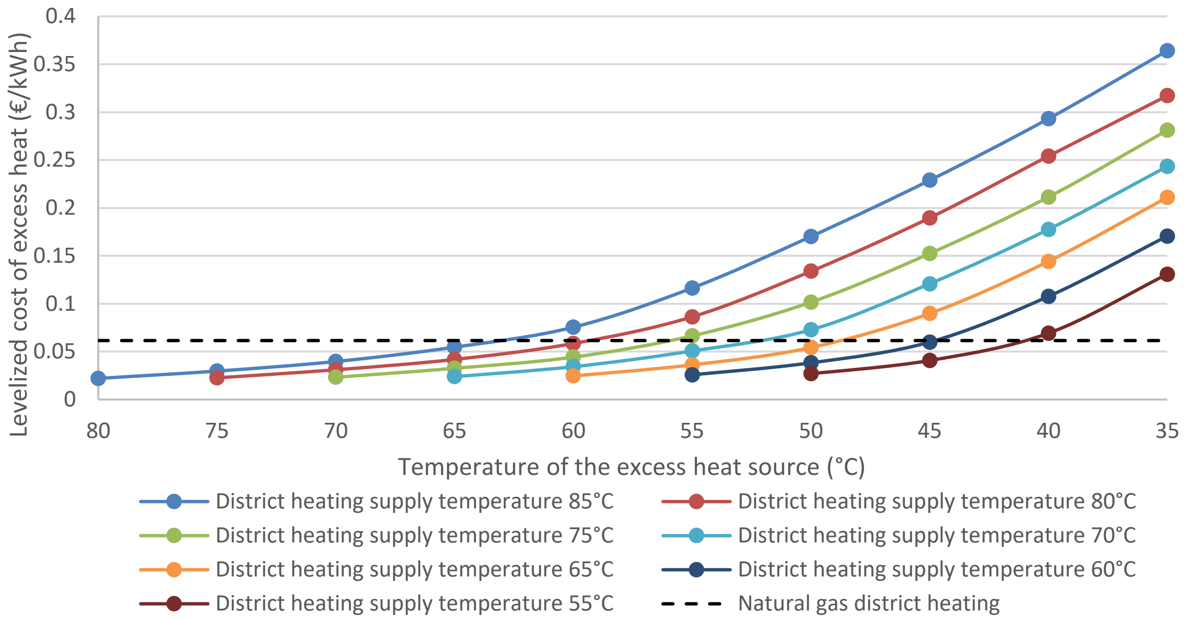

Figure 5 The effect of lowering the needed supply temperature in a district heating system on LCOEH of excess heat sources on different temperature levels

The diagram shows that in the case of lower temperatures at the end user, the feasibility of excess heat utilization increases for the lower temperatures of the source. Therefore, the threshold for the competitiveness of excess heat reduces from 63°C for the supply temperature of 85°C to 41°C for the supply temperature of 55°C. Furthermore, it can be seen that for the same temperature of excess heat source, the LCOEH decreases significantly with lower supply temperatures. For example, for the source temperature of 50°C the LCOEH reduces from 0.17 €/kWh if the supply temperature is 85°C to 0.027 €/kWh if the supply temperature is 55°C.

By taking into account the data from Figure 5, the borderline feasibility of excess heat utilisation can be plotted for different district heating supply temperatures in order to achieve better visualisation of the results. This is presented in Figure 6 and shows the decreasing trend with lower district heating supply temperatures.

This on the one hand shows the necessity of increasing the efficiency of the buildings sector and therefore reducing the temperatures, both on the district heating network side and the end user side. On the other hand, it is inevitable that the heating system will gradually transform to low temperature in the next decades and therefore the feasibility of excess heat utilization in district heating will increase significantly.

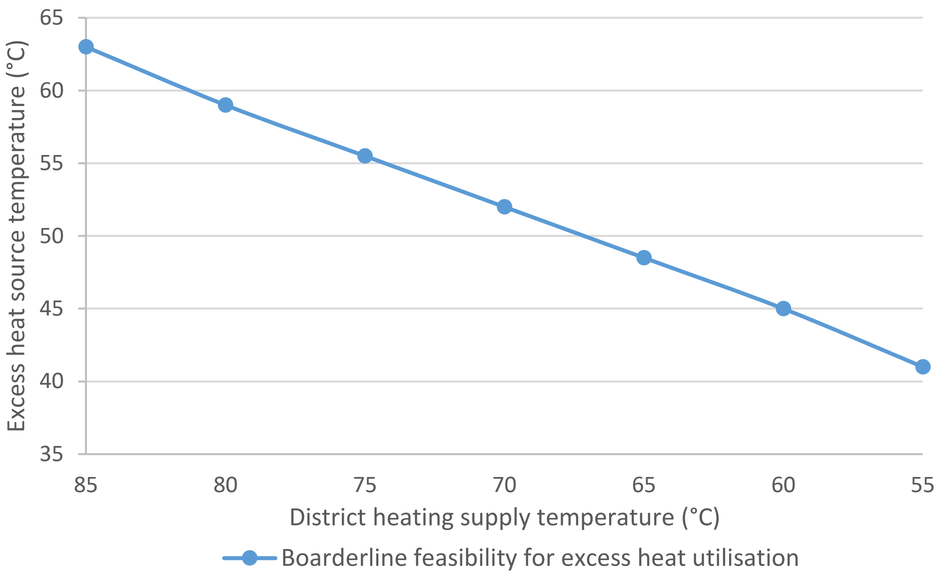

Figure 6 Decrease of the borderline feasibility excess heat source temperature with the district heating supply temperature

3.3 Maximum feasible distance of the excess heat source

The maximum feasible distance of the potential excess heat source has been analysed both for different temperatures of the excess heat source and the different district heating supply temperatures, which are influenced by the required temperature at the end users side. The analysis has been performed for a specific case in Croatia, the city of Ozalj as was described in the Methods section. The excess heat procurement costs were assumed at 1€/MWh and the pipe costs at 400 €/m.

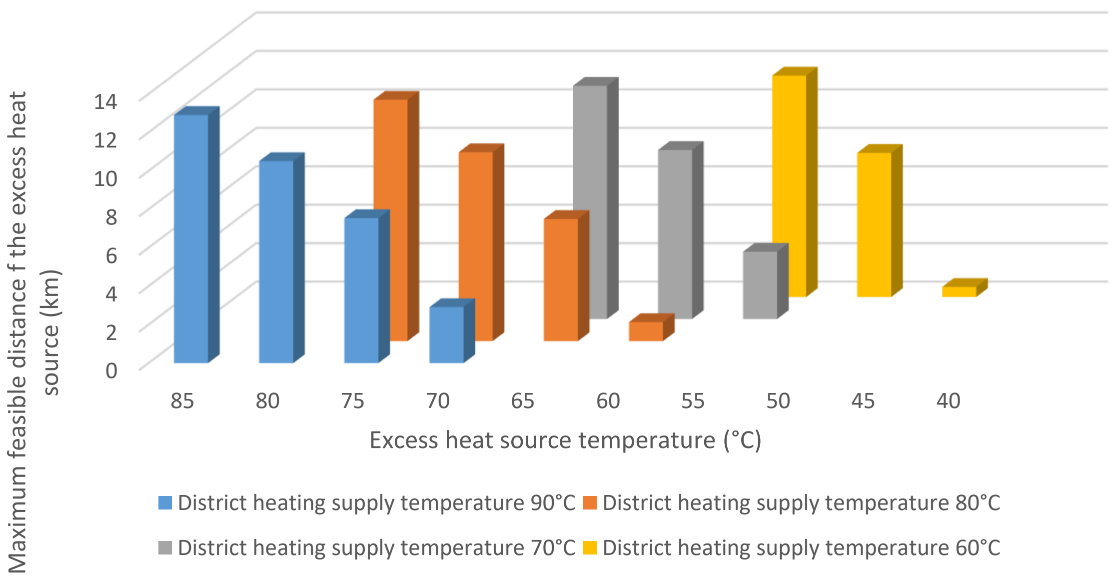

Figure 7 Variations of maximum feasible distance of the potential excess heat source with the temperature of the excess heat source and the district heating supply temperature

The results correlate with the variation of LCOEH with decreasing temperature level of the excess heat source. Therefore, it can be seen that the maximum feasible distance decreases in the case when temperature of the excess heat is lower. If the supply temperature is assumed at 90°C, the results show that at the excess heat source temperature of 70°C, it would be feasible to utilize it only in cases when the source is located at the close proximity of the primary district heating network, i.e. at the city itself.

However, if the system were to be transformed to the 4th generation network in terms of supply temperatures, lower temperature excess heat sources could be utilized. Hence, the results show that in the case of the supply temperature of 60°C, 40°C excess heat source could be utilized in cases when such a source is located at the proximity of the primary network. Furthermore, in case when the supply temperature is 90°C, the maximum distance of the excess heat source is 12.9 km at 85°C excess heat source temperature. Nonetheless, when the supply temperature is lowered, similar distances can be achieved with excess heat source temperature of 55°C. The results are graphically presented in Figure 7.

4. Conclusions

Utilizing excess heat from various industrial or service sector sources in the district heating systems depends significantly on different factors. In this work, the dependence of the capacity factor on the system configuration, as well as the temperature level differences of the source have been taken into account in order to present their influence on the LCOEH. This is a continuation of the previous work [22], which already proved that this method can be used as a criterion for excess heat utilization in district heating systems by calculating the maximum distance of the potential source from the demand.

Even though most of the calculations are usually made on the annual level, assuming that the availability of the excess heat source is constant throughout the year, this is frequently not the case. For this reason, the availability curve of this source was modelled by taking the data from literature in order to calculate its capacity factor, as one of the crucial parameters for the LCOEH calculation. Furthermore, different configurations of the system have been taken into account by implementing the scenario analysis. The calculations have been performed by using energyPRO, an energy system operation optimization tool. The results have shown that the configuration of the system has a significant impact on the excess heat utilisation, with the capacity factor ranging from 53% in Scenario 1 to 85% in Scenarios 4 and 5. It can be concluded that the storage system is needed if high utilisation rates of the excess heat should be achieved, mostly due to the mismatch between its availability and the overall heat demand. Nonetheless, this increases the LCOEH and therefore the cost optimal combination of storage and excess heat needs to be analysed in detail.

In further research, the effect of the decreasing temperature of the excess heat source on the LCOEH has been studied. In cases when this temperature is above the required supply temperature of the district heating network, this heat can be utilized directly, without the need for a heat pump. The investments are required only for the heat exchanger, while the operational costs consist of the excess heat procurement costs and the operation and maintenance. However, when the temperature of the excess heat source is lower than the needed supply temperature, the use of the heat pump is required substituting the investment and operation and maintenance costs of the heat exchanger with those of the heat pump and adding the additional cost of electricity needed for the heat pump, expressed by the unit of heat.

The results have shown that the LCOEH increases significantly with the lower temperature of the excess heat source. In the case when the supply temperature amounts to 90°C, LCOEH rises above the LCOH of the natural gas boiler district heating system at the temperature of the excess heat source of 66°C. However, another important parameter which greatly influences the results is the supply temperature of district heating, i.e. the needed temperature at the end use side. It has been shown in this research that the threshold for the competitiveness of excess heat (i.e. the temperature when the LCOEH reaches the LCOH of the gas boiler district heating) reduces from 63°C for the supply temperature of 85°C to 41°C for the supply temperature of 55°C. Furthermore, for the source temperature of 50°C the LCOEH reduces from 0.17 €/kWh if the supply temperature is 85°C to 0.027 €/kWh if the supply temperature is 55°C, showing the benefits of decreasing the temperatures at the end use side. This shows that even though the low temperature excess heat may not be feasible in this moment for the use in high temperature networks, its feasibility will significantly increase when the system is transformed towards the 4th generation of district heating with low supply and return temperatures.

Finally, the research has been validated by using the method from [22], i.e. by calculating the maximum feasible distance of the potential excess heat source from the demand, taking into account that the larger sources are usually located further from the populated areas. The results show that in the case of the supply temperature of 60°C, 40°C excess heat source could be utilized in cases when such a source is located in the proximity of the primary network. Furthermore, lowering the supply temperature results in achieving similar maximum distances both for the excess heat source temperature of 85°C, when the supply temperature is 90°C and 55°C when it is 60°C.

Acknowledgements

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Nomenclature

LCOH	Levelized cost of heat [€/kWh]
I_c	Capital cost of the production facility [€/kW]
CRF	Capital recovery factor which discounts the investment
T	Tax rate
D_{pv}	Present value of depreciation
i	Capacity factor of the production facility
O_{total}	Total operation and maintenance costs [€/kW]
c_{fuel}	Cost of fuel being used [€/kWh].
LCOEH	Levelized cost of excess heat [€/kWh]
I_{HE}	Investment cost for the heat exchangers [€/kW]
$O_{HE,total}$	Operation and maintenance costs for the heat exchangers [€/kW]
$c_{excess\ heat}$	Excess heat procurement costs [€/kWh]
I_{HP}	Investment cost for the heat pump [€/kW]
$O_{HP,total}$	Operation and maintenance costs for the heat pumps [€/kW]

$c_{el,th}$	Electricity costs of heat pump operation per unit of heat [€/kWh]
c_{el}	Electricity costs [€/kWh]
COP	Coefficient of performance
COP_{Carnot}	Carnot coefficient of performance
T_{DH}	Supply temperature of the district heating system [°C]
T_{EH}	Temperature of the excess heat source [°C]
η	Efficiency of the heat pump
R_{EH}	Extra revenue which can be used to finance the construction of the distribution network [€]
E_{total}	Total heat demand of the area for which it would be feasible to connect to a natural gas district heating system [kWh]
r_{heat}	Price of heat [€/kWh]
E_{EH}	Available excess heat [kWh]
E_{DH}	Remaining heat demand being covered by the natural gas district heating [kWh]
l	Average length of distribution network in a 100x100 m area [m]
n	Number of 100x100 m areas
c_{pipes}	Discounted cost of pipes [€/m]

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PAPER 3

EXCESS HEAT UTILISATION COMBINED WITH THERMAL STORAGE INTEGRATION IN DISTRICT HEATING SYSTEMS USING RENEWABLES

by

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District heating systems already play an important role in increasing the sustainability of the heating sector and decreasing its environmental impact. However, a high share of these systems is old and inefficient and therefore needs to change towards the 4th generation district heating, which will incorporate various energy sources, including renewables and excess heat of different origins. Especially excess heat from industrial and service sector facilities is an interesting source since its potential has already been proven to be highly significant, with some researches showing that it could cover the heat demand of the entire residential and service sector in Europe. However, most analyses of its utilisation in district heating are not done on the hourly level, therefore not taking into account the variability of its availability. For that reason, the main goal of this work was to analyse the integration of industrial excess heat into the district heating system consisting of different configurations, including the zero fuel cost technologies like solar thermal. Furthermore, cogeneration units were a part of every simulated configuration, providing the link to the power sector. Excess heat was shown to decrease the operation of peak load boiler and cogeneration, that way decreasing the costs and environmental effect of the system. However, since its hourly availability differs from the heat demand, thermal storage needs to be implemented in order to increase the utilisation of this source. The analysis was performed on the hourly level in the energyPRO software.

Keywords: *district heating, excess heat, hourly analysis, energyPRO, thermal storage*

Introduction

Heating and cooling sector is one of Europe's most energy-intensive sectors, which is responsible for around 50% of its final energy consumption [1]. Due to the high use of fossil fuels in covering the heating demand, this also leads to a high environmental impact of this sector. However, this could be substantially reduced if district heating (DH) systems are used at a much higher level in the future energy systems, which was shown in [2] proving significant cost, CO_2 emission and fuel use reductions when the share of DH is increased from the current 13% of the European heat demand [3]. Nonetheless, in order to provide such benefits, these systems must transform into the 4th generation and integrate much higher shares of

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renewables and excess heat [4]. Significant research has been already performed on the topic of the integration of renewables in DH, showing benefits of different combinations including solar thermal and thermal storage [5], adding biomass to the previous combination [6], as well as combining heat pumps with solar thermal [7], but also using geothermal energy [8]. These systems provide substantial benefits from both the economic and the environmental point of view, as was shown for five different cities in southeastern Europe [9], but also in [10]. This proves to be one of the main reasons for customer connection to DH, as shown in [11]. It can be concluded that when using intermittent heat production technologies, it is crucial to utilise thermal storage units, which should often have a seasonal character [12]. The importance of thermal storage has been proven in numerous articles, *e.g.* in [13] where authors provide a model for determining thermal storage optimal capacity, with the addition of optimal sizing of conventional sources and solar thermal and in [14] which shows the necessity of thermal storage when power to heat technologies are utilised in a smart energy system. They do, however, have certain space restrictions due to their size and therefore should be planned carefully, considering different options like phase change material indirect storage systems [15], which have also been analysed in combination with heat pumps [16].

From the perspective of sustainable heat sources for DH, excess heat from industrial and service sector facilities is especially interesting and has significant potential on both regional and national levels, as has been shown in numerous studies focusing on industrial excess heat utilisation in Japan [17], China [18], and the EU [19]. Despite a high amount of research being done on the topic of the potential of this source, its variability is rarely taken into account, which can have a high effect on the overall utilisation of this source. Therefore, this paper discusses rates of utilisation of excess heat in different configurations of the system, when the variability of excess heat availability and its mismatch with the heat demand is considered. Specifically, the contribution of this paper is in analysing the integration of thermal storage with various capacities to increase the utilisation of variable excess heat, while still remaining an economical solution.

Method

In order to analyse the different effects of excess heat utilisation in the DH system, scenario analysis has been performed. The idea was to study the integration of excess heat into the system which consists of the most common, conventional heat production units, *i.e.* natural gas cogeneration and peak load boilers, but also of zero marginal cost, renewable technologies, *i.e.* solar thermal collectors. In order to do that, a numerical example has been analysed, which will be elaborated further in the following subsections. By considering cogeneration, a link is made to the power sector since the operation of these units depends on the market prices of electricity. On the other hand, by including solar thermal in the calculations, the competing technology in terms of low marginal costs is also considered providing a full picture of the effect of excess heat integration on different heat production units. It must be noted that the analysis has been performed from the perspective of energy planning, not integrating the excess heat into the existing system but rather into the planned system, therefore being able to change the parameters of the fossil fuel units such as the required capacity of the peak load boiler.

The system has been modelled in the energyPRO software [20], which is an analytical optimisation model providing optimal operation of the system for the given heat demand in the time frame of one year. The time step for the analysis has been selected at one hour. In order to model the system, data on technology operation costs, fuel costs, as well as revenues from heat and electricity sales, is needed. Heat production capacities need to be predefined, and specific technical data of each technology need to be inserted in the model, including the technical constraints of each unit. The optimisation is performed in several steps. First, the priority number is assigned by the model to each technology based on the costs and revenues in each time step. Then the unit with the lowest priority number is put in operation, moving forwards with second lowest and continuing until the whole demand has been met.

The energyPRO software has been used as the primary tool for energy system analysis in numerous research articles already, *e.g.* analysing emission reductions and economic benefits of combining solar thermal with heat pumps in Helsinki DH [7], analysing booster heat pumps integration in DH with low system temperatures [21], developing scenarios and integrating various energy sectors, including electricity, heating and transport, as shown for the case of Pecs [22], investigating levelized cost of heat for the flexible DH in Baltics through the analysis of different combinations of production technologies [23], and many others.

Scenarios

As mentioned earlier, the main idea of the scenario analysis was to research the utilisation rate of excess heat, as well as the effect it has on the operation of other heat production technologies in the system, while taking into account the hourly variability of the source. For that reason, a numerical example has been studied. It is based on the data acquired through the CoolHeating project for the city of Ozalj in central Croatia [9], which details the heat demand and potential revenues, *i.e.* energy prices. Therefore, the scenarios developed as a part of this research will be compared with the Reference scenario, a starting point for this analysis which presents a technical concept developed for the city as a part of the CoolHeating project.

However, it must be noted that the Reference scenario is non-existent at this point, but is rather a highly developed technical concept, which has been discussed with the city and should be implemented in the coming years. It consists of a 20 MW natural gas cogeneration (CHP) unit, a 30 MW natural gas peak load boiler, as well as 10^5 m^2 of solar collectors, combined with a 30000 m^3 thermal storage system. All of these units would cover the heat demand of the city, which equals to 66.4 GWh and would transfer heat to the consumers through 16 586 m of pipes. This represents a trench length, *i.e.* only the length of the flow pipe, which is needed for additional calculations. Furthermore, in order to calculate the required amount of energy which would need to be produced in these units, heat losses need to be analysed. They have been calculated by using the empirical formula, based on real DH grids in Austria [24], which requires data on the annual grid density. It has been calculated at 4004 kWh/m/a. The losses have therefore been calculated at 3029 MWh/a, resulting in overall required heat production from DH units of 69.4 GWh.

By researching available excess heat facilities in the area, it has been concluded that a ceramic industry is operating in the relative vicinity of the city, with significant amounts of excess heat available, based on the excess heat sources map [25]. It has already been shown in [26] that the ceramic industry has high potentials for excess heat recovery, due to the high temperatures used in its processes. The overall excess heat potential from this specific ceramic industry facility amounts to 46 GWh. However, this presents a theoretically maximum excess heat availability calculated from the total CO_2 emissions of the facility, which is probably much lower in reality and therefore a more conservative value has been taken for further analysis, at 50% of the maximum value, *i.e.* 23 GWh.

In the next step, it was necessary to define the hourly availability of the excess heat source. By reviewing the existing literature, it can be concluded that the ceramic industry usually operates on a two or three-shift schedule throughout the year [27], but it is assumed that higher quantities of excess heat are produced during the working days than during the weekends. The source has been modelled in energyPRO by taking into account the assumption that its temperature is high enough in order to be utilised directly in the system, through the means of the heat exchanger and without having to use the heat pump. This assumption is logical since the source of excess heat is the ceramic industry which produces high temperature heat, as already mentioned.

The availability of ceramic industry excess heat is based on [27] and is shown in fig. 1. In order to put the variability of excess heat availability into perspective, it has been plotted alongside heat demand for a standard winter and summer week. It must be noted that the excess heat availability has been assumed the same for every week throughout the year, *i.e.* without any seasonal changes. It can already be noticed that excess heat availability and heat demand are in a significant mismatch in different seasons of the year. This will be further discussed in the results section.

