American Society of
Mechanical Engineers

ASME Accepted Manuscript Repository

Institutional Repository Cover Sheet

Primož

Poredoš

First

Last

ASME Paper Title: A thermo-economic and emissions analysis of different sanitary-water heating units

embedded within 4th-generation district-heating systems

Authors: Primož Poredoš, Boris Vidrih, Andrej Kitanovski, Alojz Poredoš

ASME Journal Title: Journal of Energy Resources Technology

Volume/Issue: 140(12)

Date of Publication (VOR* Online): July 23, 2018

<https://asmedigitalcollection.asme.org/energyresources/article-abstract/140/12/1220>

ASME Digital Collection URL: Thermo-Economic-and-Emissions-Analysis-of?redirectedFrom=fulltext

DOI: 10.1115/1.4040102

ASME ©; CC-BY distribution license

*VOR (version of record)

A thermo-economic and emissions analysis of different sanitary-water heating units embedded within 4th-generation district-heating systems

Primož Poredoš¹

Laboratory for refrigeration and district energy
University of Ljubljana, Faculty of mechanical engineering
Slovenia
E-mail: primoz.poredos@fs.uni-lj.si

Boris Vidrih

Laboratory for refrigeration and district energy
University of Ljubljana, Faculty of mechanical engineering
Slovenia
E-mail: boris.vidrih@fs.uni-lj.si

Andrej Kitanovski

Laboratory for refrigeration and district energy
University of Ljubljana, Faculty of mechanical engineering
Slovenia
E-mail: andrej.kitanovski@fs.uni-lj.si

Alojz Poredoš

Laboratory for refrigeration and district energy
University of Ljubljana, Faculty of mechanical engineering
Slovenia
E-mail: alojz.poredos@fs.uni-lj.si

ABSTRACT

This paper presents the results of a thermo-economic, primary-energy-factor and CO₂-equivalent (CO₂ (eq)), emissions-sensitivity analysis for the preparation of sanitary hot water (SHW) in 4th-generation district-heating systems. The annual required additional heat for the SHW provided by a local heating unit, based on an air-to-water heat pump, a natural-gas boiler and an electrical resistance heater, was determined using a TRNSYS simulation. Additionally, the seasonal performance factor of the heat pump under consideration was determined. The study considered three possible supply temperatures, i.e., 35, 40

¹ Primož Poredoš, University of Ljubljana, Faculty of mechanical engineering, Aškerčeva 6, 1000 Ljubljana, e-mail: primoz.poredos@fs.uni-lj.si.

and 45 °C. The results show that a local heating unit based on an air-to-water heat pump is the most efficient in terms of the used primary energy and CO₂ (eq) emissions. This unit is also the second best in terms of thermo-economic performance. The unit based on a natural-gas boiler is much more appropriate than an electrical resistance heater unit in terms of both the primary energy factor and the CO₂ (eq) emission factors for an electricity generation mix that has values higher than the average for the EU-28. The heat generated by this natural-gas unit is also cheaper than the heat produced by an electrical resistance heater based on the average price for electricity in the EU-28.

1. Introduction

District heating (DH) systems have been used all over the world for several decades because in conjunction with state-of-the-art combined heat and power (CHP) units it is possible to produce heat with a relatively low primary energy (PE) consumption and greenhouse-gas (GHG) emissions [1-3]. During this period DH systems have been divided into generations based on their size, efficiency, complexity and flexibility [4]. Currently, the 4th generation of district heating (4GDH) systems has just been put into service [5]. Each generation brings a reduction in supply temperatures, i.e., for the 4GDH the supply temperatures are 50–60 °C [6]. In comparison, the supply temperatures of the 1st generation DH systems, based on steam, were as high as 200 °C. Developments on going in DH systems could see even lower supply temperatures, with values as low as 35 °C being tested [7].

The main driver for lower flow temperatures is low-energy buildings. Lowering the supply temperatures has the following advantages: reduced heat losses through the pipes, utilization of waste-energy resources from industry, renewable energy, seasonal heat

storage and surplus wind-based electricity [8-11]. However, the supply temperatures in 4GDH systems are not suitable for the preparation of sanitary hot water (SHW), which represents a challenge, particularly to sustain suitable temperatures of a SHW distribution. A possible solution to the required temperature increase of the SHW could be to combine local heating units with the 4GDH system [12]. There is, however, an open question about which heating technology is the most appropriate in such cases [12-20].