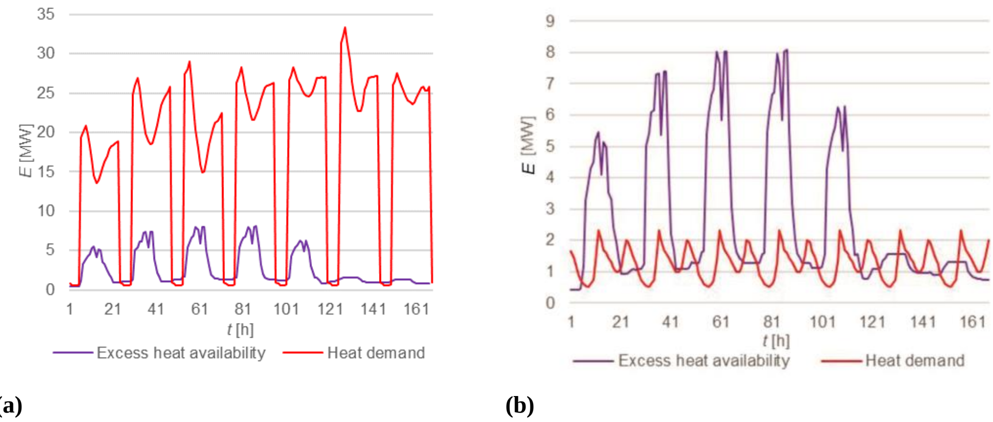

Figure 1. Excess heat availability and heat demand in a standard week in winter (a) and summer (b)

Due to these evident differences, it is evident that a thermal storage system has to be implemented at the excess heat site, in order to increase the utilisation of this source. Therefore, two scenarios have been modelled, Scenario 1 where excess heat is integrated into the system from the Reference scenario without using a thermal storage unit and Scenario 2, where a thermal storage unit is also added.

For that purpose, a series of simulations have been carried out with different capacities of thermal storage ranging from 2000 m^3 to 2.2×10^5 m^3 in order to calculate the best solution regarding thermal storage integration, when the economics of the overall system are taken into account. Then the dynamics of the system have been shown for the selected capacity of storage. Thermal storage units with lower capacities have been modelled as a steel tank, with the temperature difference from top to bottom of 40 °C, and the utilisation rate of 95%. The losses have been modelled, taking into account the storage height, insulation thickness and thermal conductivity of the insulation material (polyurethane foam), as well as the ambient temperature.

On the other hand, thermal storages with higher capacities have been modelled as a large pit unit, usually constructed to serve as seasonal storage. Technical details of all the three scenarios can be seen in tab. 1. The required input data for the model, other than technology capacities and technical constraints of the units, include the hourly electricity price, which is taken from the Croatian power exchange [28], hourly weather data, including solar irradiation and temperature, which is directly incorporated in the model for a selected location, the natural gas price at 0.3 €/m^3 [29], as well as fixed and variable operation and maintenance costs for each technology, which have been taken from [30].

Table 1. Technical details of different technologies used in the scenarios

	Reference scenario	Scenario 1	Scenario 2
P_{NGB} [MW]	30	26	27
P_{CHP} [MW]	20	20	20
A_{ST} [m^2]	10^4	10^4	10^4
V_{TS} [m^3]	3×10^4	3×10^4	3×10^4
$Q_{EH,\,max}$ [GWh]	–	23	23
V_{TSEH} [m^3]	–	–	$2000 – 2.2 \times 10^5$

The capacities are selected in such a way that the cogeneration covers the baseload, while the peak loads are covered by the peak load boiler. Solar collectors operate mostly during the summer and cover the domestic hot water demands, while seasonal thermal storage is used in order to increase the share of solar thermal in the overall heat production. Throughout the scenarios, the cogeneration and solar collector capacities have been held constant, while the peak load boiler capacity has been decreased with the introduction of excess heat to the minimal level while still covering the demand.

The system was modelled in energyPRO by using Region module, therefore modelling excess heat and the reference system as separate energyPRO sites, which both supply heat to cover the heat demand. This had to be done in such a way in order to take into account the effect of adding thermal storage on the excess heat side since it is impossible to separate two storage systems if they are modelled in the same energyPRO site. The system schematic presented in the form of the energyPRO block diagram is shown in fig. 2.

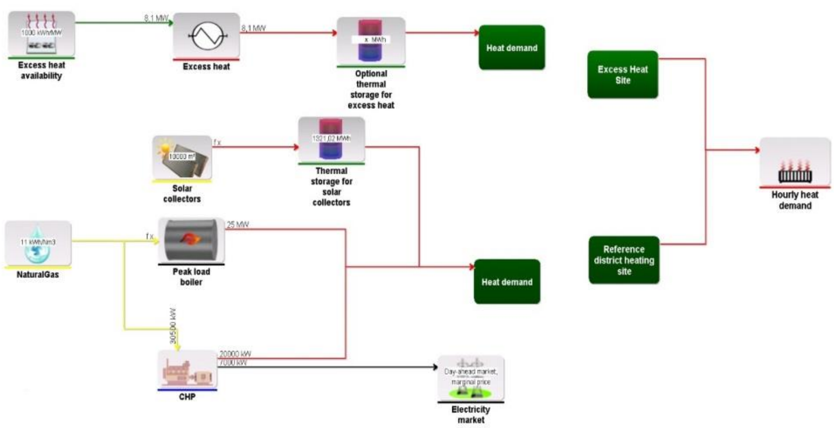

Figure 2. Schematic view of the system modelled in energyPRO

Finally, in order to compare the scenarios from the economic perspective, levelized cost of heat for the whole system has been calculated for each scenario, by using the equation presented in [31]. It has to be pointed out that the boundaries of this approach are that the results are highly case sensitive and input data-sensitive but are therefore used to present a qualitative analysis of the variable excess heat integration into the DH system.

Results

The results of the energyPRO modelling will be shown in this chapter. First, Scenario 1 will be studied in comparison to the Reference scenario. Afterwards, an addition of the thermal storage system for the excess heat in Scenario 2 will be analysed and compared to previous scenarios.

Scenario 1

Scenario 1 is compared to the Reference scenario, where no excess heat is utilised in the DH system. The annual production of heat from different production units can be seen in tab. 2. The results show that by introducing excess heat into the heat generation mix, the required peak load boiler capacity reduces, as well as its production. This results in lower natural gas consumption and consequently, the lower environmental impact of the heating sector. While cogeneration units also produce less heat, the production of solar collectors increases slightly, which will be discussed in the next paragraphs.

Table 2. Production in [GWh/a] of DH system under optimised operations, case studies: Reference scenario and Scenario 1

	Reference scenario	Scenario 1
Q_{NGB}	19.1	13.4
Q_{CHP}	40.7	36.5
Q_{ST}	9.5	9.7
Q_{EH}	–	10.4

However, this also has a negative effect on excess heat integration since only 45% of the available amount has been utilised. The problem is not just during the summer when there are excess amounts of solar energy but also during the heating season in the night. This happens since at that time, the available amount of industrial excess heat is higher than the heat demand, as was shown in fig. 1. Due to the lack of storage in Scenario 1, it is not possible to store this excess production, which is therefore wasted.

The DH production for the Reference scenario and Scenario 1 can be seen in fig. 3 for a typical winter week. The figure shows how excess heat first reduces the operation of a peak load boiler and then the operation of a CHP plant in cases of higher excess heat utilisation. Therefore, the operation of the peak load boiler has reduced from 3336 h/a to 2751 h/a, while for the CHP the reduction was from 2749 h/a to 2548 h/a. This consequently resulted in the reduction of natural gas consumption by 1137798 m^3/a.

Another benefit of the excess heat integration can be seen in fig. 4, which shows the monthly heat production for October when the heating season starts. It can be seen that with excess heat, the peak load boiler turns on approximately one month later in the heating season, allowing the seasonal thermal storage to discharge more slowly. This enables a slightly higher production from solar collectors and again reduces the natural gas consumption.

However, despite all the benefits of the excess heat integration into the DH system, when the variable availability of this source is taken into account, the results show that less than 50% of the available excess heat can actually be utilised, as previously discussed. This leads to the conclusion that storage systems need to be implemented alongside the excess heat facility in order to increase the utilisation of excess heat and further reduce the use of fossil fuels in the existing system. For that reason, Scenario 2 analysed the integration of an additional storage system for excess heat.

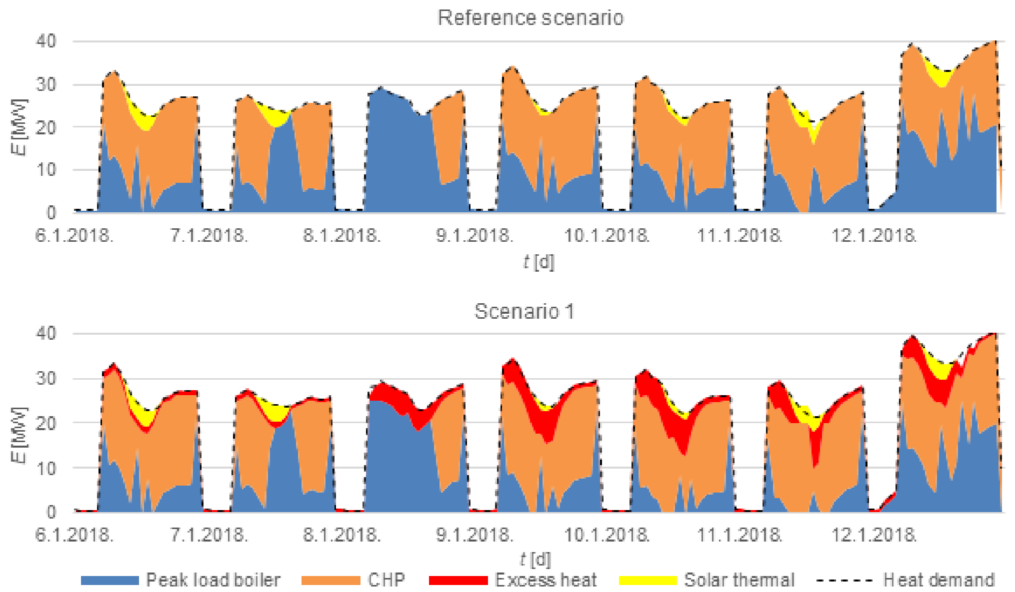

Figure 3. Thermal load of optimised operations in DH system during the typical winter week, case studies: Reference scenario and Scenario 1 (*for color image see journal web site*)

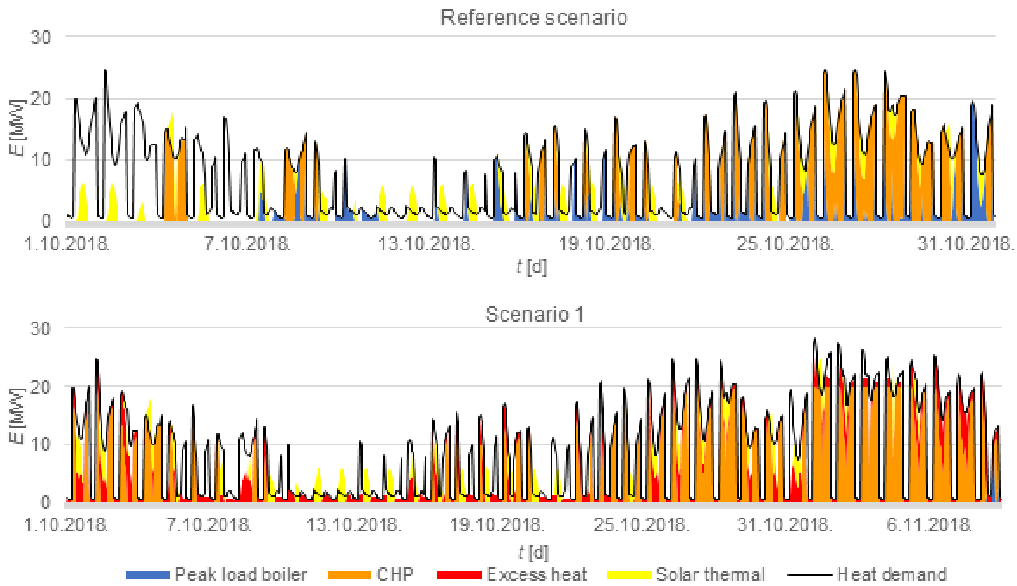

Figure 4. Thermal load of optimised operations in DH system in October, case studies: Reference scenario and Scenario 1 (*for color image see journal web site*)

Scenario 2

In order to determine the best solution in terms of thermal storage capacity for the excess heat source, a series of simulations have been carried out in energyPRO integrating different storage capacities from small buffer tanks to large pit storages. Then, the levelized

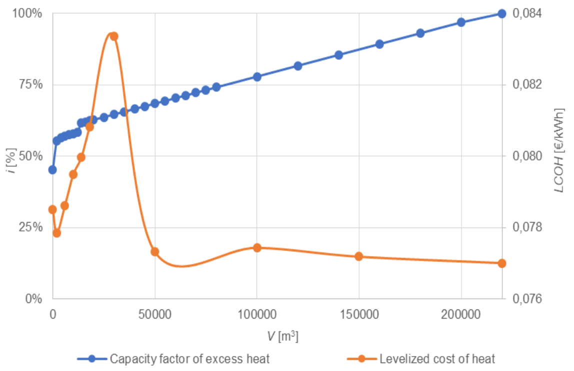

Figure 5. Thermal and economic analysis of the whole system operations for different capacities of thermal storage in Scenario 2

cost of heat has been calculated for the whole system, taking into account the results from these simulations. The resulting capacity factor of the industrial excess heat source, as well as the economics of the system when different thermal storage sizes are integrated into the system, can be seen in fig. 5.

It can be concluded that in order to utilise all of the available excess heat, a large underground thermal storage is needed, in this case with a capacity of 2.2 $\times$ 10^5 m^3, which equals to 9690 MWh. However, if this cannot be achieved due to space restrictions, relatively high capacity factors can still be achieved by implementing a smaller buffer tank, since the highest increases in the capacity factor occur at smaller capacities due to the most significant difference from the reference state, *i.e.* no thermal storage. Nonetheless, these showed to be more expensive solutions, as underground thermal storage units have a much lower specific investment cost than the buffer tanks.

Moreover, when the levelized cost of heat for the Reference scenario is calculated, it equals to 0.079 €/kWh, which shows that by using the underground thermal storage and therefore achieving a high capacity factor of excess heat, significant economic benefits can be achieved, as an addition to the environmental benefits. From fig. 5 it can be seen that lower costs of the system can also be achieved in Scenario 1, when no thermal storage is used, but also in cases of smaller buffer tanks, which increase the capacity factor significantly when compared to Scenario 1. However, when a higher-capacity buffer tank is used, the levelized cost of heat of the system increases above the levels of Reference scenario. Still, the increase is low, since the cost is only 5% higher at peak value than in the Reference scenario, which is negligible when compared to the environmental benefits of using the excess heat source. This is especially significant when the fact that excess heat can be considered as a carbon-neutral source is taken into account. This statement can be made since excess heat presents the heat that would be wasted otherwise, and its emissions are already accounted at the side of the industrial facility.

Since the least cost solution from fig. 5 is the 2.2 $\times$ 10^5 m^3 thermal storage, which enables the total utilisation of excess heat, these results will be elaborated in more detail in the next paragraphs.

Table 3. Production in [GWh/a] of DH system under optimised operations, case studies: Scenario 1 and Scenario 2

	Scenario 1	Scenario 2
Q_{NGB}	13.4	6.7
Q_{CHP}	36.5	30.6
Q_{ST}	9.7	9.7
Q_{EH}	10.4	22.9

When the results for a 2.2 $\times$ 10^5 m^3 thermal storage are calculated, it can be concluded that the utilisation of the peak load boiler is further reduced to 6.7 GWh/a, the utilisation of the CHP unit to 30.6 GWh, while the production of solar collectors remains the same as in Scenario 1, as can be seen in tab. 3. This again leads to lower natural gas consumption by 1454395 m^3/a, as well as lower environmental effect of the heating sector.

The production of different units for Scenario 2 in a typical winter and summer week is shown in fig. 6. It can be seen that in winter, the utilisation of excess heat increases both during the night hours, as well as during the day due to the implementation of the storage system. However, this only provides minor increases in the capacity factor of the excess heat source, which can already be achieved by buffer tanks with significantly lower capacities.

Figure 6. Thermal load of optimised operations in the DH system during the typical winter week: case study Scenario 2 (*for color image see journal web site*)

The highest increase in utilisation is therefore seen in the summer months when the heating demand reduces significantly, and the excess heat is being stored in the thermal storage system. In cases of lower capacity storage, it would charge rather quickly at the beginning of summer and could not store any additional heat coming from the industrial excess heat source throughout the rest of the summer. This is because of the competition with the solar collectors, which have the lowest cost during the summer and are the only used technology for covering the hot water demand in that period, while at the same time filling the seasonal thermal storage for its utilisation in the heating season. It can be concluded that when excess heat is integrated into the system with solar collectors, such as the analysed configuration, the seasonal thermal storage is required in order to utilise the source entirely and store all of the produced excess heat during the summer when solar collectors have higher priority.

The operation of excess heat thermal storage can be seen in fig. 7. The figure shows its seasonality since the daily operation has relatively small variations in comparison to the seasonal ones. This would also mean that the industries which have reduced operation during the summer months would be an ideal source of excess heat in cases when there are space restrictions and no seasonal thermal storage can be built.

Conclusions

This paper showed how the excess heat integration depends significantly on different conditions in the system when its variable availability is taken into account. The analysed case integrated excess heat into the system with solar thermal collectors who were the primary technology for supplying heat during the summer. By integrating excess heat, the solar thermal production did not reduce, as it has lower operating costs and therefore has the priority of operation. It even increased slightly since the excess heat integration enables slower discharging of the thermal storage for solar collectors in the autumn and hence their higher production. On the other hand, the operation of peak load boilers reduced significantly in all the scenarios, with the slight reductions of CHP operation as well. This resulted in much lower CO_2 emissions of the heating sector, due to the reduced consumption of natural gas.

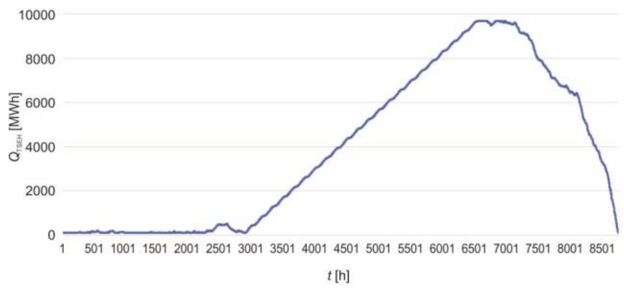

Figure 7. Excess heat thermal storage operation

However, it was shown that the maximum amount of excess heat that could be utilised is 45% for the analysed case, due to low heat demand in the night and the priority of solar in the summer. The reduction due to low night-time demands is applicable to the majority of cases in central and northern Europe, which have variable demands. For that reason, the effect of integrating a storage system at the excess heat production side was analysed by implementing multiple simulations with different storage capacities. The analysis showed that the storage actually has a seasonal character since the daily variations have a much lower effect, in cases when solar thermal is used alongside excess heat. Therefore, in order to utilise all of the available excess heat, an underground pit seasonal storage needs to be implemented. This also showed to be the economically optimal solution since it has the lowest overall levelized cost of heat. Nonetheless, if it is not possible to build such a storage unit, smaller buffer tanks can also be incorporated since they also achieve significant increases in the capacity factor for excess heat, while remaining an economically viable solution. It can be concluded from the presented research that the variability of excess heat should always be taken into account when hourly analyses are implemented since it affects the results significantly and that thermal storage must be used alongside excess heat source in order to increase its utilisation since it is a variable source, similar to intermittent renewable sources.

Acknowledgment

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Nomenclature

- *A* – area [m^2]
- *i* – capacity factor of excess heat [%]
- *E* – thermal load [MW]
- *LCOH* – levelized cost of heat [€kWh^{-1}]
- *P* – installed capacity of different production units [MW]
- *Q* – heat produced by different production units or stored in the thermal storage unit [GWh]
- *t* – time [h]
- *V* – capacity of thermal storage unit [m^3]

Subscripts or superscripts

- CHP – combined heat and power
- EH – excess heat

NGB – natural gas boiler
ST – solar thermal collectors
TS – thermal storage
TSEH – thermal storage for excess heat

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PAPER 4

Utilizing Excess Heat Through a Wholesale Day Ahead Heat Market – the DARKO model

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ABSTRACT

District heating has already proven to be a suitable solution for the decarbonisation of the most energy intensive energy sector in Europe, heating and cooling. However, to achieve this, it needs to incorporate renewable and sustainable energy sources into the generation mix which is still dominated by fossil fuels in many countries. Alongside traditional renewables like solar thermal, geothermal and biomass, excess heat from the industrial and service sector has a high untapped potential. Nonetheless, to utilize it in district heating, third party access must be granted. For that reason, a wholesale day ahead heat market has been modelled in this study and validated on a case study in the city of Sisak in Croatia. The idea was twofold: to evaluate the functionality of such a heat market and its effect on the existing system, as well as to analyse the integration of high and low temperature excess heat sources in different conditions, including the use of thermal storage, as well as the competition with low-cost renewables, i.e. solar thermal. The results have shown that the introduction of a wholesale day ahead heat market would ensure the positive total welfare in all the scenarios. The benefit for the demand side and the total welfare would increase even more if excess heat sources are integrated in the system and especially if they are combined with a thermal storage to increase their capacity factor, which would also decrease the competing effect of solar thermal. Finally, it was shown that low temperature excess heat is not feasible in the high temperature district heating and the transfer to the 4th generation district heating is required to feasibly utilise low temperature sources.

KEYWORDS

Keywords: Excess heat; district heating; heat market; renewable energy sources

1. Introduction

Heating and cooling is one of the most important energy subsectors, since it amounts to approximately 50% of the overall final energy consumption in Europe [1]. This shows that there are great potentials to increase the efficiency of this sector and subsequently decrease its environmental impact. An obvious solution are district heating systems, an efficient way of heating, which currently amounts to around 13% of the heat supply in Europe [2] and shows significant benefits over the individual fossil fuel heating solutions [3]. Despite a relatively low share on the European level, certain countries like Denmark, Iceland, Sweden, Lithuania, etc. already have a high share but still show significant potential to expand it even more. For example, a research has shown that an increase of district heating share in covering heat demand of Denmark to 70% would be an optimal solution [4]. Nonetheless, this can only be the case if these systems transform to a 4th generation [5] since numerous systems throughout Europe are still 2nd or 3rd generation of district heating, having high supply temperatures, using fossil fuel sources, encountering high losses, etc., as was shown in the comparison between the Danish and Croatian systems [6]. This would mean that district heating will have to use renewable and sustainable sources like solar thermal [7], geothermal, power to heat technologies and biomass in certain cases, when sustainability of its use can be proven [8]. Especially their combination and integration into an interconnected energy system with the use of storage technologies will lead the way towards the 4th generation, as was shown for the case of combining heat pumps, solar thermal and seasonal heat storage in Spain [9]. The benefits of using renewables over fossil fuels are significant, both from the economic and environmental point of view [10], which increases the willingness of the end users to connect to such a system [11]. Excess heat is an additional source which is interesting for sustainable district heating solutions and which can be utilized from various locations, including service sector buildings, industries, and thermal power plants. Its potential has been broadly researched, including the industrial excess heat [12], excess heat from thermal power plants [13] and the service sector and other low temperature sources of excess heat [14]. These researches show the significance of this source, especially when its relatively low environmental effects, in terms of global CO_2 reductions are taken into account, as has been shown for the case of Sweden [15]. Further benefit is its low cost, which enables its integration into district heating even when the source is located further from the heat demand [16]. However, this depends also on the temperature level of the excess heat, as discussed in [17], where it was shown that the feasibility of low temperature heat questionable in the existing high temperature networks, which further potentiates the need for the 4th generation district heating. Also, due to the variability of the excess heat source its utilisation can be decreased significantly because of the mismatch with heat demand, which decreases its feasibility. Therefore, in most cases there is a need for a thermal storage, as shown in e.g. [18] and [19].

Despite all the benefits mentioned above, district heating is still regulated as a monopoly in many cases, with one company being responsible for production, distribution, and supply of heat [20]. In these cases, there is no competition, which would decrease the cost and the environmental effect of this sector. Some countries have already deregulated their district heating sector which in theory should enable competition, but practically the situation has not changed much and there is still a large number of monopolies throughout Europe. A good example of deregulating the heat market is the Lithuanian district heating sector, where independent heat producers can supply their heat to the district heating network if their price is lower than the production costs of other units [21]. This also decreased the costs for the end users. Some other examples of a deregulated market include Sweden [22], Germany [23], and Denmark [24], among others.

This paper focuses on modelling the wholesale day-ahead heat market to determine the benefits of such a deregulated market in terms of costs for the production and the demand side, but also enabling access to additional players to increase the sustainability of the system. From that perspective, the feasibility of utilizing industrial and service sector excess heat sources in such a market is analysed, through the case study based on the system in Croatia. The heat market is modelled in a similar manner to the electricity spot market [25], but taking into account the specifics of heat and the district heating systems. Some papers have already researched the possibilities of a deregulated wholesale heat market but none, to the authors' best knowledge, have modelled in detail the full wholesale day ahead heat market and the research in this area is scarce. For example, in [26] Plexos model is used to simulate the wholesale market based on marginal cost pricing, while in [27] heat merit order is designed to make the production costs transparent. On the other hand, different parameters of the spot electricity market have been widely researched. For instance, in [28] the authors have developed a graphical approach for power-to-x scheduling in the spot electricity market in order to reduce the costs and CO_2 emissions of the electricity sector. Furthermore, in [29] the effect of photovoltaics and wind power on the spot market electricity prices is shown, concluding that these sources will reduce the price on the wholesale market, regardless of the scenario analysed.

Based on the previous gap analysis, the main contributions of this paper are as follows:

- A novel open source day-ahead heat market clearing model with optimal storage scheduling is presented and validated.
- It is shown that excess heat can and should be allowed to participate on the market as the benefits, in terms of the increase of the total social welfare, are significant.
- The feasibility of low and high temperature excess heat sources utilized in high temperature district heating systems (2nd and 3rd generation) is analysed by comparing the LCOH with the achieved price on the day ahead heat market.

2. Day-ahead market model (DARKO)

DARKO model [30] is an advanced open source [31] energy market model that incorporates different types of market orders on both sides (supply and demand) of the chain. For example, market participants can place two types of orders, simple orders, and complex orders. A graphical summary of the proposed modelling framework and energy, money and information (i.e. price and quantity of supply bids, demand offers and information related to operation of storage units) flows is presented in Figure 1. The model is highly generalized, meaning that there are no pre-set limits on the number of participants (supply, demand and storage/prosumers sides) on the day ahead market. The only limitation is the availability of the computational resources. The model obeys the following hierarchical structure: In each market area there is a single distribution network (i.e a district heating, gas or electricity network) that interlinks all the market participants (demands, generators and storages/prosumers) within that market area; each market area can also be interconnected with other neighbouring market areas through a set of transmission lines (i.e. pipes, wires etc.). These interconnection lines can positively impact the market clearing prices of neighbouring zones by shifting the merit order supply curves to the right in case of excess availability of cheap orders when the transmission capacities are high enough to accommodate the cleared energy flows from market area I to the market area X. Further information about the DARKO model can be found in the official documentation of the model [32].

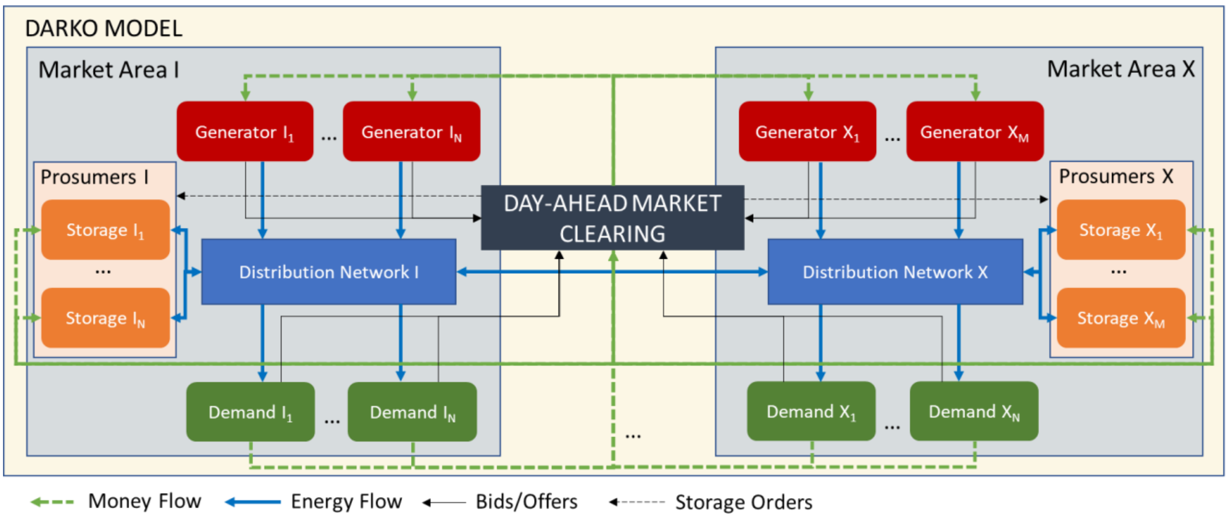

Figure 1 Graphical representation of the DARKO model. Flows between different market participants are color-coded based on the type of commodity (energy, money) and information being exchanged.

2.1. Order types

2.1.1. Simple orders

Simple orders are usually being referred to as the building blocks of the market. They are formulated in a simple way with limited number of linear constraints. Simple orders are linked to a single time step, meaning that price and quantity (availability) pair needs to be specified for each time step of the optimization horizon. Simple orders are the most flexible type of orders since their acceptance ratio (i.e., quantity supplied to the market) can have any value between 0 and maximum quantity being offered. Most orders on the energy markets are indeed simple orders.

2.1.2. Complex orders

Contrary to the simple orders, complex orders are subjected to a more complex set of constraints. These constraints are unique because one of the optimization variables is either integer or binary. Without complex orders, market clearing optimization is completely relaxed and purely linear. There are two main types of complex orders supported by the DARKO model. Block orders are the simplest type of market orders linking two or more consecutive time-intervals. They are defined as a specific quantity offered at a specific price for certain number of consecutive time intervals within the same optimization horizon (i.e., 24h in a day-ahead market). Block orders are also constrained by the minimum quantity that needs to be accepted by the market clearing algorithm (i.e., 20% of the total volume). Second type of complex orders is called flexible order. This group of orders is, in its core, analogous to block orders. The main difference between those two is that flexible order can be supplied for a maximum duration of i-1 time intervals present in the optimization horizon. Second difference is related to the way of how the order is being cleared. Flexible orders are only cleared in one time-interval providing the best social welfare (i.e., the time period is not decided by the user but by the optimization algorithm itself).

2.2. Mathematical formulation

Generally, the market clearing solution of the day-ahead markets is found by solving the Social Welfare Maximization Problem (SWMP). The aim of the SWMP is to maximize the social welfare (i.e., the economic benefits from the demand and the production side) and ensure that operational and storage constraints are obeyed at every time period of the optimization horizon. Mathematically speaking, these are well defined problems used by different market operators on a daily basis. However, currently there are no energy markets that incorporate storage orders. This addition can be fully utilized by the heating sector where energy flows between the producers and consumers are not instantaneous due to the presence of the thermal inertia in the heating and cooling networks.

2.2.1. Objective function

The objective function is formulated as the MILP problem aiming at maximization of the overall social welfare w_{tot}, under the set of primal decision variables: $V = \{x_{do}^i, x_{so}^i, x_{bo}, u_{bo}, u_{fo}^i, f_l^i, p_n^t, p'^t_n, Q\_in_s^i, Q\_out_s^i, s\_lev_s^i, s\_spill_s^i, s\_ll_s\}$:

$$\max w_{tot} = c^{do} - (c^{so} + c^{bo} + c^{fo}) \tag{1}$$

Thus, the social welfare comprises of the following functions.

Total hourly demand order cost function:

$$c^{do} = \sum_{d\in D}\sum_{o\in O}\sum_{i\in I}\left(P_{do}^{i} Q_{do}^{i} x_{do}^{i}\right) \tag{2}$$

where, P_{do}^{i}, Q_{do}^{i} is a price quantity pair of demand orders in trading period i, in €/MWh and MWh, respectively, and x_{do}^{i} is the acceptance ratio of demand orders in trading period i in %.

Total hourly simple order cost function:

$$c^{so} = \sum_{s\in S}\sum_{o\in O}\sum_{i\in I}\left(P_{so}^{i} Q_{so}^{i} x_{so}^{i}\right) \tag{3}$$

where, P_{so}^{i}, Q_{so}^{i} is a price quantity pair of simple hourly orders in trading period i, in €/MWh and MWh, respectively, and x_{so}^{i} is the acceptance ratio of simple orders in trading period i in %.

Total block order cost function:

$$c^{bo} = \sum_{b\in B}\sum_{o\in O}\sum_{i\in I}\left(P_{bo} Q_{bo}^{i} x_{bo}\right) \tag{4}$$

where, P_{bo}, Q_{bo}^{i} is a price quantity pair of block orders in trading period i, in €/MWh and MWh, respectively. The quantity of block orders might, based on the maximum availability, differ in each trading period i. The x_{bo} represents the acceptance ratio of block orders. It is important to note that block orders are, opposed to simple orders, cleared only as a binary variable for the entire optimization horizon (i.e. either all consecutive trading periods i where block order is present are cleared or not).

Total flexible hourly order cost function:

$$c^{fo} = \sum_{f\in F}\sum_{o\in O}\sum_{i\in I}\left(P_{fo} Q_{fo} u_{fo}^{i}\right) \tag{5}$$

where, P_{fo}, Q_{fo} is a price quantity pair of flexible hourly orders in €/MWh and MWh, respectively, and u_{fo}^{i} is the clearing status of flexible hourly orders in trading period i. Flexible hourly orders are cleared only once per trading horizon, optimal trading period is chosen by the optimization algorithm.

It should be noted that since the proposed mathematical formulation is a SWMP the demand quantities for simple and complex offers are always negative, while supply quantities for simple and complex orders are always positive. Furthermore, the objective function is subject to the following set of primal (Power balance, Order clearing, Energy flows, Net positions, Ramping rates and Storage related) constraints. More detailed descriptions are provided in the upcoming sections. The Lagrange multipliers (the dual values) of individual constraints (shown in brackets next to the respective constraints) are used for the derivation of the market clearing price (MCP).

2.2.2. Power balance constraints

There are three power balance constraints applicable for each node (zone). Net position of bidding node n in trading period *i* computes the local generation in each node. It also utilizes the intertemporal possibility to either charge energy into the local storage (if available) for later use or discharge it in case of favourable market conditions.

$$\begin{aligned} p_n^i = \sum_{d \in D_n} \sum_{o \in O} \left(Q_{do}^i x_{do}^i\right) + \sum_{st \in ST_n} \left({Q_{in}}_{st}^i\right) - \sum_{s \in S_n} \sum_{o \in O} \left(Q_{so}^i x_{so}^i\right) \\ - \sum_{b \in B_n} \sum_{o \in O} \left(Q_{bo}^i x_{bo}\right) - \sum_{f \in F_n} \sum_{o \in O} \left(Q_{fo} u_{fo}^i\right) \\ - \sum_{st \in ST_n} \left({Q_{out}}_{st}^i\right) \quad \forall\, n \in N, i \in I \;\; [{\pi_1}_n^i] \end{aligned} \tag{6}$$

Temporary net position of bidding node n in trading period i (${p'}_n^i$) computes the temporary change due to the flows happening between neighbouring nodes (i.e. if the cross-zonal interconnection capacity is high enough, market clearing prices in both zones are expected to be equal, meaning that the demand in a more expensive node would be satisfied by the supply bids from the cheaper node if the excess local generation capacities are high enough). This translates into the following two equalities:

$$\begin{aligned} {p'}_n^i = -\sum_{l \in L_n} \left(f_l^i\right) \quad \forall\, n \in N, i \in I \;\; [{\pi_2}_n^i] \\ p_n^i - {p'}_n^i = -\sum_{l \in L_n} \left(f_l^i\right) \quad \forall\, n \in N, i \in I \;\; [{\pi_3}_n^i] \end{aligned} \tag{7}$$

It should also be noted that when two nodes are not connected temporary net position of area equals zero.

2.2.3. Order clearing constraints

The following order clearing constraints denote the upper limits of the hourly demand and simple supply orders:

$$\begin{aligned} x_{do}^i \le 1 \quad \forall\, d \in D, o \in O, i \in I \\ x_{so}^i \le 1 \quad \forall\, s \in S, o \in O, i \in I \end{aligned} \tag{8}$$

The following order clearing constraints denote the lower and upper limits of block orders. They enforce the block orders to either be zero or between their minimum and maximum acceptance ratios. In literature this is also referred to as "fill-or-kill" constraints.

$$\begin{aligned} R_{bo}^{min} u_{bo} \le x_{bo} \quad \forall\, b \in B, o \in O \\ x_{bo} \le u_{bo} \quad \forall\, b \in B, o \in O \end{aligned} \tag{9}$$

Where R_{bo}^{min} is the minimum acceptance ratio of block orders, in %, and u_{bo} binary status of block orders, either 0 or 1. The clearing condition of flexible hourly orders is equal to:

$$\sum_{i \in I} u_{fo}^{i} \leq 1 \quad \forall f \in F, o \in O \tag{10}$$

Besides, simple orders are also constrained by the hourly ramping rates. These constraints are necessary for imposing intra temporal operational limits of thermal generators (i.e. the speed at which the thermal output can be increased between two consecutive hours).

$$\begin{gathered}
\sum_{o \in O} \left(Q_{so}^{i} x_{so}^{i}\right) - \sum_{o \in O} \left(Q_{so}^{i-1} x_{so}^{i-1}\right) \leq R_{so}^{up} \quad \forall s \in S, i \in I - \{i_1\} \\
\sum_{o \in O} \left(Q_{so}^{i-1} x_{so}^{i-1}\right) - \sum_{o \in O} \left(Q_{so}^{i} x_{so}^{i}\right) \leq R_{so}^{down} \quad \forall s \in S, i \in I - \{i_1\}
\end{gathered} \tag{11}$$

Where $R_{so}^{up}, R_{so}^{down}$ are hourly ramp up and ramp down rates of simple orders, in %/h.

2.2.4. Energy flow constraints

The energy (heat) flow constrains denote the heat transfer limitations between different regions (zones) as follows:

$$\begin{gathered}
f_{l}^{i} \leq F_{li}^{max} \\
F_{li}^{min} \leq f_{l}^{i}
\end{gathered} \tag{12}$$

Where $F_{li}^{min}, F_{li}^{max}$ are the minimum and maximum energy flow rates in the interconnection lines (pipes), in MW. Furthermore, hourly, and daily energy flow limits are imposed to mimic the realistic behaviour of heating networks (i.e., thermal inertia, heat, temperature and pressure drop(increase) rates etc.).

$$\begin{gathered}
f_{l}^{i} - f_{l}^{i-1} \leq F_{li}^{up} \quad \forall l \in L_n, i \in I - \{i_1\} \\
f_{l}^{i-1} - f_{l}^{i} \leq F_{li}^{down} \quad \forall l \in L_n, i \in I - \{i_1\} \\
\sum_{l \in L_n} f_{l}^{i} \leq F_{l}^{up} \quad i \in I \\
F_{l}^{down} \leq \sum_{l \in L_n} f_{l}^{i} \quad i \in I
\end{gathered} \tag{13}$$

Where $F_{li}^{up}, F_{li}^{down}$ are hourly ramp up and ramp down rates in the interconnection lines, in %/h. Propagation times are neglected in this modelling framework.

2.2.5. Net position constraints

Analogous to the energy flow constraints, net position constraints limit the price volatility in individual regions:

$$\begin{gathered}
p_{n}^{i} - p_{n}^{i-1} \leq C_{li}^{up} \quad \forall n \in N, i \in I - \{i_1\} \\
p_{n}^{i-1} - p_{n}^{i} \leq C_{li}^{down} \quad \forall n \in N, i \in I - \{i_1\} \\
\sum_{l \in L_n} p_{n}^{i} \leq C_{l}^{up} \quad i \in I \\
C_{l}^{down} \leq \sum_{l \in L_n} p_{n}^{i} \quad i \in I
\end{gathered} \tag{14}$$

Where $C_{li}^{up}, C_{li}^{down}$ are maximum hourly increase and decrease rates of the net positions in individual zones, in %/h. These inequality constraints also guarantee that the sudden and drastic heat drops (increases) (heat is chosen because of the way how the heat is being traded on the heat market, pressure, temperature, and other heat network related parameters are all directly related to the heat being supplied) between two consecutive time periods are prevented and security of the network is guaranteed.

2.3. Heat market features and storage constraints

Additional uniqueness of the heat networks opposed to the power networks is the slower response rate to the sudden increase(decrease) of heat supply(demand) which is mainly caused by the heat inertia in the networks. Thus, each branch of the network needs to be modelled as a small but expensive (low efficiency) thermal storage that can shift some portion of the oversupply to a consecutive time period.

2.3.1. Storage charging and discharging

The amount of energy that can either be charged or discharged in a given time period is limited by the state of charge of the storage unit and by the predetermined inflows and outflows (i.e. in the power sector the equivalent for this can be observed in hydro dams, while in heating sector this refers to a solar thermal or some other generation that is directly connected to the storage unit but that is not participating on the market).

$$\begin{gathered}\frac{Q_{out}{}_{st}^{i}}{\eta_{discharge}} \leq S_{level}{}_{st}^{i-1} + S_{inflow}{}_{st}^{i} \quad \forall\, st \in ST, i \in I - \{i_1\} \\ Q_{in}{}_{st}^{i} \cdot \eta_{charge} \leq S_{max}{}_{st} - S_{level}{}_{st}^{i-1} + S_{outflow}{}_{st}^{i} \quad \forall\, st \in ST, i \in I - \{i_1\} \\ Q_{in}{}_{st}^{i} \leq Q_{max}^{charge}{}_{st} \quad \forall\, st \in ST, i \in I \\ Q_{out}{}_{st}^{i} \leq Q_{max}^{discharge}{}_{st} \quad \forall\, st \in ST, i \in I\end{gathered} \tag{15}$$

where $Q_{in}{}_{st}^{i}, Q_{out}{}_{st}^{i}$ are hourly charge and discharge rates, in MWh, $\eta_{charge}, \eta_{discharge}$ are charging and discharging efficiencies, in %, $S_{level}{}_{st}^{i}$ is the state of charge of the storage unit, in MWh, $S_{inflow}{}_{st}^{i}, S_{outflow}{}_{st}^{i}$ are externally imposed inflows and outflows (i.e. from external energy source not participating in the market) in MWh and $Q_{max}^{charge}, Q_{max}^{discharge}$ are maximum hourly charging and discharging capacities, in MW.

2.3.2. Storage boundary

Besides charging and discharging constraints, storage units are also constraint by the storage minimum state of charge. It is especially important that storage level at the end of the optimization horizon (i.e. at the last hour of each day) is always at a certain (predetermined or optimized) level:

$$\begin{gathered}S_{final}{}_{st} \leq S_{level}{}_{st}^{i} \quad \forall\, st \in ST, i \in I = N \\ S_{min}{}_{st} \leq S_{level}{}_{st}^{i} \quad \forall\, st \in ST, i \in I \\ S_{level}{}_{st}^{i} \leq S_{max}{}_{st} \quad \forall\, st \in ST, i \in I\end{gathered} \tag{16}$$

where $S_{final}{}_{st}$ is the minimum state of charge at the last time interval of the optimization horizon, in MWh, and $S_{min}{}_{st}, S_{max}{}_{st}$ are lower and upper boundaries of the state of charge of the storage unit, in MWh.

2.3.3. Storage balance

Besides all previous constraints, energy stored in a given time period is also limited by the state of charge from the previous period as follows:

$$S_{level}{}_{st}^{i-1} + S_{inflow}{}_{st}^{i} + Q_{in}{}_{st}^{i} \cdot \eta_{charge} \leq S_{level}{}_{st}^{i} + \frac{Q_{out}{}_{st}^{i}}{\eta_{discharge}} + S_{spill}{}_{st}^{i} \quad \forall st \in ST, i \in I - \{i_1\} \tag{17}$$

where $S_{spill}{}_{st}^{i}$ stands for the amount of energy that is wasted or irreversibly thrown into the environment (i.e., this might be the case if the bidding price of storage units is so high that its cheaper to just release it into the air) and is expressed in MWh.

3. Case study

In order to validate the model described in the previous section, a case study was analysed through five different scenarios. The selected city is the city of Sisak, located in central Croatia. Here it must be noted that the case study consists of the real heat demand data, real data on the existing production units, but also the assumed data on excess heat potentials from various actors, as well as assumed data on solar thermal plant, due to the lack of any detailed information on these actors. The details of the case study are elaborated in the next paragraphs.

The city of Sisak is a mid-sized city in the central Croatia, with a population of 47 768. District heating is already present in Sisak, covering the heat demand of around 22% of the households. The existing production units consist of natural gas cogeneration, natural gas heat only boilers and a biomass cogeneration plant. For this analysis, the natural gas cogeneration plant is excluded since it operates based on the electricity demand, i.e., its primary purpose is selling electricity. Therefore, only the heat only boilers (HOBO_GAS_1) and the biomass cogeneration (CHP_BIO) are considered in the analysis in terms of existing district heating units. The overall demand of district heating connected customers equals to 59 GWh for households and service sector, and 28 GWh for the industrial facilities. The hourly demand profile is shown in the appendix, in Figure A 1.

For this analysis, three different zones have been defined to take into account different temperature levels of the industrial and household heat demand, as well as different heat transfer mediums. The existing district heating production plants have been allocated to the Zone 1 (Z1), along with the industrial demand, based on their physical location and the heat carrier. In Z1, steam is used as a heat carrier for covering the industrial demand. Also, all the heat produced in Z1 for the district heating system (households/service sector) is in a form of steam and it is being transported to the main heating station, where the heat is exchanged with the hot water system, used for covering the demand of households/service sector buildings. Therefore, the heat demand of these users is allocated to the Zone 2 (Z2), where hot water is used as a heat carrier. The overall length of the distribution network in Z1 is 8350 m, while the length in Z2 is 21 600 m.