One of the first studies in which an exergetic evaluation of different heat pump (HP) booster configurations in a low-temperature DH was performed was reported by Ommen, T. S. et al. [13]. They suggested two main configurations: in the first one a HP was implemented on the primary side of the SHW heat exchanger, while in the second configuration a HP was implemented on the secondary side. They reported that the first case is superior to second case in terms of exergetic efficiency (0.52 vs. 0.44, respectively, at a supply temperature of around 45 °C).

Another study in which, besides exergy efficiency, energy efficiency and annual heating costs were also compared for several different heating systems for the supplementary heating of SHW, was performed by Elmegaard, B. et al. [14]. Those systems were based on conventional district heating systems, systems based on an electrical resistance heater and three HPs applying R134a and R744 refrigerants. The system based on a HP with the R134a refrigerant and with hot-water storage installed was reported to be the best in terms of exergetic efficiency (25%) among the systems based on HPs and an electric resistance heater. The overall best system in terms of exergetic efficiency (28%) was found to be a conventional low-temperature system. The same system also had the

lowest annual costs for the heat production of sanitary hot water with €690 (compared to a system based on a HP for a 159 m² house with €740) and lowest CO₂ emissions with a 1.0 Mg/year (compared to the system based on a HP with 1.1 Mg/year).

Despite the high exergy efficiency of low-temperature district heating systems, there is a great disadvantage of such systems, since these temperatures are suitable for *Legionella* proliferation with SHW circulation. To mitigate this problem, Yang X. et al. [15] proposed different systems with decentralized substations that could mitigate the aforementioned problem. The authors suggested that replacing a bypass pipe with an in-line supply pipe and a HP could reduce the heat losses by up to 39% compared to the conventional system and by up to 12% compared to the conventional system with a bypass. In a later study, Yang X. et al. [16] performed an evaluation of five different SHW heating systems in conjunction with ultra-low-temperature district heating. In order to avoid the proliferation of *Legionella*, supplementary heating devices were installed in all the substations. To compare all the systems, an energy and economic assessment was performed. They found that substations with in-line electric heaters had the lowest electricity consumption for SHW preparation (1.4 and 1.9 DKK/kWh), while the substations with storage tanks and HPs with a coefficient of performance (COP) of 4.5, had higher electricity consumption and, consequently, higher costs for SHW preparation (4.4 DKK/kWh).

A study in which energy, economic and exergetic performance for several different heating substations for three different supply temperatures of DH at 35 °C, 50 °C and 65 °C was performed by Yang X. et al. [17]. The COP of the heat pump that was considered

in one example of a heating substation was 4.5. Similar to the previous study, they found that the substation with the in-line electric resistance heater performed better in the case of 50 and 65 °C supply temperatures, while in the case of the 35 °C supply temperature the best solution was reported to be based on an individual micro tank solution.

A feasibility study with a micro HP local heating unit (COP = 5.3) for SHW preparation in the case of a low-temperature DH system with a supply temperature of 40 °C was performed by Zvingilaite et al. [18]. Later, a similar study, but as a pilot experimental project, was performed by Brand, M. [19]. They investigated local heating units based on small HPs (also called micro boosters) with a COP of 4.5 in Birkerød (Copenhagen, Denmark). Each booster, with a 140 L tank, was installed in four houses built in the 1970s and used DH water as the source of heat. The increase in the temperature for the SHW was from 40 °C to 55 °C. This study revealed that the heat losses through the DH network in the case of low-temperature DH (40/25 °C) were reduced by 43%, compared to a conventional DH system (80/40 °C). Another interesting pilot project with local heating units based on an electrical resistance heater (ERH), also called an electrical booster, was performed in Odder (Denmark) [20]. The project involved five buildings, each having both floor and radiator heating. Each booster raised the temperature of the SHW from 37 °C to 45–60 °C. The heat losses through the DH network were reduced by 50% compared to a conventional DH system (80/40 °C). An interesting study in which the authors compared two types of SHW supply was performed by Østergaard P.A. et al. [12]. A DH system based on central HPs was compared to a DH system based on central HPs with an additional smaller booster HP. The main difference between the two systems was that the second

system had the potential to lower the supply and return temperatures of the DH system. All the simulations were performed using the energyPRO [21] simulation model. The results show significantly lower DH temperature levels for the case of the DH system with an additional smaller booster HP. This leads to a higher coefficient of performance (COP) for the central HPs as well as to reduced heat losses through the DH pipes. They also found that this solution is better than an individual boiler or HP. However, the investment costs were not considered in this particular study as the authors reported that the micro booster technology is still under development.