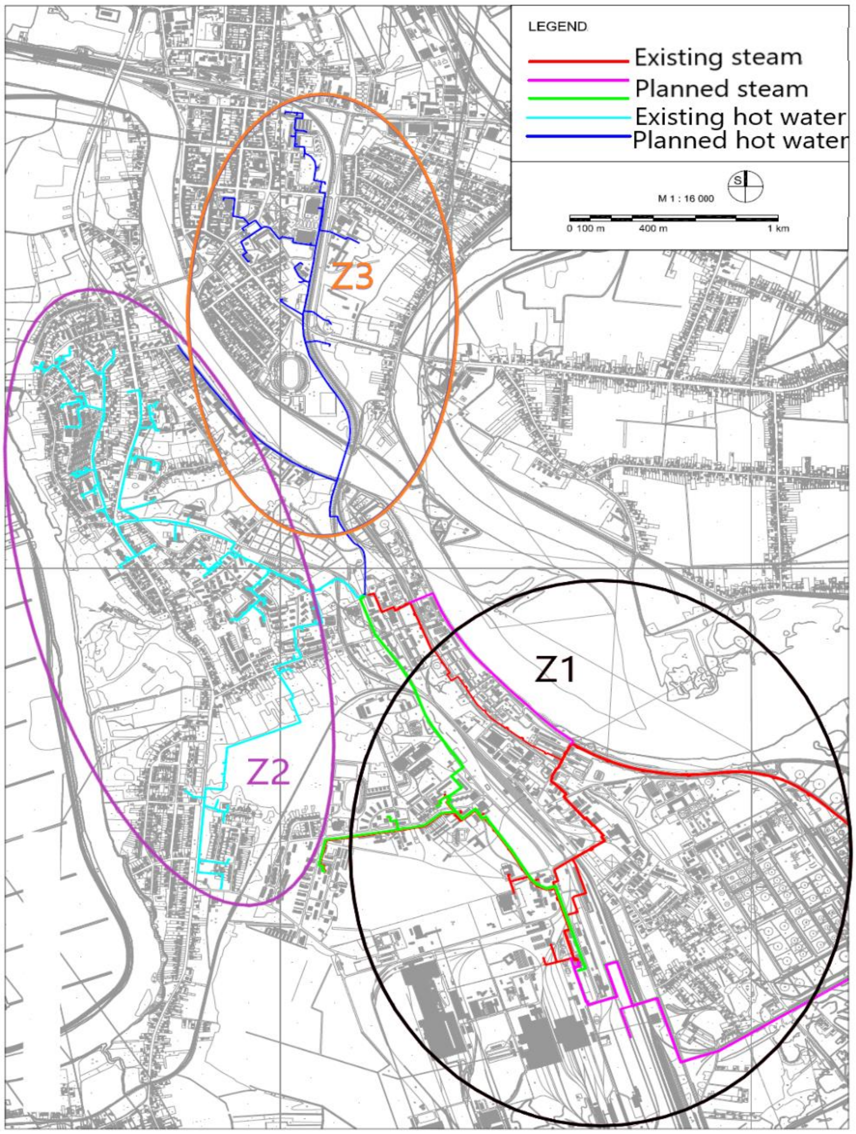

Figure 2 The location of the main zones analysed in this study, map based on [33]

Furthermore, an additional district heating demand is added for this analysis and allocated to Zone 3 (Z3). It is based on the assessment of the potential for expanding the district heating system of Sisak across the river Sava, to the old part of the city [33]. Currently, this demand is being covered either by the individual natural gas boilers or the central natural gas heat only boiler. This heat only boiler actually represents a small district heating system since it covers the demand of several buildings, however, in Croatian law smaller systems are not regarded as district heating, but rather closed heating systems. It is planned to connect this demand, as well as the natural gas boiler (HOBO_GAS_3) to the district heating system of Sisak in the near future and therefore both were included in the analysis as a part of Z3. The planned length of the distribution network in Z3 is 2066 m. The temperature level of Z2 and Z3 has been assumed constant throughout the year and averages 85°C. Therefore, the system presents a 3rd generation district heating, which is a standard in many European countries, including Denmark, Sweden, Latvia and Poland among others [34].

The map of the city of Sisak, with the existing and planned distribution networks and the allocated zones is shown in Figure 2. This map is based on the map elaborated as a part of the report on the potential for expanding the district heating system of Sisak [33]. A more detailed explanation of the existing production units and demands will be provided in the next subsection, focused on the individual scenarios.

3.1. Scenarios

In order to validate the heat market model and study the effect of integrating different excess heat actors in the heat market under various circumstances, five scenarios have been developed. In Scenario 1, the idea was to assess the impact of implementing the wholesale heat market in the current situation, i.e., taking into account the current demands and production units and assuming that the demand in the old part of the city (Z3) is connected to the main district heating system of Sisak. This scenario would then act as a reference for other scenarios. It must be noted that there is currently no thermal storage in the system, but it was necessary to model the short-term storage capacity of the distribution network itself. This was done through calculating the overall volume of the network, for which the average pipe diameter was assumed based on [35]. Therefore, for Z1 the calculated network storage capacity is 1.13 MWh, for Z2 2.47 MWh and for Z3 0.42 MWh. These values have been validated through literature since they correspond to the networks of similar length calculated in [36].

In Scenario 2, three excess heat facilities are added to the market as additional production units. These include industrial excess heat from the refinery located in Z1 (EH_IND), service sector excess heat from hospital in Z2 (EH_HOSP) and service sector excess heat from the supermarket in Z3 (EH_SMARK). To represent these sources in the market, several assumptions needed to be made, since no detailed data on the excess heat potential is available at the moment. First of all, the available excess heat from the refinery has been calculated by combining the Heat Roadmap Europe method presented in [37] and the maximum available excess heat potential from chemical industry in Croatia presented in [12], giving the maximum availability of this source 10.3 GWh. Its availability has not been assumed constant but variable (Figure A 3) , by applying the variation presented in the previous research of the authors [18], while the temperature level has been assumed high enough for the direct utilization through the heat exchanger. Service sector excess heat facilities have been added to the analysis to also consider the low temperature excess heat sources, which need a heat pump to increase the temperature level to the required district heating supply temperature. Since there was no real data on the excess heat potentials from the hospital and the supermarket, this was assumed based on the literature. The available excess heat from the hospital has been assumed based on the ReUseHeat project at 450 MWh [38], while from the supermarket it has been assumed at 3.5 GWh, based on the average capacity of heat that can be recovered from a supermarket in Sweden [39]. The temperature levels of these sources have been assumed at 80°C for the supermarket (based on high excess heat temperatures from the freezing processes using CO_2 as a medium [40]) and 50°C for the hospital. The availability has been presumed constant throughout the year.

Through the previous research of the authors, mainly Refs. [17] and [18], it has been concluded that the main competitors of excess heat sources in terms of feasibility are low cost technologies like solar thermal. Furthermore, there is a plan in development to include solar district heating into the system in Sisak in the near future. For these reasons, Scenario 3 presumes the inclusion of a solar thermal field to the heat market of Scenario 1, in order to define the differences of using solar thermal instead of excess heat. This technology was modelled in such a way that its annual production roughly corresponds to the available excess heat potential from all the sources. The production from solar thermal, as well as the required capacity of the dedicated thermal storage unit (TS_SOLAR) was modelled in the energyPRO software [41]. This provided the maximum production from this technology in each hour (Figure A 3), the charging/discharging profile of thermal storage and the capacities of both solar thermal and thermal storage. These data were used as an input in the DARKO model.

The final step in the analysis was assessing the impact of using both the solar thermal and excess heat units in the heat market, alongside the existing district heating production plants. Therefore, in Scenario 4, all the available heat production units are participating in the heat market, while in Scenario 5, an additional seasonal thermal storage unit (TS_EH) is added in order to increase the production from excess heat. This storage can be used only by the excess heat sources and it was chosen as a seasonal pit storage based on the results from the previous research of authors which showed the necessity of such a unit when utilizing excess heat in combination with solar thermal [18]. Its charging/discharging behaviour is optimized by running the heat market model with a 365-day time horizon (i.e., full year in advance), providing an optimal state of charge of all storage units for this scenario. This profile is shown in the Appendix, in Figure A 4. The expected impact of storage units, run by the market operator, can be summarized as follows:

- More exploitation opportunities for variable technologies – during the off-heating season (i.e. summer months) when variable technologies such as solar thermal or variable excess heat have the highest availability, the state of charge of seasonal storage units at the start and at the end of each optimization horizon increases. This consequently impacts the demand in that particular zone (i.e., demand rises because storage unit must charge certain amount of energy in order to reach the minimum state of charge at the end of the optimization horizon)
- Price variability decreases – during the off-heating season market clearing price would mimic the price of cheapest technology (i.e., solar thermal), however, if the storage capacity is high enough to absorb all the excess heat being generated, market clearing price would mimic the second cheapest unit etc. During the heating season, the opposite situation would be true. The cheap energy accumulated during the off-heating season can be released lowering the demand. This would also be reflected on the market clearing price diminishing the clearing opportunities for the more expensive technologies (i.e., backup gas unit)
- Total welfare increases – combined effect of previous two points is reflected on the increase of the total welfare.

Table 1 Available capacities on the heat market for each of the scenarios in [MW] for heat production technologies and [MWh] for thermal storage technologies

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
HOBO_GAS_1	8	8	8	8	8
HOBO_GAS_2	44	44	44	44	44
HOBO_GAS_3	11	11	11	11	11
CHP_BIO	12	12	12	12	12
EH_IND	-	3.7	-	3.7	3.7
EH_SMARK	-	0.4	-	0.4	0.4

EH_HOSP	-	0.05	-	0.05	0.05
SOLAR	-	-	14.3	14.3	14.3
TS_SOLAR	-	-	44	44	44
TS_EH	-	-	-	-	4500

An overview of the installed capacities of the production units participating on the market in each of the scenarios is shown in
Table 1, while the system scheme for scenario 5 (when all the available technologies are allowed to participate on the market) is presented in the appendix, in Figure A 5. Since there are no requirements for block production from none of these units, all of them are bidding as simple order units, as defined in Section 2.1. For offers on the heat market, prices were defined in such a way that they are slightly above the bidding price of the most expensive existing technology, in order to make sure that the demand will be satisfied in each hour of the year. Bidding prices of the heat production units were calculated by taking into account the discounted investment, operation and maintenance (O&M) costs and fuel costs in order to consider all the expenses for the heat production. Exceptions are HOBO_GAS_1 and HOBO_GAS_3, since it is assumed that these units are already amortized due to their age and therefore their bidding price includes only the fuel costs. The main motivation behind this approach is due to the particularities of the district heating sector. For example, district heating systems are usually isolated systems supplying heat to individual neighbourhoods or cities, and only in rare cases to larger regions with over a million consumers. Opposed to electricity sector, there are no opportunities to exchange heat with neighbouring regions or countries. This means that each district heating system is rather unique and acts as a standalone system. Thus, generalizations that would be applicable to all systems are hard if not impossible to make. Opposing to the electricity sector where ancillary services are provided by the same units on the reserve markets, in the heating sector the existence of these services is rather limited (i.e., heat can be supplied even if temperature levels are not 100% satisfied). Furthermore, revenues from capacity additions in form of government subsidies observed in the electricity sector are limited and outdated. Thus, due to all these reasons, opportunities for additional income streams are limited and not uniquely spread among different market participants. By using the bidding prices which include the discounted fixed costs, the aforementioned facts are taken into account and the chance of achieving feasibility of the market actors is increased, all the while the merit order is kept the same. This has also been discussed for the electricity markets, e.g., in [42] where authors debate using the same approach for bidding on the European markets in order to ensure the feasibility of the producers. They point out that day ahead electricity markets are usually modelled by using marginal cost bidding, but that this does not reflect the situation in real markets, in which strategic bidding is observed. Furthermore, this could prevent the missing money problem, which is a well-known issue in the electricity markets [43]. Similar propositions have been made in [44], where authors argue that the better energy price formation should be prioritized to reduce the effect of the missing money. The economic data for calculating the bidding prices are presented in the Appendix, in Table A 1, while the prices used for bidding and offering have been shown in Figure A 2.

4. Results and discussions

In the following subsections, the results of the scenario analysis will be presented and discussed. These are divided to the energy part (role of different technologies in covering the demand), economic part (achieved prices on the market) and the detailed analysis of the excess heat feasibility in the wholesale heat market.

4.1. Cleared bids

The first requirement of the heat market is that the heat demand is satisfied in every hour of the year. Since the current heat offer prices are modelled in such a way that they are higher than the highest bidding price of the existing technologies, the demands of each zone are satisfied in every hour. The cleared bids from the heat production technologies are shown in Figure 3. The results of Scenario 1 are expected and show that most of the demand is covered by the biomass cogeneration plant, while the peak load boilers, especially HOBO_GAS_3 have a rather low production. This happens due to the much lower price of the cogeneration, which results in the capacity factor of almost 70% for this unit.

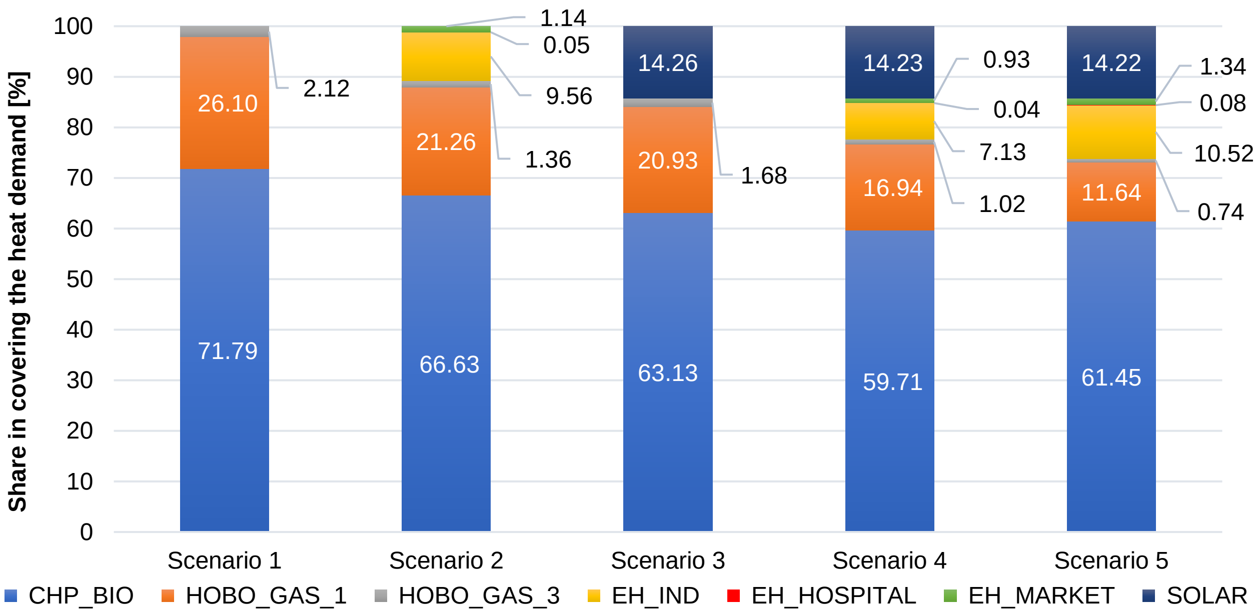

Figure 3 Cleared bids from different heat production technologies in five scenarios, expressed through the share in covering the heat demand

When excess heat units from industry and service sector are added to the market as additional players, the share of fossil fuel units and the biomass cogeneration decreases. This is presented as Scenario 2 and shows that approximately 10.7 % of heat demand is covered by these units. However, not all the available excess heat is cleared in Scenario 2, especially due to the high costs of the low temperature excess heat from the hospital, which sold only 10.9% of the available amount. Despite the assumed higher temperature of the supermarket heat which results in lower bidding price, only 31.9% of its available heat has been sold. This is due to the fact that in certain hours of the year all of the heat demand is covered by the cheapest units (CHP_BIO and EH_IND) and there is no need for additional heat, despite the fact that it is cheaper than the fossil fuel boilers in a number of hours. Even the excess heat from industry sold only 90.2 % of the available heat regardless of being the cheapest unit in this scenario, because of its variability which results in the mismatch with the heat demand in the summer months. This shows the need for a thermal storage system to increase the amount of cheap heat on the market, which was analysed in Scenario 5. The capacity factor of excess heat in the three scenarios where these sources are included in the analysis is shown in Table 2. It represents the amount of sold heat in relation to the maximum available amount.

Table 2 The capacity factor of different excess heat sources in [%] for Scenario 2, 4 and 5

	EH_SMARK	EH_IND	EH_HOSP
Scenario 2	31.96	90.22	10.85
Scenario 4	26.20	67.51	9.03
Scenario 5	37.70	99.94	17.80

On the other hand, the aforementioned is prevented from happening in Scenario 3 where instead of excess heat, solar thermal collectors are added to the market. This is because of a dedicated thermal storage which was modelled alongside solar collectors. Furthermore, the bidding price of solar collectors is the lowest of all the technologies, even when the costs of the storage system are taken into account and therefore almost all its available heat is sold to the market in this scenario, which results in a further decrease of operation of the existing units.

Scenario 4 shows how the excess heat sources are completely underutilized when there are other low bidding price technologies available on the market, such as solar thermal, and no thermal storage is available for the excess heat. On the other hand, the number of accepted bids from solar thermal practically remains the same as in Scenario 3. It clearly shows that solar thermal is a direct competitor to the excess heat, since it reduces its capacity factor to 67.5% for the industrial source, 26.2% for the supermarket and to just 9% for the hospital. However, this scenario does result in a lower number of cleared bids from the fossil fuel units, causing the lower environmental effect of the system. These results further potentiate the need for a storage unit which would act as a seasonal storage to increase the utilization of excess heat.

When a seasonal thermal storage is added, it can be seen in Figure 3 and Table 2 that almost all of the bids from the industrial excess heat source are accepted, while the production from solar thermal remains mostly the same. This results in the further decrease of the operation of fossil fuel units from more than 28% of heat production in Scenario 1 to just above 12% in Scenario 5. It enables a decrease of the environmental effect of the district heating sector by a large margin since all the other technologies used for heat production can be deemed sustainable, but also renewable (the emissions of pollutants from the excess heat sources are usually considered to be zero, since they are already attributed to the industrial or service sector from which the heat is extracted and the heat would be produced anyway and wasted in the air or water [16]). However, despite the complete utilisation of the industrial excess heat, the low temperature excess heat sources show no major increase of their utilisation due to the high costs, which brings into question their overall feasibility. This will be discussed in the next sections, where the focus will be on the economics of the analysed scenarios. The reasons for this are mainly to define which scenario results in the lowest costs for the demand side, what is the effect of different technologies on the MCP of the existing zones, what effect does the implementation of the seasonal thermal storage have on the costs of the system, etc.

4.2. Market clearing price

The most important economic indicator of the heat market is the hourly market clearing price, which defines the price at which market is cleared, i.e., where the supply cost and demand cost curves cross. MCP can then be used to analyse various other factors, which will be done in the following paragraphs. First, the effect of implementing the heat market will be analysed from the perspective of the demand side. This is done by multiplying the MCP with the demand in each hour of the year in the 3 zones, which gives the total cost for the demand side when all the values are summed up on the annual level. The results are shown in Figure 4 and illustrate the effects of integrating industrial and service sector excess heat through the heat market on the costs of the end users.

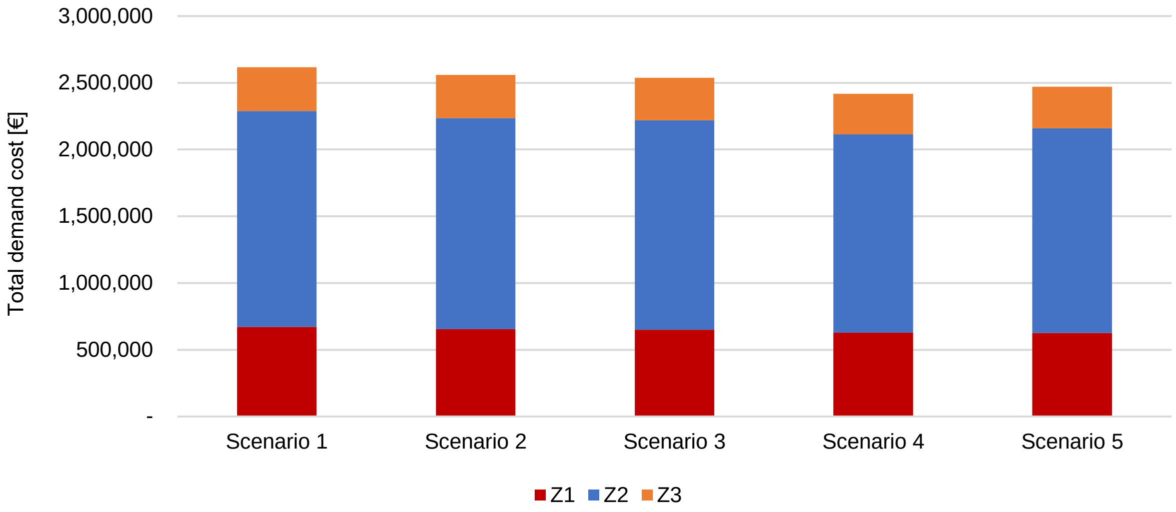

Figure 4 The total costs of the demand side divided per zones for each of the scenarios

If the current production plants and demands in Sisak are integrated in a day ahead heat market, the total cost for the demand side would amount to 2,616,398 € (Scenario 1). This does not represent the total cost for the end users, but rather the wholesale costs which would be marked up with supplier costs and the distribution costs to achieve the final end user cost (tax excluded). When excess heat is integrated in Scenario 2, the demand costs decrease slightly by 2.2% and are even more decreased when solar thermal is integrated alongside excess heat in Scenario 4, by 7.6%. Here it can be observed that Scenario 5 has a bit higher costs than Scenario 4, which happens due to the thermal storage unit which enables accepting more bids from the excess heat sources and therefore the cost (i.e., the average MCP in that case) is increased. However, Scenario 5 still has the second lowest cost of all the analysed scenarios. When considering the environmental effect of having the lowest production from fossil fuel technologies, the advantages of Scenario 5 prove to be the highest among the analysed scenarios. Finally, the results show the high benefit of introducing the wholesale heat market for the end users, in terms of reducing their costs especially when low bidding price technologies are used, such as solar thermal and excess heat.

The MCP of each zone is shown by a box & whiskers diagram in Figure 5, which aggregates the hourly values of the whole year. In this diagram, the whiskers represent the minimum and the maximum value that occurs in the selected period, the x represents the mean value and the middle line represents the median value. The bottom line of the box represents the first quartile, while the top line of the box represents the third quartile. The figure shows that the mean MCP in Z1 decreases slightly from Scenario 1 to Scenario 5, but the differences are rather small between all the scenarios. This is because excess heat and solar thermal cannot bid in Z1 since its demand is for industrial processes and its temperatures are assumed too high for these sources. However, they do affect the MCP in this zone indirectly through reducing the need for HOBO_GAS units in other zones, which enables increased production of cheaper CHP_BIO for covering Z1 demand.