A review of the literature shows that the combination of a low-temperature DH system with local heating units that raise the temperature of the SHW has great potential. However, there are still some unresolved questions regarding the eligibility of a particular heating unit concerning thermo-economic (TE), primary energy factor (PEF) and CO₂ (eq) emission factor (CO₂ (eq) EF) analyses. The aim of this paper is to present the results of these analyses, in which several local heating units were compared. Those units, embedded in the 4GDH, are based on an ERH, an air-to-water heat pump (AWHP), and a natural-gas boiler (NG boiler). The main novelty of the presented paper is the PEF and CO₂ (eq) EF analyses of the proposed local heating units by considering the PEF and CO₂ (eq) EF for the electricity generation mix (EGM) and natural gas (NG) for the EU-28. Both factors were based on the GEMIS 4.95 model [22]. Furthermore, the particular study performed a thermo-economic (TE) analysis considering the electricity and NG prices, based on the EUROSTAT database [23] for the EU-28 in the period 2011–2015. All three analyses were performed as a sensitivity analysis, where the lowest, average and highest

values were considered. In the TE analysis the investment costs of the local heating units that are currently available on the market were also taken into consideration.

2. Methods

The presented study was conducted for a four-family-member residential dwelling. In order to perform the TE, PEF and EF analyses in the case of different local heating units the required additional heat for the SHW was determined. In the case of a local heating unit based on an air-to-water heat pump (AWHP) the SPF was also determined. The required additional heat for both the SHW and the SPF were determined using the simulation tool TRNSYS. The schematics of the local heating unit used in a simulation with TRNSYS and its connection to the SHW storage, the heat exchanger, the DH and the sanitary cold water (SCW) supply are shown in Fig. 1.

2.1. Simulation of the required additional heat for the SHW

The following considerations were used in the simulation of the required additional heat for the SHW:

- Analyzed period: 1 year (5-minute time step)
- Each local heating unit was producing water at 55 °C. Due to heat losses (5 °C) the SHW at the user temperature was set to 50 °C
- Supply temperature for the DH system was 35, 40 and 45 °C
- Supply temperature for the SCW in Ljubljana (N 46 3' 23'', E 14 30' 29'') varied, as shown in Fig. 2.

- The heat-exchanger effectiveness was set to 0.95
- According to ISO 13612 the daily SHW consumption of a household with a family for shower use is 126 l/day of 50 °C water.
- According to ISO 13612 we assumed two different patterns of SHW usage for the weekdays and weekends, as shown in Fig. 3
- An anti-legionella measure was also considered. It was implemented each week for 1 hour by superheating the SHW to 62 °C
- SHW storage is wrapped in heat insulation with a U value of 0.6 W/m²K and placed inside the dwelling.
- The SHW storage volume is 80 L and was chosen according to ISO 13612

2.2. Simulation of SPF for an AWHP

The following considerations were used in the simulation of the AWHP's SPF:

- The evaporator of the AWHP was considered to be positioned outside the dwelling
- The analyzed period was 1 year, with a 5-minute time step
- The SPF calculation, which is the ratio between the generated heat and the consumed electrical energy of the AWHP, was performed using the test reference year of Ljubljana [24]. An example of a simulation-based calculation of an AWHP's COP is shown in Fig. 4.
- Frost formation on the evaporator coils in the case of an AWHP and a de-frosting program was not considered

It is obvious that in the case of a water-to-water heat pump (WWHP) with an evaporator connected to the DH return, the SPF factor would be significantly higher. However, the micro booster WWHP technology is still under development, so the investment costs in the case of such a system are not known. There is also another option based on using the heat from the air inside the heating substation. However, various aspects influence the variation of the air temperature inside the heating substation, which is not a subject covered in this study. Based on this information we decided to use an AWHP that is currently available on the market with its evaporator placed outside the dwelling and with known investment costs. Additionally, we performed a simulation for two hypothetical cases in which we calculated the SPF factor of a WWHP that has an evaporator connected to the DH return and the SPF factor of an AWHP that has an evaporator inside the heating substation. All the parameters as well as the results of those hypothetical simulations are shown in Table 1. As expected, the SPF in both additional cases is significantly higher (WWHP SPF = 3.66 - 4.00 and AWHP SPF = 3.60) than the SPF of the AWHP, where the heat source is the external air (AWHP SPF = 3.28).

2.3. Important simulation results

The main output of the proposed simulation was the annual consumption of additional required heat for the SHW, which was determined to be 1330, 1075 and 821 kWh/a in the case of DH supply temperatures of 35, 40 and 45 °C, respectively. This amount of heat includes the heat for the anti-legionella superheating program as well as the SHW storage heat losses. In the case of the SPF of an AWHP simulation the annual SPF factor, which

was used in all subsequent analyses, was determined to be 3.28 for all three supply temperatures of the DH. The main reason for the SPF invariance with respect to the DH supply temperature is that the heat source and the heat sink of the AWHP were the same for all three DH supply temperatures. All the important simulation-based calculated values are presented in Table 2.

3. Thermo-economic assessment

The TE assessment, performed for three local heating units, based on a NG boiler, an AWHP and an ERH, considered the EU-28's electricity and NG prices for domestic consumers between 2011 and 2015. The prices for each individual EU country were found in the EUROSTAT database and include all taxes and levies. The TE calculation was based on the methodology that is thoroughly described in [25], but with the assumption that the additional annual electricity, cleaning and maintenance costs were not taken into consideration. The efficiency of the NG boiler was calculated according to the standard [26]. The main outputs of the TE calculation were the average final costs for heat production [€/kWh], the average annual final costs [€/a], and the relative share of final costs [/]. All the outputs also took into consideration the investment costs for all three local heating units that are currently available on the market. Therefore, the term final costs denotes the inclusion of the investment costs in the aforementioned outputs. The relative share of the final costs of the NG boiler and the ERH local heating units are calculated with respect to the AWHP. The main reason for that is the AWHP has the

highest investment costs and to check whether or not the AWHP is competitive with the two local heating units that have significantly lower investment costs.

One example of the TE calculation by considering the EU-28's average prices for electricity and NG for domestic consumers with all three local heating units in the case of 1330 kWh/a for the required additional heat is shown in Table 3.

The results for all the other examples of the TE assessment based on a fixed average gas price in the EU-28 of 0.0974 €/kWh are presented in Fig. 5. The calculation was performed for the average as well as the lowest and highest prices for electricity in the EU-28. Based on the data provided by EUROSTAT, the lowest price for electricity is in Bulgaria (0.0832 €/kWh in 2014), while the highest price is in Denmark (0.3068 €/kWh in 2015). The local heating unit based on a NG boiler has the highest relative share of final costs for all three units (1.32 and 1.16 for the case with 1330 and 1075 kWh/a), except for the case with 821 kWh/a of required additional heat (0.98) in the case of the lowest electricity price in the EU-28. For the EU-28's average electricity price the NG boiler becomes the most thermo-economically efficient local heating unit (with discrete values for the relative share of the final costs equal to 0.96, 0.87 and 0.77), while for the EU-28's highest electricity price the relative share of the final costs further decreases compared to the AWHP (0.76, 0.71 and 0.65). The ERH has the lowest share of final costs (0.94, 0.81 and 0.66) only in the case of the EU-28's lowest electricity price, while for the EU-28's average and highest electricity prices the relative share of the final costs rises rapidly (1.59, 1.42, 1.21 and 1.93, 1.76 and 1.54, respectively). The AWHP is the second-most thermo-economically efficient local

heating unit for all three typical electricity prices in the EU-28 as well as all three values of the required additional heat for the SHW.

The results of the TE analysis in the case of the fixed required additional heat for SHW at 1075 kWh/a and with the EU-28's lowest, average and highest electricity and NG prices for domestic consumers are presented in Fig. 6. Based on the data provided by EUROSTAT, the EU-28's lowest price for NG is in Romania (0.0272 €/kWh in 2012), while the EU-28's highest price is in Sweden (0.2070 €/kWh in 2012). The local heating unit based on a NG boiler is the most thermo-economically efficient when considering the EU-28's lowest (with discrete values for the relative share of the final costs equal to 0.44, 0.33 and 0.27) and the average NG price (relative share of the final costs equal to 0.87 and 0.71). There is one exception, at the point defined as the EU-28's lowest electricity price and average NG price (relative share of the final costs equal to 1.16). Compared to the AWHP, the NG boiler (with the relative share of final costs equal to 2.28, 1.72 and 1.40) is thermo-economically less efficient for the EU-28's highest NG price. The same conclusion goes for the ERH, since its relative shares of the final costs are 1.76 and 1.42. There is an exception for the EU-28's lowest electricity price, where the ERH becomes more thermo-economically efficient compared to the AWHP (with the ERH relative share of the final costs equal to 0.81).