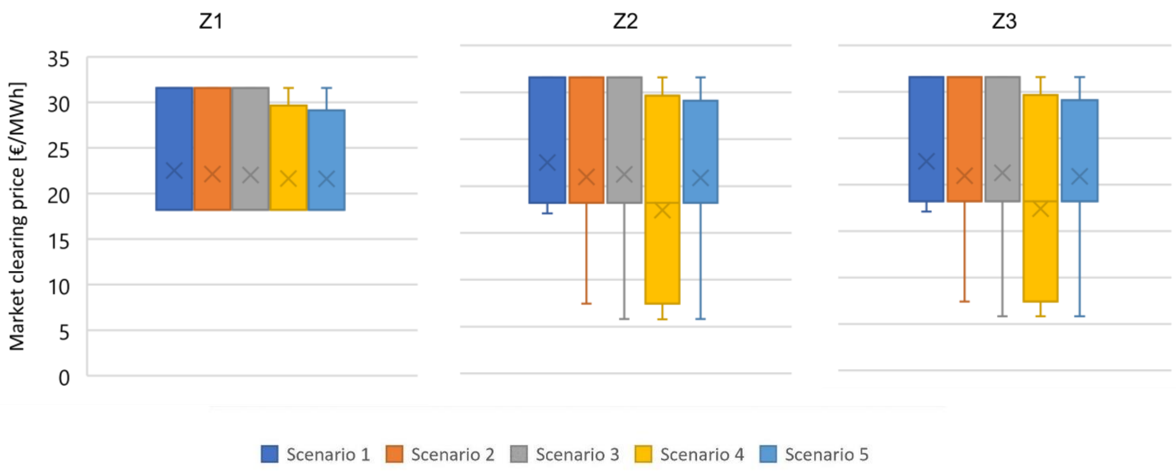

Figure 5 Market clearing price for each zone and scenario

On the other hand, the changes of the MCP between the different scenarios in Z2 and Z3, where excess heat and solar thermal are allowed to place bids, are much more evident. It can be seen that with the introduction of excess heat in Scenario 2, the minimum achieved MCP is reduced significantly, which reduces the mean value of MCP in Z2 from 22.52 €/MWh in Scenario 1 to 20.96 €/MWh in Scenario 2. This value is a bit higher in Scenario 3, at 21.27 €/MWh because of the variable availability of solar thermal, which is unavailable in most hours during the winter, while excess heat is available throughout the whole year.

Scenario 4 shows the highest variations in MCP for Z2 and Z3, as well as the lowest mean MCP of all scenarios at 17.44 €/MWh. This happens because there is no thermal storage for excess heat and therefore its bids are accepted only in those hours when it has the low price, which has a significant effect on the overall cost, but results in a low share of excess heat in the overall generation mix as was already shown in Figure 3 and Figure 4. Scenario 5 on the other hand results in the second lowest mean MCP. It should be noticed that in Z1, Scenario 5 has the lowest MCP of all the scenarios, as the share of utilized excess heat is increased and the need for expensive fossil fuel boilers is reduced. Therefore, the demand of Z1 can be covered by a lower cost CHP_BIO throughout the longest period of time. Finally, the differences between Z2 and Z3 prices are existent due to the changes in distribution network storage capacity of two zones but these are practically negligible. For that reason, in the following figures, only Z1 and Z2 will be illustrated.

Figure 6 and Figure 7 show the duration curve for the market clearing price in Z1 and Z2 respectively. For Z1 it can clearly be seen that Scenario 1 results in the lowest number of low MCP hours in the year, while Scenario 5 results in the highest. However, MCP does not fall below 18.21 €/MWh in none of the scenarios due to the lower impact of excess heat and solar thermal on Z1, as previously elaborated, and the lowest cost MCP corresponds to the bidding price of CHP_BIO. On the other hand, the results for Z2 show that even lower MCP can be achieved, especially for Scenario 4 in which the price is below 8 €/MWh for 3233 hours in the year. Scenario 2 and Scenario 3 also achieve MCP below 8€/MWh but for a much shorter time period, i.e., 919 hours for Scenario 2 and 475 hours for Scenario 3. In contrast, the MCP of Scenario 5 is at 18.21 €/MWh through most of the year and falls below that for a much shorter period of time. This higher price, compared to Scenario 4, is due to the thermal storage unit, which enables the higher utilisation of excess heat but also storing this heat during the hours in which it would otherwise be directly used on the market and reduce the need for CHP_BIO.

Therefore, by implementing TS_EH, the production of CHP_BIO as a marginal production technology increases.

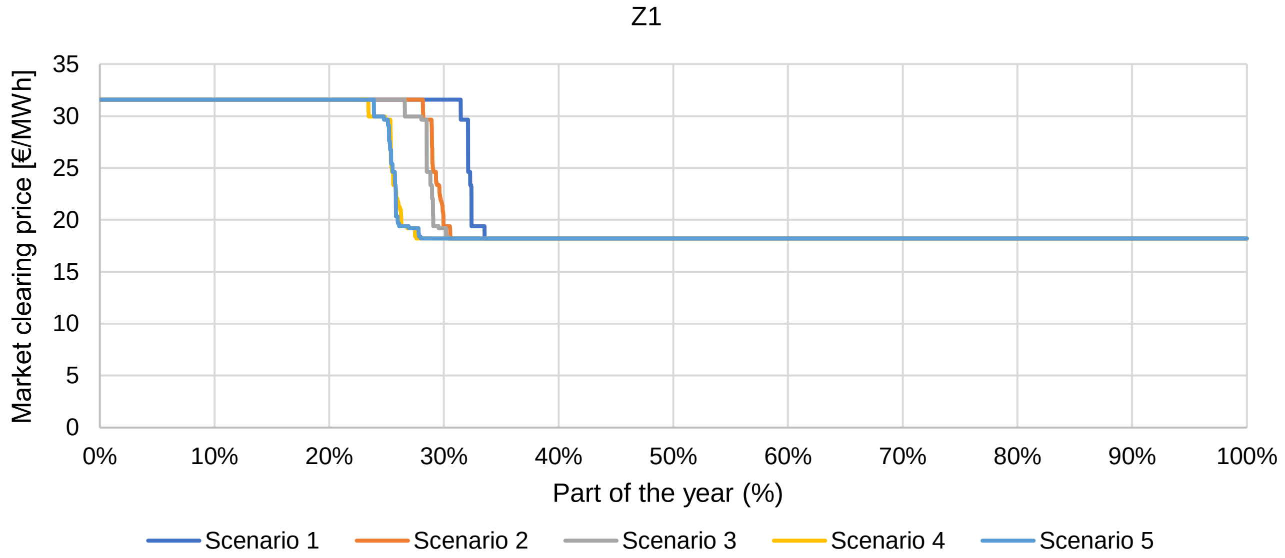

Figure 6 Load duration curve of the market clearing price for Z1

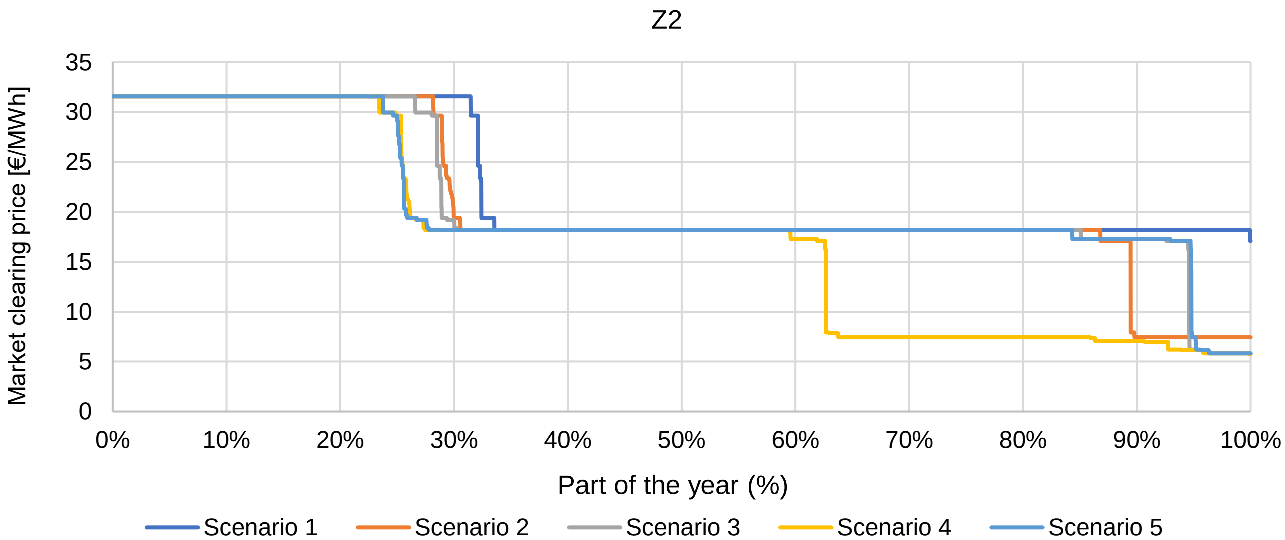

Figure 7 Load duration curve of the market clearing price for Z2

The difference between MCP of Scenario 4 and Scenario 5 in Z2, which are the most interesting for this study, is shown on an hourly level in Figure 8. Here it can easily be seen at which hours Scenario 4 has a lower MCP than Scenario 5. The differences can be most easily observed during the summer period, i.e., outside of the heating season. Because of the thermal storage unit, the MCP of Scenario 5 remains below the bidding price of HOBO_GAS in autumn for approximately 1.5 months longer than in Scenario 4, meaning that HOBO_GAS does not need to be turned on before the middle of November. The same can be observed in the spring, when HOBO_GAS turns off already at the end of March in Scenario 5, while in Scenario 4 it is still needed until the middle of April. On the other hand, the MCP of Scenario 5 is much higher on average during the non-heating season, when compared to Scenario 4 because of the need for the CHP_BIO operation in times when thermal storage is being charged. This figure clearly shows the effect of the thermal storage operation on the market clearing price. While in Scenario 4, the lower price is achieved during the summer due to the demand being covered mainly by solar thermal and industrial excess heat, Scenario 5 enables the utilisation of a higher amount of excess heat sources through the implementation of thermal storage, and reduces the number of high MCP periods, which translates to the reduced use of HOBO_GAS units.

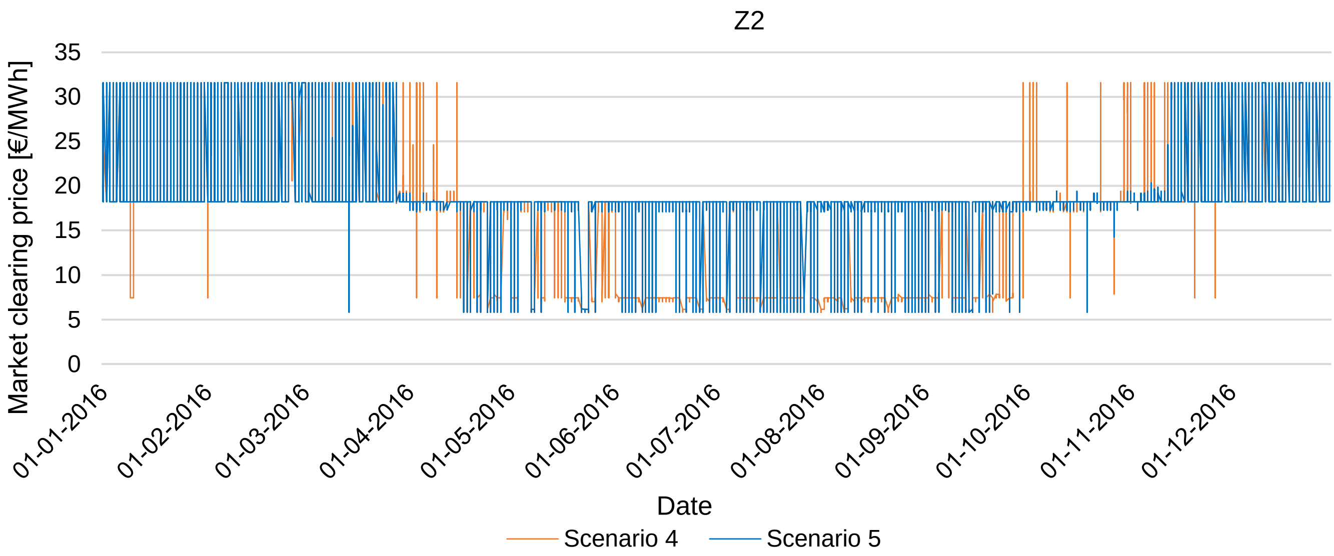

Figure 8 Hourly market clearing price of Scenario 4 and Scenario 5 in Z2

Finally, since the objective function of the day ahead heat market optimizes social welfare, it is necessary to provide the analysis of this parameter. Overall social welfare on the annual level is shown in Table 3.

Table 3 Total welfare of all the scenarios, on an annual level

Scenario	Total Welfare [€]
Scenario 1	3,681,941
Scenario 2	4,022,894
Scenario 3	4,175,062
Scenario 4	4,444,681
Scenario 5	4,604,915

The figures show that the total welfare is maximal in Scenario 5, due to the fact that the highest amount of excess heat and solar thermal bids are accepted in the market. Taking into account both the production and the demand side benefits, Scenario 5 is obviously the most optimal solution, even when environmental effect is not considered. Furthermore, it can be seen that all the scenarios have a positive total welfare providing the further benefit of implementing the wholesale day ahead heat market.

4.3. Levelized cost of heat

As previously mentioned, these scenarios have been based on the current situation in the city of Sisak, where HOBO_GAS and CHP_BIO already exist. Their feasibility will therefore not be discussed in more details since they are already built. On the other hand, excess heat units and solar thermal have not been built yet and therefore it is necessary to analyse whether their participation on the heat market would be feasible, i.e. should these units be built in the first place. This is done by calculating the levelized cost of heat (LCOH) for these production units and comparing it to the average achieved price on the market. LCOH is used based on the previous research from authors [16], which showed that it is a good criterion for calculating the feasibility of excess heat. From the perspective of this paper, LCOH provides a minimum price at which excess heat and other market actors can feasibly participate on the heat market. It has been calculated by using the equation provided in the previous research from the authors [16], [17] and is presented in Table 4. Here, the difference between the bidding price in the market and LCOH needs to be pointed out. While both use discounted investment, fixed and variable O&M, fuel costs and other sources of costs, LCOH uses data on the real utilisation, i.e. the capacity factor of the unit for which it is calculated. Therefore, it can be calculated only after the results from the heat market are acquired.

Table 4 Levelized cost of heat in [€/MWh] for excess heat sources and solar thermal in different scenarios

	Scenario 2	**Scenario 3**	**Scenario 4**	**Scenario 5**
EH_IND	9.42	-	12.59	8.50
EH_SMARK	60.40	-	72.05	48.46
EH_HOSP	184.00	-	218.50	103.80
SOLAR	-	6.39	6.42	6.23

The results show that the lowest LCOH is achieved for SOLAR, due to its high capacity factor and low costs. On the other hand, LCOH of excess heat varies significantly depending on the source. If the source is an industrial facility, where there is no need for a heat pump due to the high temperature level, LCOH is rather low in all the scenarios. This is not the case for the excess heat from the supermarket and the hospital due to the need for an additional heat pump. Especially high LCOH is calculated for the hospital excess heat due to its lower temperature level and therefore lower coefficient of performance of the heat pump. Even in Scenario 5, where thermal storage is available, the high price does not enable higher utilization of these sources and therefore results in high LCOH.

Table 5 Achieved average price in [€/MWh] of the excess heat sources and solar thermal on the heat market in various scenarios

	Scenario 2	**Scenario 3**	**Scenario 4**	**Scenario 5**
EH_IND	22.49	-	23.45	23.18
EH_SMARK	30.32	-	30.93	31.16
EH_HOSP	31.18	-	31.16	31.33
SOLAR	-	19.81	15.42	18.37

As mentioned earlier, these values need to be compared with the average achieved price of these units on the market, which is shown in Table 5. It was calculated by multiplying the cleared bid of each technology with a MCP in every hour of the year, summing these values and dividing them with the overall production from this technology. Based on Table 5 it can be concluded that solar thermal is a very feasible solution in such markets. The same can be said for the excess heat from the industry since the achieved average price was significantly higher than the LCOH in every scenario. However, low temperature excess heat sources have such a high LCOH in Scenario 2, 4 and 5 due to the low capacity factor that despite achieving a higher average price they still remain infeasible. These results are in line with the previous research [17] which showed the infeasibility of the low temperature excess heat sources.

A couple of facts can be discussed based on these results. First, it can be seen that the lower temperature excess heat sources are currently not suitable for the traditional high temperature district heating systems since the low COP of the heat pump results in high electricity costs and therefore low feasibility of this source. On the other hand, high temperature industrial excess heat has a high feasibility, regardless of its capacity factor since there is no need for a heat pump and the costs in general are much lower. Solar thermal has proven to be a big competitor to the low temperature excess heat due to its low costs and it was shown that in most cases it will reduce the operation of excess heat sources. This leads to the fact that thermal storage is required for excess heat in situations when there is a competition with low bidding price technologies like solar thermal, but also when these sources operate alongside traditional production units, due to their variable availability. However, the feasibility of low temperature excess heat would increase significantly if the supply temperature of the district heating network would decrease. This shows the necessity of transforming the existing 2nd and 3rd generation systems to the low temperature 4th generation district heating to utilize various low temperature sustainable heat sources.

5. Conclusion

The main idea of this paper was to analyse the functionality of a wholesale day ahead heat market and specifically to investigate the feasibility of excess heat utilisation from different temperature level sources when it participates in such a market. For that purpose, an open source energy market model (DARKO) was developed, which was validated on a case study based on a mid-size city in Croatia, the city of Sisak. The results of the analysis showed that a day-ahead heat market would facilitate the addition of new heat generation capacities such as excess heat or solar thermal and would decrease the final cost for the demand-side. The lowest costs for the demand side turned out to be in Scenario 4, when excess heat from industry, supermarket and hospital, as well as solar thermal collectors are added to the current system, resulting in a decrease of costs by 7.6% compared to Scenario 1. However, in this scenario solar thermal reduces the capacity factor of the excess heat sources significantly (industrial excess heat 67%, excess heat from supermarket 26% and excess heat from hospital 9%) due to its low bidding cost. Therefore, from the environmental perspective, Scenario 5 provides better results since the utilization of excess heat is increased, while the utilization of solar thermal remains roughly the same. This can only be achieved if a seasonal thermal storage is built, which was proven to be a precondition for achieving a high capacity factor of the excess heat utilization. Despite not being the cheapest solution (although it is the second cheapest solution with just 2.3% higher costs compared to Scenario 4) for the demand side, the total welfare of Scenario 5 turned out to be the highest at 4,604,915 €, meaning that it is the most optimal solution from the perspective of the model, which maximizes the total welfare of the system.

By taking a closer look at the feasibility of different excess heat sources when participating at the heat market, it can be concluded that low temperature excess heat sources, like service sector facilities (supermarkets and hospitals in this paper) are not feasible in the existing high temperature district heating systems. This has been analysed by calculating the levelized cost of heat for each of the excess heat sources and solar thermal and comparing it to the average achieved price on the market. In Scenario 5, where the capacity factor of all these technologies was the highest, both the excess heat from industry and solar thermal heat were feasible. However, excess heat from hospital and the supermarket, which were assumed to have a low temperature, were still not feasible, with levelized cost of heat being higher than the achieved price by 72.5 € and 17.3 € respectively. This shows the need for the low temperature 4th

generation district heating systems, which would decrease the costs of low temperature excess heat sources and make them a viable solution in the heat market.