The conclusions based on Figs. 5 and 6 are made on the basis of the huge range of electricity and NG prices in the EU-28. However, the ratios between the electricity and NG prices are country dependent. Hence, the TE analysis for a specific country must be carried out on the basis of local (country-dependent) electricity and NG prices. This is

proved for the case of the Slovenian market, where the electricity and NG prices including all taxes and levies are 0.115 and 0.088 €/kWh [27, 28], respectively. The ratio between the electricity and NG prices in Slovenia (ratio = 1.30) is much lower than the EU ratio, based on the average prices (ratio = 2.05). As a result, the AWHP in the case of required additional heat of 1330 kWh/a is the most thermo-economically efficient local heating unit compared to the NG boiler (relative share of final costs equal to 1.01) and ERH (with a share of 1.06) local units. With less required additional heat the AWHP becomes the least thermo-economically efficient. There is an interesting breakthrough of the ERH, since for 821 kWh/a of required additional heat this unit becomes the most thermo-economically efficient unit of the three (with a share of 0.786). It also surpasses the unit based on the NG boiler (with a share of 0.792). This breakthrough is the result of the low ratio for the electricity-to-NG price, as noted before.

4. Assessment of the primary energy factor

A comparison of the primary energy factor (PEF) for the required additional heat generation between all three local heating units was based on the PEFs of the two heat sources: electricity and NG. The methodology for the PEF assessment used in this study is described in [25]. One of the main reasons why the PEF assessment is valuable is the inclusion of the primary energy required for extraction, transport, conversion, distribution, transmission and control losses of the particular heat/energy source [29].

The PEFs of the electricity and NG for the specific EU country in 2010 were provided by the GEMIS model database version 4.95 [22]. The average PEF value of the EGM (PEF =

2.48) in the EU-28 was also based on the GEMIS model and was calculated using PEF values between 2010 and 2013. Regarding the PEF of the EGM for a specific EU country, the PEFs were determined for all 28 EU countries (including the UK). This also applies to the PEFs of NG, but the data from the following countries were missing: Cyprus, Finland and Malta. In addition, the PEFs for both electricity and NG in Croatia were based on data from 2005.

An example of a PEF calculation that considers the average PEF for the EGM and NG for all three local heating units in the case of 1330 kWh/a of required additional heat are shown in Table 4.

Considering the lowest, average and highest PEFs for the EGM and NG, the AWHP is the most efficient in terms of the consumed PE for the whole range of the PEF for the EGM, as shown in Fig. 8. In the case of the highest PEF, which comes from France (PEF = 3.59), the NG boiler unit has the lowest relative shares of consumed PE (1.24, 1.36, 1.55) in the case of the lowest (PEF = 1.22 in Estonia), average (PEF = 1.34) and highest (PEF = 1.53 in Romania) PEF for NG. The relative shares of the consumed PE rise to 1.79, 1.97 and 2.25 when considering the average PEF for the EGM. With the lowest PEF, which comes from Latvia (PEF = 1.54), the NG boiler unit is still the second-most efficient in terms of consumed PE, with its relative share of consumed PE equal to 2.89 and 3.17. The only exception is in the case of the highest PEF for NG, since this unit, with its relative share equal to 3.62, is outperformed by the ERH with a relative share of 3.28. This value is in fact the SPF factor for the AWHP.

5. CO₂ (eq) emissions assessment

Numerous initiatives on a global scale are striving to reduce greenhouse-gas (GHG) emissions, which could help reduce the rates of global warming. Energy use, which corresponds to about two-thirds of human activities producing GHGs, is responsible for about 90% of the CO₂ emissions [30]. Hence, besides the TE and PEF analyses, it is vital to assess the CO₂ (eq) emissions for all three local heating units. The CO₂ (eq) emission factor (CO₂ (eq) EF) for heat production was calculated from:

$$E_{hp} = \frac{E_{hs}}{\eta_b} \text{ and } E_{hp} = \frac{E_{hs}}{SPF} \quad (1)$$

where E_{hs} denotes the CO₂ (eq) emission factor for the heat source, η_b denotes the efficiency of the boiler and SPF denotes the simulation-based seasonal performance factor of the AHP. The annual emitted CO₂ (eq) was calculated from:

$$m_{CO_2 \text{ eq}} = E_{hp} \cdot Q_{SHW} \quad (2)$$

where Q_{SHW} denotes the annual required additional heat for SHW. The CO₂ (eq) EFs for the electricity and natural gas of the specific EU country for 2010 were provided by the GEMIS model database version 4.95 [22]. The average CO₂ (eq) EF value of the EGM (0.3538 kg CO₂ (eq)/kWh) in the EU-28 was also based on the GEMIS model for the period 2010–2013. Regarding the CO₂ (eq) EF of a specific EU country, the EFs were determined for all 28 EU countries (including the UK). This also applies to the EFs of natural gas, but the data from the following countries were missing: Cyprus, Finland and Malta. In addition, the EFs for both the electricity and NG in Croatia were based on data from 2005.

An example of the CO₂ (eq) emissions calculation by considering the average CO₂ (eq) EF for the EGM and NG of all three local heating units in the case of 1330 kWh/a of required additional heat are shown in Table 5.

The results of all the other examples for the lowest, average and highest values of the CO₂ (eq) EF for the EGM and NG are shown in Fig. 9. The AWHP unit is the most efficient in terms of CO₂ (eq) emissions across the whole range of EGM EFs, except for one case, as detailed below.

In the case of the heating unit based on the ERH the relative share of the emissions is 3.28 times greater than the AWHP across the whole range of EGM EFs. This unit is comparable to the unit based on a NG boiler, which has relative shares of emissions at 2.62, 2.94 and 3.30, just for the case of the average EGM EF.

When considering the lowest EGM EF (0.096 kg CO₂ (eq)/kWh in France), the unit based on the NG boiler produces 9.64, 10.82 and 12.15 times more emissions than the AWHP across the whole range of the EF for NG. This range is defined by the following values: lowest (0.254 kg CO₂ (eq)/kWh in Ireland), average (0.285 kg CO₂ (eq)/kWh) and highest (0.407 kg CO₂ (eq)/kWh in Romania).

If the EGM EF approaches the highest value, the NG boiler has a smaller relative share of emissions (0.93) than the AWHP, but just in the case of the lowest NG EF. In the other two cases the NG boiler unit has a higher share (1.04 and 1.17) than the AWHP.

6. Conclusions

This paper presents a TE, PEF and CO₂ (eq) EF analysis for sanitary hot water preparation in 4th-generation district-heating systems. As a result of many positive effects on energy and exergy efficiency in the case of ultra-low DH supply temperatures, DH systems with supply temperatures down to 35 °C are currently under test. However, such low temperatures are not suitable for SHW preparation. This issue could be solved by applying a local heating unit, which could raise the SHW temperature to suitable levels. Based on a review of the currently available literature, there are no existing studies that would employ the TE, PEF and CO₂ (eq) EF analyses for local heating units that are based on a NG boiler, AWHP and ERH. The main novelty of the presented paper is the PEF and CO₂ (eq) EF analyses for the proposed local heating units. The PEF and CO₂ (eq) EF for the EGM and NG were determined by the GEMIS 4.95 model. Furthermore, this study has taken into consideration the real investment costs for the local heating units that are currently available on the market. All three analyses were performed as a sensitivity analysis, where the lowest, average and highest values were considered.

Hence, in this study we prepared a TRNSYS simulation in which the annual required additional heat for SHW was determined for a four-member-family residential dwelling. With this tool the SPF of an AWHP-based local heating unit was determined. Besides the SPF, the main output of the proposed simulation was the required additional heat, with values of 1330, 1075 and 821 kWh/a for the case of a DH system with supply temperatures of 35, 40 and 45 °C, respectively.

The TE analysis revealed that for the average (0.1999 €/kWh) and highest values (0.3068 €/kWh) of the EU-28's electricity price a local heating unit based on a NG boiler is the

most thermo-economically efficient. Compared to the AWHP the NG boiler's relative shares of final costs were 0.77–0.96 and 0.65–0.76 times smaller for both considered prices. The unit based on the AWHP was the second-most thermo-economically efficient system for the EU-28's electricity price range. Except for the EU-28's lowest electricity price (0.0832 €/kWh) the unit based on the ERH was the most expensive of the three units in terms of the relative share of the final costs for the average (rel. share: 1.21–1.59) and highest (rel. share: 1.54–1.93) electricity price in the EU-28.

When considering the TE for a fixed required additional heat for SHW at 1075 kWh/a and with the lowest (0.0272 €/kWh), average (0.0974 €/kWh) and highest (0.0207 €/kWh) NG price in the EU-28, the AWHP was again the second-most thermo-economically efficient system across the whole range of electricity prices in the EU-28. In the case of the lowest NG price the relative share of the final costs for a unit based on a NG boiler was significantly smaller (0.27–0.44) than the AWHP unit.

The PEF analysis revealed that the unit based on the AWHP is the most efficient in terms of the consumed PE. The unit based on the ERH consumes 3.28 times more PE than the AWHP. The NG boiler in the case of the EU-28's lowest PEF for the EGM (PEF = 1.54) has a relative share of consumed PE (2.89–3.62) similar to the ERH unit. This share decreases to 1.24–1.55 in the case of the EU-28's highest PEF for the EGM (PEF = 3.59).