Acknowledgements

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Nomenclature

Abbreviations	Description
CHP_BIO	Biomass cogeneration
DARKO	Day Ahead Market Optimization
EH_HOSP	Excess heat from the hospital
EH_IND	Industrial excess heat
EH_SMARK	Excess heat from the supermarket
HOBO_GAS	Natural gas heat only boiler
LCOH	Levelized cost of heat
MCP	Market clearing price
O&M	Operation and maintenance costs
SOLAR	Solar thermal
SWMP	Social Welfare Maximization Problem
TS_EH	Thermal storage for excess heat
TS_SOLAR	Thermal storage for solar thermal

Sets	Units	Description
i		trading period
d		Demand
s		Simple
b		Block
f		Flexible
n		node
l		line
st		storage
o		Order type

Variables	Units	Description
x_{so}^{i}	%	acceptance ratio of simple orders in trading period i
x_{do}^{i}	%	acceptance ratio of demand orders in trading period i

x_{bo}	%	acceptance ratio of block orders
u_{fo}^{i}	-	clearing status of flexible hourly orders in trading period i
c^{do}	€	Total cost of demand orders
c^{so}	€	Total cost of simple orders
c^{bo}	€	Total cost of block orders
c^{fo}	€	Total cost of flexible orders
f_{l}^{i}	MWh	Flow in the interconnection lines in trading period i
p_{n}^{t}	MWh	Net position of bidding node n in trading period *i*
p'^{t}_{n}	MWh	Temporary net position of bidding node n in trading period i
${Q_{in}}_{st}^{i}$	MW	hourly storage charge rates
${Q_{out}}_{st}^{i}$	MW	hourly storage discharge rates
${S_{level}}_{st}^{i}$	MWh	state of charge of the storage unit in trade period i
w_{tot}	€	Total welfare
${S_{spill}}_{st}^{i}$	MWh	the amount of energy that is wasted or irreversibly thrown into the environment

Integer Variables	**Units**	**Description**
u_{bo}		binary status of block orders

Parameters	**Units**	**Description**
P_{do}^{i}	€/MWh	price of demand orders in trading period i
Q_{do}^{i}	MWh	quantity of demand orders in trading period i
P_{so}^{i}	€/MWh	price of simple orders in trading period i
Q_{so}^{i}	MWh	quantity of simple orders in trading period i
P_{bo}	€/MWh	price of block orders
Q_{bo}^{i}	MWh	quantity of block orders in trading period i
P_{fo}	€/MWh	price of flexible orders
Q_{fo}	MWh	quantity of flexible orders
R_{bo}^{min}	%	minimum acceptance ratio of block orders
R_{so}^{up}	%/h	hourly ramp up of simple orders
R_{so}^{down}	%/h	hourly ramp down of simple orders
F_{li}^{max}	MW	maximum energy flow rates in the interconnection lines

F_{li}^{min}	MW	minimum energy flow rates in the interconnection lines
F_{li}^{up}	%/h	hourly ramp up rate in the interconnection lines
F_{li}^{down}	%/h	hourly ramp down rate in the interconnection lines
C_{li}^{up}	%/h	maximum hourly increase rate of the net positions in individual zones
C_{li}^{down}	%/h	maximum hourly decrease rate of the net positions in individual zones
$\eta_{discharge}$	%	Storage charging efficiency
η_{charge}	%	Storage discharging efficiency
$S_{max_{st}}$	MWh	upper boundary of the state of charge of the storage unit
$S_{min_{st}}$	MWh	lower boundary of the state of charge of the storage unit
$S_{final_{st}}$	MWh	minimum state of charge at the last time interval of the optimization horizon
$S_{inflow_{st}}^{i}$	MWh	externally imposed storage inflows
$S_{outflow_{st}}^{i}$	MWh	externally imposed outflows

Appendix

Table A 1Economic data for the analysed heat production technologies

Technology	**Investment cost**	**Fixed O&M cost**	**Variable O&M cost [€/MWh]**	**Discount rate [%]**	**Lifetime [years]**	**Fuel cost [€/MWh]**	**Reference**
HOBO_GAS	60,000 €/MW	2000 €/MW	1.1	8	20	30	[45]
CHP_BIO	1,450,000 €/MW	71,250 €/MW	2.3	8	14	15	[45], [46]
EH_IND	542,000 €/MW	2 % invest.	-	8	20	-	[47]
EH_SMARK	1,240,000 €/MW	2000 €/MW	2.7	8	25	-	[45]
EH_HOSP	1,240,000 €/MW	2000 €/MW	2.7	8	25	-	[45]
SOLAR	489 €/MWh	0.09 €/MWh	0.2	8	30	-	[45]

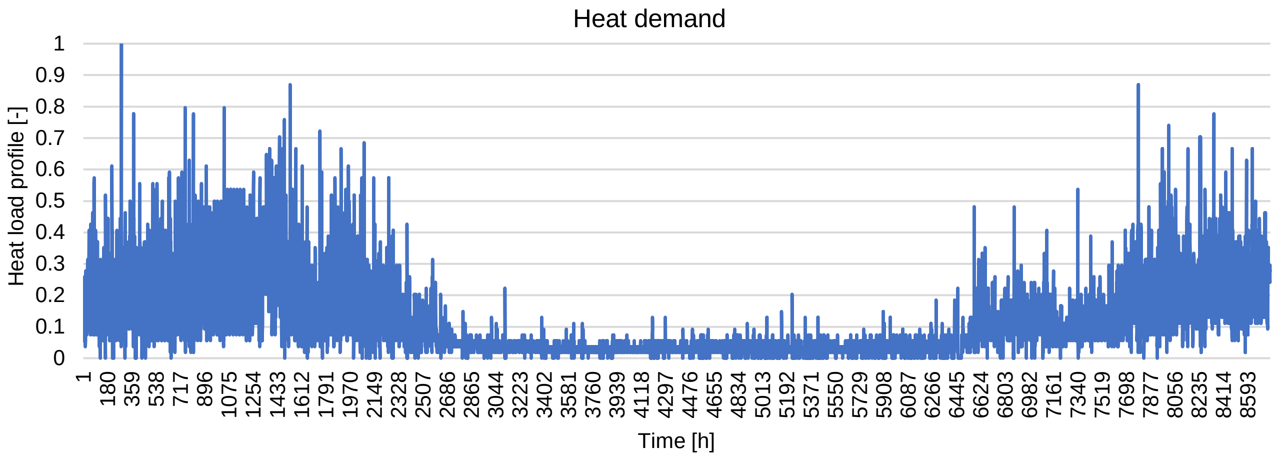

Figure A 1 Heat demand profile for Z2, also applied to Z3

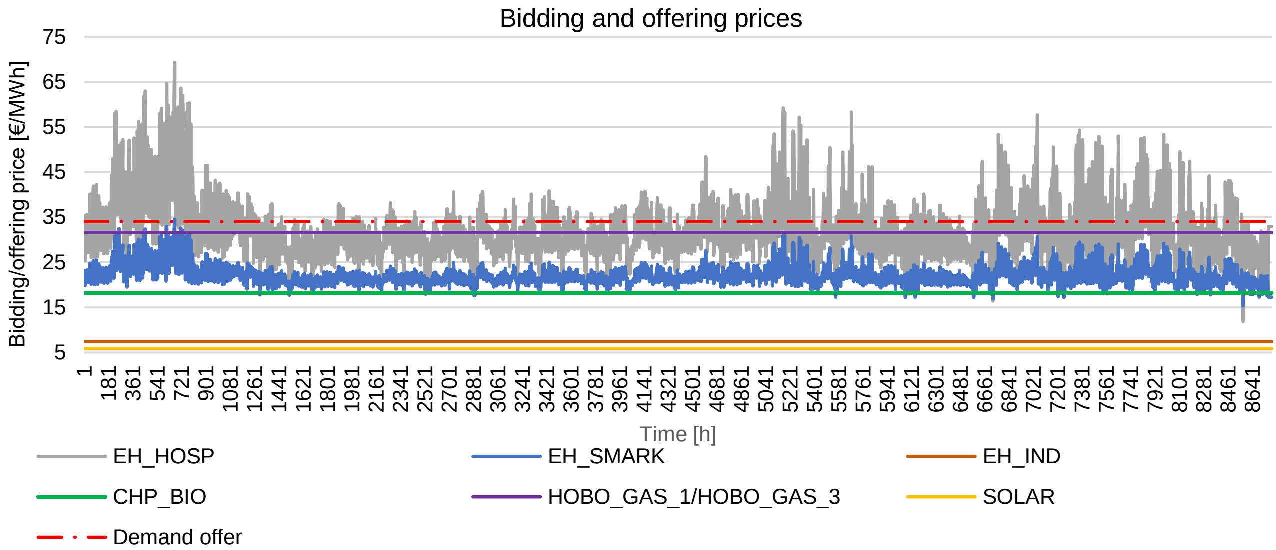

Figure A 2 Bidding prices of different technologies and demands analysed in the paper

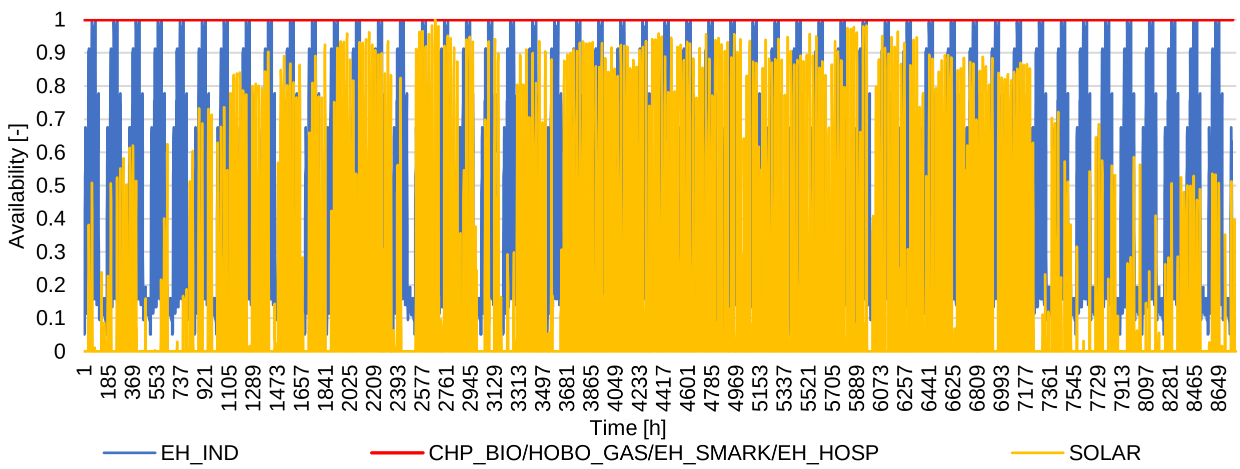

Figure A 3 Availability factor for the technologies participating on the market

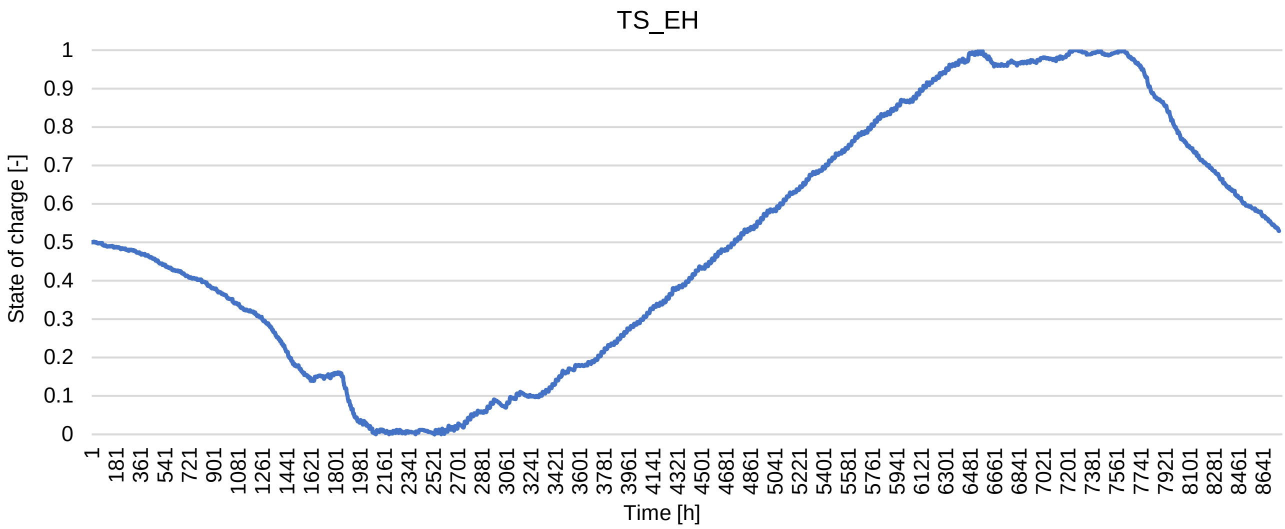

Figure A 4 Optimized thermal storage profile used for the seasonal storage in Scenario 5

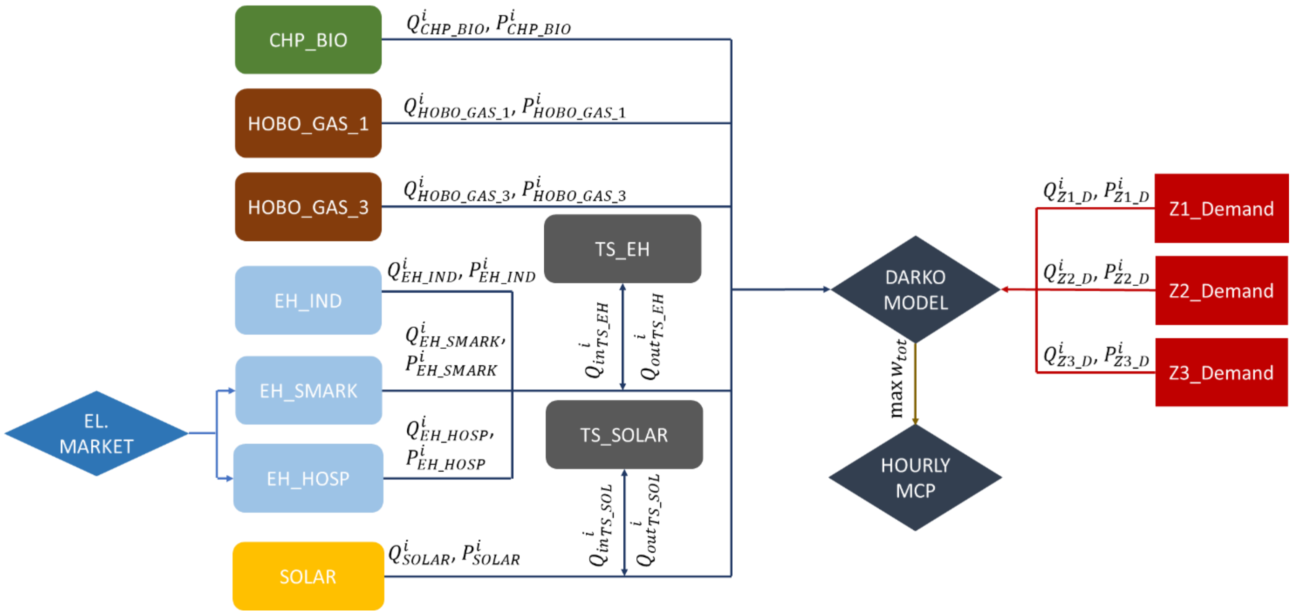

Figure A 5 System schematic for Scenario 5

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PAPER 5

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Research paper

Bidding strategies for excess heat producers participating in a local wholesale heat market

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ABSTRACT

The heating sector of the European Union covers 80% of the household's final energy consumption, which shows its relevance for the energy transition to the carbon neutral society, as set out in the Green Deal. Since most of the heat demand is located in the high heat density areas, district heating shows to be a promising solution for reducing the environmental impact of this sector, as it enables the utilisation of renewable energy sources and the use of high efficiency production technologies. An especially interesting source for district heating is excess heat from various industries and tertiary sector buildings, which has a significant technical potential. However, to enable excess heat producers to supply their heat to district heating, third-party access needs to be granted, which calls for a deregulated heat market.

This work consists of analysing two different bidding strategies which can be applied on the heat market: total cost and marginal cost biding. The focus here is to research the feasibility of the excess heat sources when different bidding strategies are used, especially when low temperature excess heat is considered, which has variable hourly costs due to the electricity demand for operating a heat pump. The results show that, despite the increased capacity factor of low temperature excess heat when marginal cost biding is used, it remains infeasible when supplying heat to the high temperature district heating networks through a heat market. Therefore, lower temperature district heating is a necessity for a feasible utilisation of low temperature excess heat. Finally, the effect of the power market prices on the low temperature excess heat feasibility was analysed and it was shown that it is significant, which led to the conclusion that introducing a higher share of renewables into the power market could foster the utilisation of these heat sources.

1. Introduction

At the end of 2019 European Commission published the Green Deal, the plan to make the economy of the European Union sustainable (European Commission, 2019). This includes reducing the net greenhouse gases emissions to net zero levels, which cannot be achieved without the decarbonisation of the energy sector and specifically the heating sector, which is responsible for almost 80% of the final energy consumption in buildings (European Commission, 2021). District heating, especially when integrated with renewables and excess heat, is an obvious solution for decreasing the environmental impact of the heating sector and as such has been recognised by the Commission in the EU Strategy on Heating and Cooling (European Commission, 2016). This shows the potential and the need for further exploration of the low cost and low emission sources for district heating. Previous research has indicated that increasing the share of such systems would reduce indirect and direct heating system costs, while decreasing the emissions of the pollutants, with the optimal share being 70% for a country like Denmark (Lund et al., 2010). On the other hand, currently only around 13% of the overall heat demand in Europe is covered by district heating (Connolly et al., 2014) and the shares differ significantly depending on the geographical location. While northern and central Europe have higher shares, southern European countries like Spain lag behind despite the recent advances and the analysed potential (Balboa-Fernández et al., 2020). Also, there is a high diversity of energy sources currently being used, with a number of systems still using fossil fuels and high temperature networks resulting in considerable losses, the so called 2nd and 3rd generation (Čulig-Tokić et al., 2015). Other systems, especially in northern Europe, are much more developed and use significant shares of renewables, have low temperature networks and can be generally classified as 4th generation district heating (Sorknæs et al., 2020). Even the 5th

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generation is already being increasingly mentioned, as a system which has ultra-low temperature levels and which can therefore utilise low temperature sources (Lund et al., 2021) and provide bidirectional flow (Bilardo et al., 2021). Such sources are usually renewables, in the form of solar thermal or geothermal (Rutz et al., 2017, 2019).

However, another interesting source is excess heat from various activities, such as industrial processes, service sector buildings, data centres, etc. It may not be renewable at its source, but if not used in district heating, this heat would be wasted nonetheless and therefore it can be argued that it is neutral from the environmental perspective. It has already been shown that excess heat has a significant potential, when utilised from the industrial facilities (Papapetrou et al., 2018), thermal power plants (Colmenar-santos et al., 2016) or the low temperature sources such as service sector (Lygnerud et al., 2019). The benefits are considerable, from the environmental, as pointed out in the case of Sweden (Broberg Viklund and Johansson, 2014), but also from the economic perspective in certain cases. For example, it was shown that industrial excess heat, that has a temperature high enough to be utilised directly through the heat exchanger, can be feasibly utilised even if it is located several kilometres from the heat network (Doračić et al., 2018). On the other hand, the feasibility of excess heat source decreases with its temperature level, as shown in Doračić et al. (2020b), which brings in question the viability of low temperature sources, such as service sector facilities, in the existing 2nd and 3rd generation systems. Another issue which arises by using these sources is their low utilisation rate if the variable availability of the source is considered, which calls for the use of thermal storage systems, as shown by Fitó et al. (2020) and Doračić et al. (2020a). Additionally, in Doračić et al. (2020a) it was specifically concluded that thermal storage units used for increasing the excess heat capacity factor have a seasonal character due to non-decreasing availability of excess heat during the summer on the one hand and low heat demands on the other.

For excess heat to be utilised in district heating, usually there is a need for enabling third-party access, which requires a deregulated heat market. Currently, this is in most systems not the case since they are regulated as monopolies, which results in one utility being responsible for the whole process (Stennikov and Penkovskii, 2020). However, deregulation would facilitate competition, which in turn would enable a decreased environmental impact of the sector due to the penetration of cheaper renewable technologies and consequently lower prices. This was already shown in some countries like Lithuania (Jonynas et al., 2020) and Denmark (Bürger et al., 2019). The focus of this paper is on the implementation of the wholesale day-ahead heat market, which was developed as a model in the authors previous research (Doračić et al., 2021) and was already shown to be a good facilitator for adding new players, such as excess heat, to the existing systems. Still, to potentiate the feasible utilisation of various production units, in Doračić et al. (2021) authors considered only the total costs when defining the bidding prices. Total cost bidding was already proven as a good solution for increased feasibility of market producers in the power markets in Van Bracht et al. (2017), where authors debate using this approach for bidding on the European power markets due to the aforementioned reasons. They point out that in literature, power markets are usually modelled by utilising marginal cost bidding, but the situation in the real markets is different and incorporates strategic bidding. Similar statements are made in (Hogan, 2017), where it is argued that improved bidding strategies should be prioritised to decrease the impact of the missing money problem, a well-known issue in the power markets (Woo et al., 2019). In terms of heat markets, to the best knowledge of authors, total cost bidding has only been proposed and studied in Doračić et al. (2021). On the other hand, marginal cost bidding is the most widely used bidding strategy due to the reduced requirement of input data and consequently the simplicity. Heat markets are seldomly researched so far and are mostly modelled by using marginal cost bidding. For example, in Liu et al. (2019) authors use marginal cost pricing to simulate the heat market in the Plexos model, while in Moser et al. (2020) marginal cost was used to design the heat merit order to make the production costs transparent. However, the differences between the two bidding strategies on the heat market have not been studied so far. This is especially relevant from the perspective of the merit order of technologies with variable bidding prices, like low temperature excess heat sources, whose capacity factor and subsequently feasibility could significantly change in case of a different bidding strategy. Therefore, the key contributions of this paper are as follows:

- Total cost bidding is compared to the marginal cost bidding on the day ahead heat market by using the DARKO model to define the benefits of each bidding strategy from the producer and consumer side
- The impact of different bidding strategies on the utilisation of low temperature excess heat on such a market is analysed, focusing on the effect on the merit order due to its bidding price variability
- The impact of the electricity market prices on the bidding price of low temperature excess heat is studied, considering four consecutive years: from 2017 to 2020

2. Method

2.1. Day-ahead market clearing model

In this study an advanced open source (Pfenninger et al., 2017) day-ahead market clearing model DARKO (Pavičević, 2020) is used for optimal matching of the demand bids and supply offers under the total welfare maximisation principle. In the previous research of the authors (Doračić et al., 2021), the model was already validated and the results showed that such a heat market would facilitate the addition of new heat generation capacities such as excess heat or solar thermal and would decrease the final cost for the demand-side. On a further note, the additional benefit of implementing the heat market through the DARKO model was shown in the form of a positive total welfare for all the scenarios. This model features various market order types on demand and supply side under complex set of rules. E.g., heat market participants are allowed to place two different kinds of orders: complex (block and flexible orders) and simple orders. Furthermore, the market operator can optimally allocate the available storage capacities for additional increase of the social welfare through presence of storage orders and accompanying operational constraints. Topological features of the model are presented in Fig. 1. Bidding areas are linked by interconnections (lines) each representing a given topology. Energy between neighbouring areas can only flow through these lines. Lines are oriented from source to sink bidding areas (i.e. A->B, B->C etc.). A positive value indicates a flow from A->B whereas a negative value indicates a flow from B->A (the numbers in brackets of Fig. 1 represent examples of energy flows in MWh, to make it clearer for the reader). Lines are limited by the available transfer capacity (ATC), and other restrictions such as losses, tariffs, and flow variation between two consecutive hours or optimisation horizons (i.e. hourly/daily flow ramping rates). The ATC, mimicking energy flows between different zones; net positions, the upper and lower bounds on the market clearing fluctuations between consecutive time intervals; and zonal ramping rates, the increase or reduction in zonal output per minute, are limited on both hourly and daily basis. Moreover,

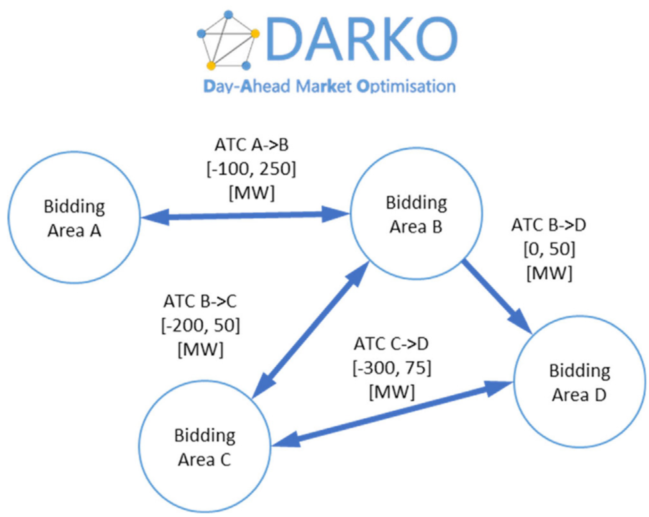

Fig. 1. ATC topology of the DARKO model.

the energy transactions between supply and demand orders from different bidding zones are encouraged and limited only by the network constraints (electricity, heat, gas etc.).