Considering the CO₂ equivalent emissions analysis the unit based on the AWHP is again the most efficient in terms of CO₂ (eq) emissions, except for the case of the EU-28's highest EGM emissions (1.000 kg CO₂ (eq)/kWh) and the EU-28's lowest NG emissions (0.254 kg CO₂ (eq)/kWh). In that case the unit based on the NG boiler has a 0.93 relative

share compared to the AWHP. The ERH unit would emit 3.28 times more emissions than the AWHP. This relative share is comparable to the share of a unit based on a NG boiler (2.62–3.30) in the case of the average EGM EF (0.354 kg of CO₂ (eq)/kWh). The NG boiler unit has the highest relative share (9.64–12.15), which is seen in the case of the lowest EGM EF (0.096 kg CO₂ (eq)/kWh).

The final highlights based on the presented results are:

- The local heating unit based on the AWHP is the most efficient in terms of the consumed PE and CO₂ (eq) emissions. Because of the relatively high investment costs, this unit is the second best in terms of thermo-economics across the whole range of the EU-28's prices for electricity. However, this study considered an AWHP where the evaporator is outside the dwelling. We also performed a hypothetical study in which the SPF of an AWHP and a WWHP unit were determined. In the case of both units, the evaporator was placed inside the heating stations and connected to the DH system's return. The calculated SPFs were in the range 3.60–4.00, which could, based on the AWHP, be even more attractive with respect to the TE.
- In some EU markets with the lowest electricity prices the units based on ERH possess a great threat to technologies that are significantly more suitable in terms of environmental aspects. We proved that in the case of the EU-28's lowest electricity price the ERH unit has a relative share of final costs equal to 0.66–0.94, compared to the AWHP. This was also proven for the case of the Slovenian market,

since the price ratio between electricity and NG (1.3) is much lower than the EU-28's average (2.05).

- The unit based on the NG boiler is significantly more appropriate than the ERH unit in the case of PEF and CO₂ (eq) EF for EGM values higher than the EU-28's average. From the TE point of view the NB boiler unit is also cheaper in the case of the average and the highest electricity prices in the EU-28.
- In EU markets with the lowest CO₂ (eq) EF for EGM the use of NG boiler units must be seriously considered, since compared to the AWHP a NG boiler would emit approximately 10 times more CO₂ (eq).

Nomenclature

E	emission factor, /
m	annual emitted CO ₂ (eq), kg CO ₂ (eq)
Q	annual required additional heat for sanitary hot water, kWh
SPF	seasonal performance factor, /

Greek letters

η	efficiency, /
--------	---------------

Subscripts or Superscripts

b	boiler
CO ₂ eq	CO ₂ (eq) emissions
hp	heat production
hs	heating system
SHW	sanitary hot water

Acronyms

4GDH	4 th -generation district heating
AWHP	air-to-water heat pump
COP	coefficient of performance
DH	district heating
EF	emission factor
EGM	electricity generation mix
ERH	electrical resistance heater
HP	heat pump

NG	natural gas
NGB	natural-gas boiler
PE	primary energy
PEF	primary-energy factor
SCW	sanitary cold water
SHW	sanitary hot water
SPF	seasonal performance factor
TE	thermo-economic
WWHP	water-to-water heat pump

References

- [1] Song, Zhi-Ping. 2008. "A Theoretical Study on Decentralized Space Heating System." *Journal of Energy Resources Technology* 130 (3):032401-032401-9. doi: 10.1115/1.2955479.
- [2] Herrmann, Stephan, Steffen Kahlert, Manuel Wuerth, and Hartmut Spliethoff. 2017. "Thermo-Economic Evaluation of Novel Flexible CAES/CCPP Concept." *Journal of Energy Resources Technology* 139 (1):011902-011902-10. doi: 10.1115/1.4035424.
- [3] Mollenhauer, Eike, Andreas Christidis, and George Tsatsaronis. 2017. "Increasing the Flexibility of Combined Heat and Power Plants With Heat Pumps and Thermal Energy Storage." *Journal of Energy Resources Technology* 140 (2):020907-020907-8. doi: 10.1115/1.4038461.
- [4] Levihn, Fabian. 2017. "CHP and heat pumps to balance renewable power production: Lessons from the district heating network in Stockholm." *Energy* 137:670-678. doi: <https://doi.org/10.1016/j.energy.2017.01.118>.
- [5] Lund, Henrik, Neven Duic, Poul Alberg Østergaard, and Brian Vad Mathiesen. 2016. "Smart energy systems and 4th generation district heating." *Energy* 110:1-4. doi: <https://doi.org/10.1016/j.energy.2016.07.105>.
- [6] Lund, Henrik, Sven Werner, Robin Wiltshire, Svend Svendsen, Jan Eric Thorsen, Frede Hvelplund, and Brian Vad Mathiesen. 2014. "4th Generation District Heating (4GDH): Integrating smart thermal grids into future sustainable energy systems." *Energy* 68:1-11. doi: <https://doi.org/10.1016/j.energy.2014.02.089>.