Formation of the intra zonal and intra temporal price equilibrium is presented in Fig. 2. Intra zonal price equilibrium can only be achieved if the ATC is sufficiently high to transfer excess production from a "cheaper" bidding area to the "more expensive" bidding area. Intra temporal price equilibrium can only be guaranteed if storage capacities inside the zones and ATC capacities between neighbouring zones are high enough to allow for price and energy shifts between them (i.e. if bidding zone A has an excess production of e.g. 100 MWh at the price of 10 €/MWh at time interval t = i after markets A and B are coupled and local storage is sufficient to store this excess "cheap" energy, this energy can be dispatched later on in time interval t = i+n at the price of 10€/MWh when the market clearing price is higher and energy required to achieve market coupling is equal to or lower than 100 MWh.).

For simplicity reasons, only the objective function and power balance constraints relevant for this study are assessed in the upcoming chapters. A more detailed explanation of the model and all the modelling constraints is presented in Doračić et al. (2021), Sebestyén et al. (2020) and Pavičević (2020).

2.1.1. Objective function

It is necessary to solve a Social Welfare Maximization Problem (SWMP) in order to obtain the market clearing price (MCP) in the wholesale day-ahead heat market. This must be done under the certain set of operational and storage related constraints which have to be followed at each time period in the optimisation horizon. As of today, energy markets which include storage orders do not exist. However, these can be fully exploited by the district heating sector, since the flows of energy, i.e. heat, between the production and consumption side are not instant due to the occurrence of thermal inertia in the distribution network. The objective function of the DARKO model is formulated as the Mixed Integer Linear Programming (MILP) problem with the aim of maximising the total social welfare w_{tot}, under the set of different primal decision variables: $V = \left\{x_{do}^i, x_{so}^i, f_l^i, p_n^t, p_n^{\prime t}, Q\_in_s^i, Q\_out_s^i, s\_lev_s^i, s\_spill_s^i, s\_ll_s\right\}$:

$$\max w_{tot} = c^{do} - c^{so} \qquad v \in V \tag{1}$$

Two functions comprise the total social welfare: First is the overall cost function of hourly demand orders:

$$c^{do} = \sum_{d \in D} \sum_{o \in O} \sum_{i \in I} \left(P_{do}^i Q_{do}^i x_{do}^i\right) \tag{2}$$

where, P_{do}^i, Q_{do}^i represent price quantity pairs of various demand orders in the trading period *i*. These are expressed in €/MWh and MWh, respectively. Furthermore, x_{do}^i represents the demand orders acceptance ratio in trading period i (%). Second function is the overall cost function of simple hourly orders:

$$c^{so} = \sum_{s \in S} \sum_{o \in O} \sum_{i \in I} \left(P_{so}^i Q_{so}^i x_{so}^i\right) \tag{3}$$

where, P_{so}^i, Q_{so}^i represent price quantity pairs of various simple orders in the trading period *i*. These are expressed in €/MWh and MWh, respectively. Furthermore, x_{so}^i represents the simple orders acceptance ratio in trading period i (%). Here it has to be noted that the demand quantities are always presented as negative values and the supply quantities as positive values, due to SWMP. Despite the fact that multiple types of orders can be calculated with the DARKO model (i.e. simple, block, flexible orders), the analysed heat market producers have no requirements for block production and therefore are bidding as simple order units on the heat market. Simple orders are the most flexible type of orders since their acceptance ratio (i.e., quantity supplied to the market) can have any value between 0 and maximum quantity being offered.

2.1.2. Power balance constraints

In this study, three power balance constraints are applied for different nodes, i.e. zones. Local production is calculated through the net position of the bidding zone n in the trade period *i*. Optimal decisions on thermal storage charging, if such a storage is available, are also made by considering this constraint. Heat is therefore stored in thermal storage in order to be used when more beneficial market situation is achieved. The variables in square brackets present the dual values, i.e. Lagrange multipliers, which are used to derivate the market clearing prices (MCP), which define the price at which the market is cleared, i.e., where the supply cost and demand cost curves cross.

$$p_n^i = \sum_{d \in D_n} \sum_{o \in O} \left(Q_{do}^i x_{do}^i\right) + \sum_{st \in ST_n} \left(Q_{in\,st}^{\;i}\right) - \sum_{s \in S_n} \sum_{o \in O} \left(Q_{so}^i x_{so}^i\right) - \sum_{st \in ST_n} \left(Q_{out\,st}^{\;i}\right) \quad \forall n \in N, i \in I \quad [\pi_{1\,n}^{\;i}] \tag{4}$$

To consider the energy flows between the adjoining zones, the temporary difference is calculated through the temporary net position of the bidding zone *n* in the trade period *i*. When there is a high enough interconnection capacity between two zones, it is expected that the MCP in these zones will be equal. This means the cheaper zone supply bids would satisfy the more expensive zone demand in case of a high enough interconnection capacities and surplus heat production capacities between the two zones. This can be presented by the following equations:

$$p_n^{\prime i} = -\sum_{l \in L_n} \left(f_l^i\right) \quad \forall n \in N, i \in I \quad [\pi_{2\,n}^{\;i}] \tag{5}$$

$$p_n^i - p_n^{\prime i} = -\sum_{l \in L_n} \left(f_l^i\right) \quad \forall n \in N, i \in I \quad [\pi_{3\,n}^{\;i}]$$

Finally, it needs to be mentioned that the temporary net position of two zones which are not connected equals to zero.

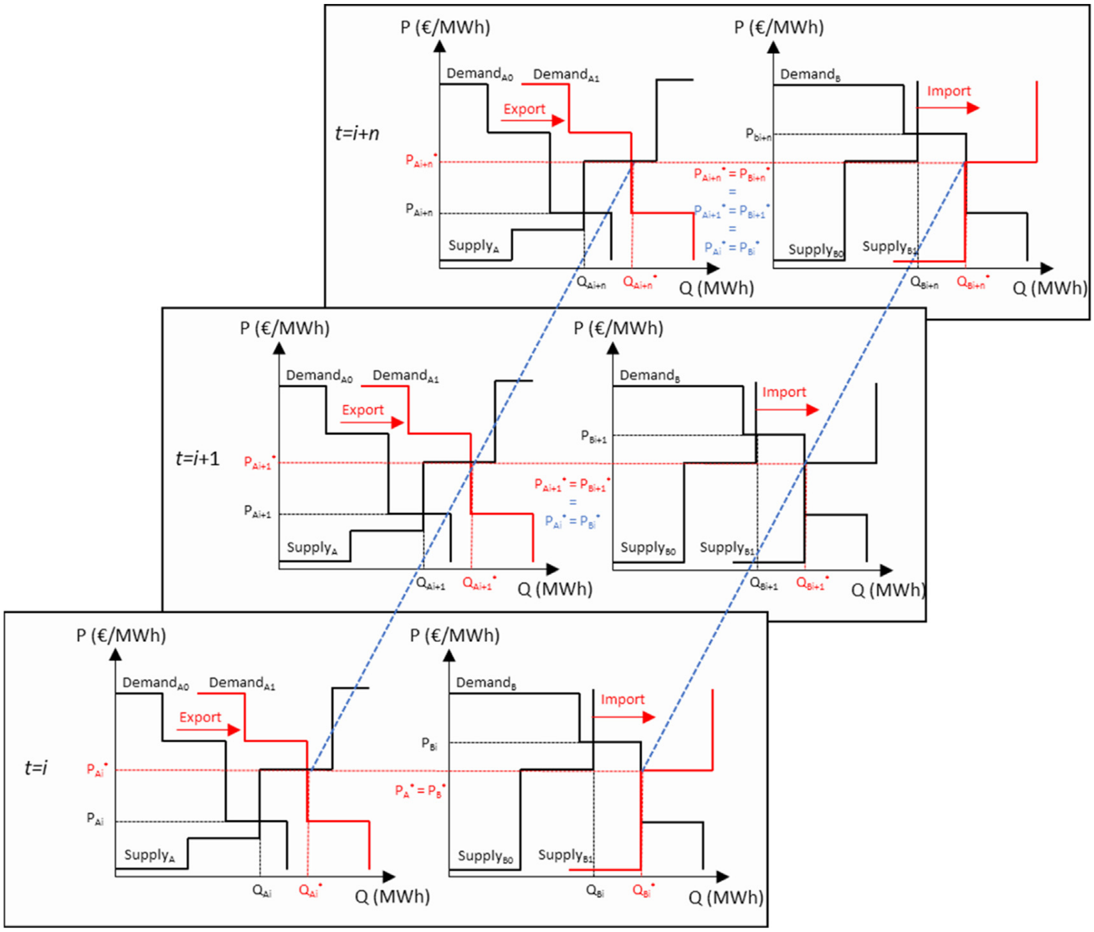

Fig. 2. Intra-zonal and intra-temporal price equilibrium formation in DARKO model. Red lines indicate shifts in the demand and supply orders due to available interconnections and blue lines indicate intra temporal price equilibrium due to storage. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.2. Biding price formation

As mentioned earlier, two biding strategies will be analysed in this paper: total cost biding and marginal cost biding. In a case of a day-ahead power market, the majority of papers and simulations use marginal cost biding, for example Ma et al. (2020), Nitsch et al. (2021) and Banaei et al. (2021). However, it must be noted that the real bids on the market are not necessarily formed by using marginal costs, as debated in Van Bracht et al. (2017). They conclude that strategic biding is observed on the real power markets and therefore analyse different biding strategies, including total cost biding, marginal cost biding, next cluster biding and oligopoly biding as the means of ensuring the feasibility of the producers. Heating sector especially has its specifics which affect the possible biding strategies, as well as the profitability of the producers on such a heat market. Overall, it can be argued that heat market participants have limited additional income stream opportunities due to the lack of reserve markets where these producers could offer ancillary services, as opposed to the electricity market. Additionally, district heating are typically isolated, local systems which supply heat to separate cities or neighbourhoods, hence there are no opportunities for heat exchange between different regions and/or countries. Due to these reasons, total cost biding was used as a biding strategy in the previous work of authors (Doračić et al., 2021), but it is still necessary to compare it to marginal cost biding in terms of economic and energy parameters.

2.2.1. Total cost bidding

Total cost bids are calculated by considering all the costs associated to the individual technology, including the discounted investment, variable and fixed operation and maintenance costs and the costs for fuel. The equation is provided below.

$$c_{total\ cost} = \frac{I \cdot d}{8760 \cdot \left(1 - (1+d)^{-N}\right)} + \frac{O_{fixed}}{8760} + O_{variable} + c_{fuel} \qquad (6)$$

In the above equation, I are the investment costs in €/MW, d is the discount rate in %, N is the technology lifetime in years, O_{fixed} are fixed operation and maintenance costs in €/MW, $O_{variable}$ are variable operation and maintenance costs in €/MWh and c_{fuel} are fuel costs expressed per unit of heat in €/MWh. By taking into account all the discounted costs during the technology lifetime, total cost bidding contributes to the maximum feasibility of the producers participating on the heat market. On the other hand, this bidding strategy results in highest costs for the heat buyers, due to higher achieved market clearing prices on the market. Since the capacity factor of each production unit is not known at this stage, total costs are calculated by assuming the maximum production from all producers. As can be seen in the above equation, all the investment costs are discounted by taking into account the discount rate and the lifetime of each technology. The discount rate for all the technologies was assumed at 8% (Liu et al., 2019)

2.2.2. Marginal cost bidding

On the other hand, marginal cost bids are calculated by considering only the variable costs required to produce an additional unit of heat. The equation is provided below.

$$c_{marginal\ cost} = O_{variable} + c_{fuel} \quad (7)$$

It must be noted that the fuel costs represent the electricity costs in the case of low temperature excess heat sources, due to the need for a heat pump. However, these costs must be expressed per unit of heat, by taking into account the coefficient of performance of the heat pump, as explained in the previous work of authors (Doračić et al., 2020b). When compared to total cost bidding, marginal cost bidding results in lower feasibility of the producers but also lower costs for the heat buyers. However, this depends on the specific technology and has a higher effect on the low fuel cost technologies. In case of high fuel costs, the difference between total cost and marginal cost bids is significantly lower, as will be seen in the results section. Economic data for calculating the bids is provided in Table 1, while the resulting bids are shown in Section 3.

2.3. Numerical example

The numerical example has been used to analyse different biding strategies and their effect on the operation of the system in general and specifically low temperature excess heat sources. It is based on the existing district heating system in Sisak, which is located in central Croatia, and several assumptions related to the planned short-term expansion of the network, including the connection of new renewable powered supply technologies. This particular system configuration has been selected for the analysis due to several reasons: it was already used by the authors for previous analyses and therefore provides a good reference point and it uses the historical data. Hence, more details about previous work can be found in Doračić et al. (2021), The main technical information is provided in the following bullet points:

- The production units considered in the analysis consist of the existing biomass cogeneration (CHP_BIO) and natural gas boilers (HOBO_GAS), as well as the industrial excess heat (EH_IND), hospital excess heat (EH_HOSP), supermarket excess heat (EH_SMARK) and solar thermal (SOLAR). Apart from CHP_BIO and HOBO_GAS, no units currently exist and their capacities are assumed based on their theoretical potential (Doračić et al., 2021). Solar thermal and excess heat are enabled to store in the dedicated thermal storage units
- Existing heat demand can be divided to demand for industry and demand for household, amounting to 28 GWh and 70 GWh respectively
- In order to consider different heat transfer mediums and corresponding temperature levels, as well as the locations of production units and demands, these have been allocated to 3 different zones in the simulated heat market. In Z1, the heat transfer medium is steam, which is used to cover the industrial demand and only HOBO_GAS_1 and CHP_BIO can place bids there. On the other hand, in Z2 and Z3 the heat transfer medium is hot water used to cover the demand of households in these zones and all the available units can place bids there. Z2 represents the current district heating system of Sisak (excluding industrial demand), while Z3 represents the planned extension of the system (Vidak et al., 2015) and consists of household heat demand and HOBO_GAS_3

The economic and technical data of the supply units participating on the heat market in the elaborated numerical example are shown in Table 1. For all the units, a discount rate of 8% was used. Additional costs occur for CHP_BIO and HOBO_GAS in terms of fuel costs for biomass and natural gas. These were assumed at 15 €/MWh and 30 €/MWh, respectively. Additionally, when calculating total cost bids for CHP_BIO, the revenue from the sold electricity was taken into account, which is being sold at the fixed feed in tariff price. Furthermore, it has to be pointed out that for EH_IND, it was assumed that its temperature is sufficient to be utilised directly through the heat exchanger, while EH_HOSP and EH_SMARK represent the low temperature excess heat sources, assumed at 50 °C and 80 °C respectively. Therefore, these sources require the use of the heat pump to boost their temperature to the district heating supply level, which has been assumed at 85 °C. This means that the supplementary cost of electricity for the electric heat pumps needs to be included when calculating marginal and total costs of the low temperature excess heat (Doračić et al., 2020b). It must be pointed out that it was assumed that all the production units, including the high and low temperature excess heat supply their heat to the supply line. Supplying low temperature excess heat to the return line was not the focus of this paper.

3. Results and discussion

3.1. Merit order

When marginal cost and total cost bids have been calculated for each of the technologies participating on the heat market in the previously described numerical example, they have been compared to each other on the yearly level graphically, as shown in Figs. 3 and 4.

When total cost bidding is used, the technology with the lowest bids is solar thermal, followed closely by the high temperature industrial excess heat. These bids are assumed not to change during the year since all of their cost components are constant and do not contain any external variables. This is also assumed for the next technology in the merit order, the biomass cogeneration, whose fuel price is defined by multi annual contracts and therefore does not change during the year. However, in some hours of the year excess heat from the supermarket has a lower bidding price than the biomass cogeneration. Nevertheless, these bids differ on an hourly level due to different market prices on the electricity market which is needed for powering the heat pump and in most hours, it is a more expensive technology when compared to biomass cogeneration. Since even lower temperature of hospital excess heat is presumed, it always comes after the higher temperature supermarket excess heat in the merit order and its bids are even higher than the ones for HOBO_GAS in many hours during the year. This is the reason for a low capacity factor of low temperature excess heat in such a market, as already shown in Doračić et al. (2021). Additionally, it is necessary to further discuss the constant bidding prices of CHP_BIO throughout the year. Since bidding prices of low temperature excess heat sources vary from hour to hour, it could be expected that the cogeneration unit, whose bidding price is also affected by the sold electricity, would show the same variations. However, the reason why this is not the case in this example is that this particular power plant receives a feed in tariff for the produced electricity (as a renewable, biomass power plant) and therefore does not sell its electricity on the power market. In case it was selling its electricity on the power market, its bidding prices on the heat market would also be variable. However, this was not analysed in this manuscript and such configurations will be tackled in the future research of the authors.

On the other hand, when marginal cost bidding strategy is utilised, the situation changes as presented in Fig. 4. The proposed two bidding strategies have the lowest effect on HOBO_GAS, a technology with relatively low fixed and large variable costs (costs related to natural gas). Therefore, changing the strategy

Table 1
Economic and technical data of the heat production units in the numerical example.

Unit	Capacity	Investment	Fixed O&M	Variable O&M	Lifetime	Reference
CHP_BIO	12 MW	1,450,000 €/MW	71,250 €/MW	2.3 €/MWh	14 years	Energinet (2020) and Bogdan (2017)
HOBO_GAS_1	52 MW	60,000 €/MW	2000 €/MW	1.1 €/MWh	20 years	Energinet (2020)
HOBO_GAS_3	11 MW	60,000 €/MW	2000 €/MW	1.1 €/MWh	20 years	Energinet (2020)
EH_IND	3.7 MW	540,000 €/MW	2% invest	1.24 €/MWh	20 years	Hackl and Harvey (2013)
EH_HOSP	0.05 MW	1,240,000 €/MW	2000 €/MW	2.7 €/MWh	25 years	Energinet (2020)
EH_SMARK	0.4 MW	1,240,000 €/MW	2000 €/MW	2.7 €/MWh	25 years	Energinet (2020)
SOLAR	14,390 MWh	489 €/MWh	0.09 €/MWh	0.2 €/MWh	30 years	Energinet (2020)

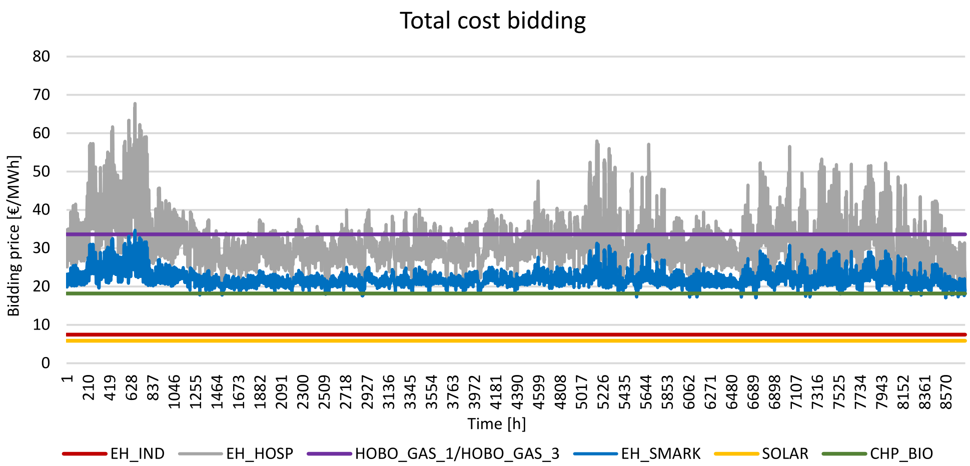

Fig. 3. Bidding prices of different heat production technologies when using total cost bidding.

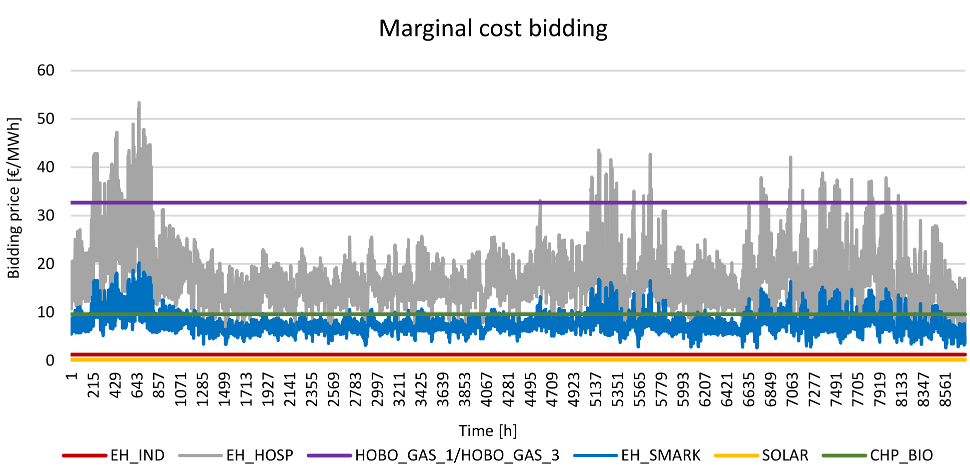

Fig. 4. Bidding prices of different heat production technologies when using marginal cost bidding.

from marginal cost bidding to total cost bidding results in only a 3% decrease of HOBO_GAS bidding price which is why it remains the most expensive technology in most hours throughout the year. However, the technologies with variable bidding prices, i.e. low temperature excess heat sources, decrease their bidding prices significantly when marginal cost bidding is used. This means that their merit order is significantly different and changes from the most expensive to a more affordable. While EH_SMARK had mostly higher bidding prices than CHP_BIO when total cost bidding was used, now it has lower bidding prices for the majority of time.

The same can be noticed for EH_HOSP, which now has mostly lower prices than HOBO_GAS and in some cases even lower than CHP_BIO. It is expected that this will increase the utilisation rate of the low temperature excess heat by quite some margin, which will be discussed in the next subsection. Furthermore, it can be noticed that use of different bidding strategies did not affect the merit order of already cheap solar thermal and industrial excess heat. These remain the production technologies with the lowest bids on the market. Also, when only the technologies with constant bids throughout the year are compared (SOLAR, EH_IND, CHP_BIO and HOBO_GAS), the merit order does not change in general. However, HOBO_GAS and CHP_BIO are affected by the variable cost technologies, as mentioned in the previous paragraph. As was already mentioned, HOBO_GAS was least affected by the two bidding strategies. However, other technologies were affected to a much higher extent. For example, the ones with no fuel, or other intensive variable costs like solar thermal and industrial excess heat decreased their bidding prices by more than 80% in marginal cost bidding. The others, however, had a much lower decrease due to the existence of rather high fuel costs in case of HOBO_GAS and CHP_BIO, or electricity costs in case of EH_SMARK and EH_HOSP.

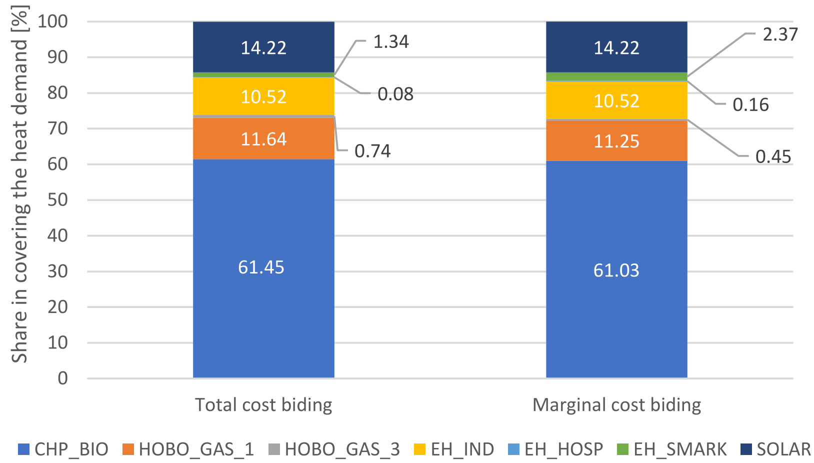

Fig. 5. Cleared production technology bids for two biding strategies, presented as the share in supplying the overall heat demand.

Table 2
Capacity factor of low temperature excess heat source in [%] when different biding strategies are applied.

	EH_SMARK	EH_HOSP
Total cost biding	37.70	17.80
Marginal cost biding	66.84	36.19

3.2. Heat market simulation results

In the next step of the analysis, two scenarios have been analysed, as previously elaborated: total cost biding scenario and marginal cost biding scenario. In this subsection, several indicators have been calculated and presented in order to compare these two biding strategies from different perspectives. First, the heat production analysis is shown in Fig. 5. This figure shows the cleared bids when total cost biding and marginal cost biding are used, presented as the share in supplying the overall heat demand. Immediately it can be seen that the number of cleared bids for SOLAR and EH_IND remains the same in both cases, since these two technologies remain the ones with the lowest costs, hence the lowest bids. Both are utilised to the maximum of their potential.

Changes can be noticed in terms of cleared bids of other production technologies, however in terms of covering the overall heat demand they seem rather small. This is because the theoretical potential of EH_HOSP and EH_SMARK is rather low compared to the overall heat demand. Nonetheless, it can still be noticed that the cleared bids from EH_HOSP practically double when marginal cost biding is used, while cleared bids for EH_SMARK also increase substantially. This results in the lower production from CHP_BIO, which is a base unit and therefore is not impacted by this change to a large extent. Finally, it can be argued that the biggest effect of different biding strategies in terms of heat production is on the low temperature excess heat. Therefore, Table 2 presents the comparison of these two strategies in terms of the capacity factor of low temperature excess heat.

From this, it can be seen that using marginal cost biding enables a much higher utilisation of the low temperature excess heat, due to their bidding prices going being below the prices of CHP_BIO, i.e. the merit order changes as already discussed. However, the overall capacity factor of these two low temperature sources is still not very high, due to the rather high variable costs, i.e. electricity costs necessary for the heat pump operation. Hence, the economic feasibility of low temperature excess heat for these two biding strategies will be analysed in more detail in the next subsection. The overall conclusion in terms of heat production analysis is that different biding strategies affect the number of cleared bids from different production technologies, however this effect is rather limited to the technologies with variable marginal costs. In the analysed numerical example, due to the rather low available amount of low temperature excess heat, this effect is not significant when overall heat production is considered.

In terms of economic analysis, the achieved hourly MCPs are presented by a box and whiskers diagram in Fig. 6. It is a graphical representation of aggregating hourly data on an annual level. The maximum and minimum values throughout a year are presented by the whiskers, the mean value is presented by the x, while the median is presented by the medium line. The bottom and top line of the box represent the first and the third quartile, respectively.

It can be seen that in all the zones, the mean value of MCP reduces significantly when marginal cost biding is applied. In Z1, this reduction is slightly lower at 30.2%, while in Z2 and Z3 it amounts to 33.4%. The minimal MCP in Z2 and Z3 also decreased meaningly due to the rather low marginal price of the cheapest technology (in this case SOLAR) at 0.2 €/MWh. However, the maximal MCP remained similar in all the cases, due to the demand for a peak load natural gas boiler, whose bidding price does not change much when different biding strategies are applied, as discussed previously. The effect of different strategies is lower in Z1 due to the fact that solar thermal and excess heat are not permitted to bid in that zone. However, the changes are still evident due to the high production from CHP_BIO, whose marginal costs differ significantly when compared to its total costs. Overall, from the perspective of the producers, total cost biding results in fairly higher MCPs and consequently higher revenues. As previously argued and shown in Table 2, marginal cost biding enables higher utilisation of the low temperature excess heat sources. However, Fig. 6 shows that alongside increased utilisation, the prices which can be achieved at the market are proportionally reduced, which brings in question the increased low temperature excess heat feasibility due to the use of marginal cost biding.

From the consumer side, the effect of different biding strategies can easily be shown by calculating the overall demand side costs. The calculation is performed by multiplying the MCP in every hour with the corresponding cleared demand in that particular hour. By summing up all the hourly values, overall annual cost of the demand side is presented in Table 3.

Logically, the overall demand cost is lower when the marginal cost biding is used. The difference between the two biding strategies amounts to 370,608€, i.e. 15%. This difference is not significant, which leads to a conclusion that the effect of different biding strategies is stronger on the production side than the demand side. It has to be pointed out that the costs from Table 3

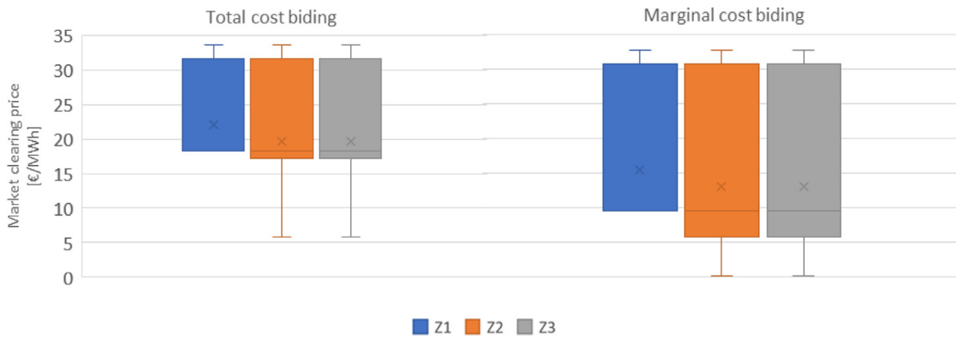

Fig. 6. Market clearing prices for different zones when total cost and marginal cost biding are applied.

Table 3
Overall cost in [€] for the demand side for different biding strategies in each zone.

	Total cost biding	Marginal cost biding
Z1 demand cost	626,356	471,064
Z2 demand cost	1,533,077	1,354,200
Z3 demand cost	312,293	275,855
Overall demand cost	2,471,727	2,101,119

present the costs at the supplier side, and not at the end user side since the end users cannot participate directly on the wholesale heat market. Therefore, marginal cost biding increases the benefit for the heat suppliers but the change of price for the end user depends on the business model of the supplier.

Finally, in terms of the overall social welfare, which is the objective function of the DARKO model used in this analysis, marginal cost bidding results in its increase by 29%. This happens due to the increased welfare at the demand side, but also due to the higher utilisation rate of the excess heat sources. Therefore, from the social welfare perspective, using marginal cost biding is a more optimal solution than using total cost biding.

3.3. Excess heat feasibility

In the previous subsections, it has been demonstrated that low temperature excess heat does not have a high utilisation rate when total cost biding is used, due to its high total cost and therefore unfavourable position on the merit order. It was already shown (Doračić et al., 2021) that this results in a significantly high levelized cost of excess heat (LCOEH), which cannot be matched by the achieved revenue of these sources on the market and which therefore results in their infeasibility. However, when marginal cost biding is used, the capacity factor of low temperature excess heat increases by almost double, which inevitably decreases LCOEH. Nevertheless, marginal cost biding also results in lower achieved prices on the market and therefore it is necessary to analyse the relation between LCOEH and achieved market price for the low temperature excess heat sources in order to see if the use of marginal cost biding might make these sources feasible on such a market.

LCOEH has already been defined as a criterion for feasibility calculation of excess heat (Doračić et al., 2018) and has been used in several studies for this purpose (Doračić et al., 2020b). It presents a minimum price that the excess heat needs to achieve on the market in order to be feasibly utilised. Therefore, if the average price that the excess heat source achieves on the market during the year is lower than the LCOEH, it is unfeasible to utilise this source. On the other hand, if the average price on the market is higher than LCOEH, it is feasible. LCOEH for excess heat sources using total cost and marginal cost biding is presented in Fig. 7. Since the utilisation rate of low temperature excess heat sources increased, LCOEH of both EH_SMARK and EH_HOSP decreased by 36.2% and 41.6% respectively. However, these figures are still rather high and it is impossible to achieve feasibility, especially when the lower MCP due to the marginal cost biding is taken into account. To prove this, the average achieved price on the market has also been calculated for the excess heat sources and plotted alongside LCOEH in Fig. 7. It has been calculated by multiplying the cleared bid in every hour by the MCP in that hour, summing up the values for the whole year and dividing by the overall production of each source. It can be seen that regardless of the biding strategy, the only source which achieves a higher price on the market than the LCOEH is high temperature industrial excess heat, while low temperature sources remain infeasible in both cases.

3.4. Electricity price variation

It was shown in the previous results that low temperature excess heat cannot be feasible when utilised in a wholesale heat market alongside other production technologies with lower production costs. Here it is important to point out that the presented numerical example has been focused on the 3rd generation district heating systems, which have higher supply temperatures and are still the prevalent generation of systems in many countries of Europe (Averfalk et al., 2017). The increased feasibility of low temperature excess heat with lower district heating supply temperatures was already shown in the previous research of authors (Doračić et al., 2020b) and will therefore not be the focus of this work.

The reason for the low utilisation rate and therefore low feasibility of low temperature excess heat in the presented numerical example is high variable costs of this source, which mostly consist of the cost for electricity for heat pumps. However, it has to be noted that the biding prices have been calculated by using the electricity prices from the Croatian Power Exchange (CROPEX) for 2017 (Croatian Power Exchange, 2021). More precisely, the hourly values of the day ahead prices on the CROPEX market were used for the whole year. Nevertheless, these prices can vary significantly on a year to year basis, due to several factors including the development of the power sector, meteorological conditions, economic situation, etc. For example, the average hourly electricity price on the CROPEX power market was 51.91€/MWh in 2017, 51.96€/MWh in 2018, 49.30 €/MWh in 2019 and 38.08 €/MWh in 2020 (Croatian Power Exchange, 2021). This shows a considerable reduction of average electricity market prices by 26.6% in 2020, compared to the reference year 2017. Therefore, an analysis of the biding prices for EH_SMARK and EH_HOSP has been performed with electricity prices from 4 consecutive years on the CROPEX day ahead power market, i.e. from 2017 to 2020. These are all publicly available at the CROPEX webpage. The results will be shown only for the marginal cost biding due to

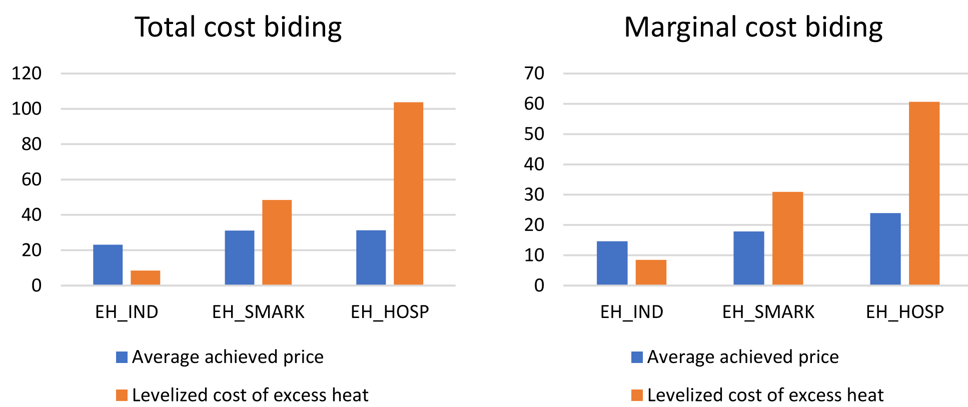

Fig. 7. Average achieved price and levelized cost of excess heat for two biding strategies.

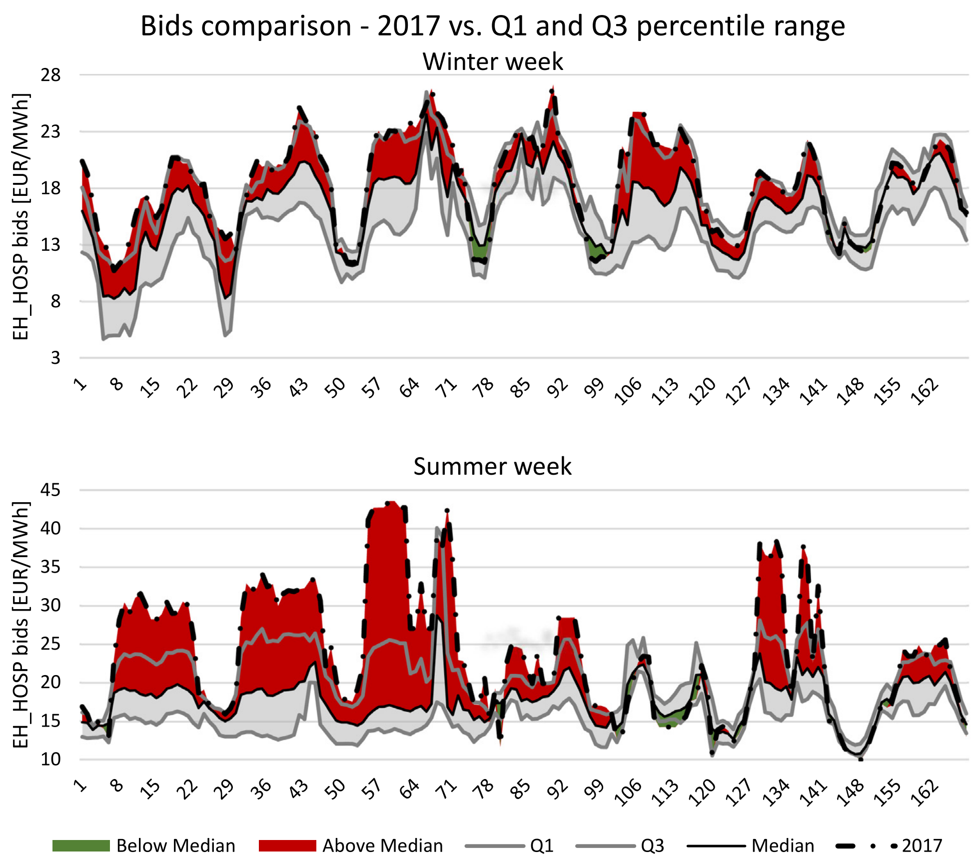

Fig. 8. Comparison of EH_HOSP bids for 2017 with the quartile and median values for the period 2017–2020, for a typical winter week (up) and a typical summer week (down).

higher total welfare values, as shown above. However, the same conclusions could also be applied to total cost biding since the bids would be reciprocally changed.

Fig. 8 compares the EH_HOSP bids for 2017 with the quartiles and median value of bids in the period 2017–2020. A typical winter week (1st January–7th January) and a typical summer week (1st August–7th August) have been visualised. It can easily be seen that the values for 2017 are much higher than the standard values in the analysed period, which shows a great effect of electricity prices in different years on the bids of low temperature excess heat. Throughout the majority of time, EH_HOSP bids in 2017 are higher than the median in the analysed period and are mostly in the 4th quartile (i.e. in the 25% of the most expensive bids). Since the qualitative effect of electricity prices on the EH_SMARK bids is the same as for EH_HOSP, it will not be presented graphically.

In order to make further analysis of the effect of different electricity prices on low temperature excess heat feasibility, market simulations with marginal cost biding have been performed and key performance indicators have been presented below. While the number of accepted bids of the other production units does not change, it does change for EH_SMARK and EH_HOSP, which consequently changes their capacity factor, as shown in Table 4. Here it must be noted that these changes affected only CHP_BIO, which changed its share of covering heat demand accordingly. However, due to a low available excess heat amount, this effect on CHP_BIO is rather insignificant, i.e. it ranges from 60.21% to 60% throughout the years.

Table 4
Capacity factor of low temperature excess heat sources in [%] for different years.

	EH_SMARK	EH_HOSP
2017	66.84	36.19
2018	64.33	38.66
2019	66.38	37.36
2020	69.42	43.71

It can be seen that decreased electricity prices, especially in 2020 lead to an increase of the capacity factor of EH_SMARK and EH_HOSP, but this increase is not significant, and it still remains too low for achieving a low enough LCOEH for these sources to be feasible. For example, in 2020 LCOEH of EH_SMARK reduced by 7.2% compared to 2017, while for EH_HOSP it reduced by 18.9%. Nevertheless, the average price these sources achieve on the market was also reduced and therefore they remained infeasible.

Despite this, it was proven that electricity prices affect the low temperature excess heat sources feasibility and that reduced prices on the electricity market could foster the feasibility and utilisation of this source. This is especially relevant from the perspective of the participation of renewable energy sources on the electricity markets since they have been shown to reduce the prices (Kolb et al., 2020). Therefore, increased utilisation of renewables could also foster the utilisation of low temperature excess heat, enabling a more efficient and sustainable heating sector.

4. Conclusions

This paper focused on the effect of different biding strategies on the low temperature excess heat feasibility, as well on the overall effect on the production and end user side. First of all, total cost biding and marginal cost biding have been compared in terms of their impact on the merit order in the analysed numerical example. While most production units kept the same position in the merit order in either of the biding strategies, low temperature excess heat sources were affected significantly, and they moved up in the merit order when marginal cost biding was used. This in turn changed the merit order of biomass cogeneration, which moved down in certain hours of the year. The highest effect of using different biding strategies was on the technologies with no fuel costs (solar thermal and high temperature industrial excess heat), while the others were affected to a much lower extent due to fuel costs in case of biomass cogeneration and natural gas boilers, or electricity costs in case of low temperature excess heat.

These two biding strategies were further compared by simulating the heat market operation on an annual level by using the DARKO model. It was shown that applying marginal cost biding results in a higher number of accepted bids from the low temperature excess heat, due to their improved position in the merit order. Therefore, the capacity factor of EH_SMARK increased from 37.7% in total cost biding to 66.8% in marginal cost biding, while the capacity factor of EH_HOSP increased from 17.8% to 36.2%. This mostly affected the production from CHP_BIO, which decreased from covering 61.5% of the demand to 61.03%. This decrease is not significant due to the low amount of available excess heat in the city. Furthermore, the MCP in all the analysed zones reduces by more than 30%, resulting in lower profits for the production side when marginal cost biding is applied. On the other hand, the benefits for the suppliers increase since the overall demand cost decreases by around 15%. However, it has to be pointed out that this cost decrease concerns only the suppliers and not the end users and therefore the effect on the end users would depend on the business model of the suppliers.

Since the focus of this paper was to see how different biding strategies affect low temperature excess heat feasibility, the average achieved price on the market for EH_HOSP and EH_SMARK was compared to the levelized cost of heat for both sources. It was shown that despite the increased capacity factor of these two sources when marginal cost biding is used, the lower prices on the market (due to lower MCPs) still lead to infeasibility of these low temperature sources on such a market configuration. This infeasibility is both due to low the excess heat source temperatures and therefore high electricity costs for boosting the temperature to district heating supply levels; as well as due to high temperatures of the analysed district heating system supply which presents the 3rd generation system (assumed supply temperature of 85 °C). Therefore, decreased district heating supply temperatures are still needed in order to increase the feasibility of low temperature excess heat. However, another option of increasing the feasibility of low temperature excess heat in the existing high temperature district heating systems would be by connecting these sources to the return line of the district heating network, which would remove the requirement of heat pump in cases of low temperatures of the return line. This way, the feasibility of the low temperature excess heat sources would correspond to the high temperature excess heat. This will be studied in further detail in the future research.

However, another parameter which effects the feasibility of low temperature excess heat is the electricity price, which varies on the power markets annually, depending on different conditions. For that reason, biding prices of low temperature excess heat were analysed by taking into account electricity prices from the Croatian Power Exchange in 4 consecutive years. Results have shown that electricity prices can have a strong effect on the increased utilisation and therefore increased feasibility of low temperature excess heat. This is especially important from the perspective of renewable energy sources which decrease the prices on the power market and could therefore also enable a more efficient and sustainable heating sector through fostering the utilisation of excess heat.

Nomenclature

Abbreviations		**Description**
ATC		Available transfer capacity
CHP_BIO		Biomass cogeneration
CROPEX		Croatian Power Exchange
DARKO		Day Ahead Market Optimisation
EH_HOSP		Excess heat from the hospital
EH_IND		Industrial excess heat
EH_SMARK		Excess heat from the supermarket
HOBO_GAS		Natural gas heat only boiler
LCOH		Levelized cost of heat
LCOEH		Levelized cost of excess heat
MCP		Market clearing price
O&M		Operation and maintenance costs
SOLAR		Solar thermal
SWMP		Social Welfare Maximisation Problem
Sets	**Units**	**Description**
i		Trading period
d		Demand
s		Simple

n		Node
l		Line
st		Storage
o		Order type
Variables	**Units**	**Description**
x_{so}^{i}	%	Acceptance ratio of simple orders in trading period i
x_{do}^{i}	%	Acceptance ratio of demand orders in trading period i
c^{do}	€	Total cost of demand orders
c^{so}	€	Total cost of simple orders
f_{l}^{i}	MWh	Flow in the interconnection lines in trading period i
p_{n}^{i}	MWh	Net position of bidding node n in trading period *i*
$p_{n}^{'i}$	MWh	Temporary net position of bidding node n in trading period i
$Q_{in_{st}}^{i}$	MW	Hourly storage charge rates
$Q_{out_{st}}^{i}$	MW	Hourly storage discharge rates
$S_{level_{st}}^{i}$	MWh	State of charge of the storage unit in trade period i
w_{tot}	€	Total welfare
$S_{spill_{st}}^{i}$	MWh	The amount of energy that is wasted or irreversibly thrown into the environment
Parameters	**Units**	**Description**
c_{fuel}	€/MWh	Fuel cost
$c_{totalcost}$	€/MWh	Total cost bid
$c_{marginalcost}$	€/MWh	Marginal cost bid
d	%	Discount rate
I	€/MW	Investment costs
N	years	Technology lifetime
O_{fixed}	€/MW	Fixed operation and maintenance costs
$O_{variable}$	€/MWh	Variable operation and maintenance costs
P_{do}^{i}	€/MWh	Price of demand orders in trading period i
Q_{do}^{i}	MWh	Quantity of demand orders in trading period i
P_{so}^{i}	€/MWh	Price of simple orders in trading period i
Q_{so}^{i}	MWh	Quantity of simple orders in trading period i

CRediT authorship contribution statement

Borna Doračić: Conceptualization, Methodology, Software, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Matija Pavičević:** Methodology, Software, Writing – original draft, Writing – review & editing. **Tomislav Pukšec:** Writing – review & editing, Supervision. **Neven Duić:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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