- [7] Gulev L. 2016. "District Heating – More Than 100 Years of History, but Still Rapidly Developing". Hot Cool, International Magazine on District Heating and Cooling 4:4.
- [8] Ozgener, Leyla, and Onder Ozgener. 2008. "Monitoring of Energetic and Exergetic Performance Analysis of Salihli Geothermal District Heating System." *Journal of Energy Resources Technology* 130 (2):022302-022302-7. doi: 10.1115/1.2932945.
- [9] Micheli, D., P. Pinamonti, M. Reini, and R. Taccani. 2013. "Performance Analysis and Working Fluid Optimization of a Cogenerative Organic Rankine Cycle Plant." *Journal of Energy Resources Technology* 135 (2):021601-021601-11. doi: 10.1115/1.4023098.
- [10] Stein-Brzozowska, Gosia, Christian Bergins, Allan Kukoski, Song Wu, Michalis Agraniotis, and Emmanouil Kakaras. 2016. "The Current Trends in Conventional Power Plant Technology on Two Continents From the Perspective of Engineering, Procurement, and Construction Contractor and Original Equipment Manufacturer." *Journal of Energy Resources Technology* 138 (4):044501-044501-12. doi: 10.1115/1.4032731.
- [11] Lund, Rasmus, and Soma Mohammadi. 2016. "Choice of insulation standard for pipe networks in 4th generation district heating systems." *Applied Thermal Engineering* 98:256-264. doi: <https://doi.org/10.1016/j.applthermaleng.2015.12.015>.
- [12] Østergaard, Poul Alberg, and Anders N. Andersen. 2016. "Booster heat pumps and central heat pumps in district heating." *Applied Energy* 184:1374-1388. doi: <https://doi.org/10.1016/j.apenergy.2016.02.144>.
- [13] Ommen, T. S. and Elmegaard, B., 2012, "Exergetic evaluation of heat pump booster configurations in a low temperature district heating network,". Proc. of ECOS 2012, Firenze University Press, In U. Desideri, G. Manfrida, & E. Sciubba (Eds.).

- [14] Elmegaard, Brian, Torben Schmidt Ommen, Michael Markussen, and Johnny Iversen. 2016. "Integration of space heating and hot water supply in low temperature district heating." *Energy and Buildings* 124:255-264. doi: <https://doi.org/10.1016/j.enbuild.2015.09.003>.
- [15] Yang, Xiaochen, Hongwei Li, and Svend Svendsen. 2016. "Decentralized substations for low-temperature district heating with no Legionella risk, and low return temperatures." *Energy* 110:65-74. doi: <https://doi.org/10.1016/j.energy.2015.12.073>.
- [16] Yang, Xiaochen, Hongwei Li, and Svend Svendsen. 2016. "Evaluations of different domestic hot water preparing methods with ultra-low-temperature district heating." *Energy* 109:248-259. doi: <https://doi.org/10.1016/j.energy.2016.04.109>.
- [17] Yang, Xiaochen, Hongwei Li, and Svend Svendsen. 2016. "Energy, economy and exergy evaluations of the solutions for supplying domestic hot water from low-temperature district heating in Denmark." *Energy Conversion and Management* 122:142-152. doi: <https://doi.org/10.1016/j.enconman.2016.05.057>.
- [18] Zvingilaite, E., Ommen, T., Elmegaard, B. and Franck, M.L., "Low temperature DH consumer unit with micro heat pump for DHW preparation," Available at: http://heating.danfoss.com/pcmpdf/vfi102_low-temp-dh-consumer-unit_130829.pdf, [accessed 10.2.2017].
- [19] Brand, M., "Experience with Micro Heat Pump Supplied by Ultra-Low-Temperature District Heating," Proc. Proceedings of the 18th International Conference on District Energy, SDDE 2015, 2015 March 22-24; Portorož, Slovenia.

- [20] Brand, M., "District Heating Substation with Electrical Booster Supplied by 40°C Warm District Heating Water,," Proceedings of the 19th International Conference on District Energy, SDDE 2016, 2016 March 20-22; Portorož, Slovenia.
- [21] energyPRO. Available at: <<http://www.emd.dk/energypro/>>, [accessed 10.2.2017]
- [22] GEMIS, version 4.95; Global Emission Model Integrated Systems, 2010. Available at: <<http://iinas.org/gemis.html>>, [accessed 10.2.2017]
- [23] Eurostat. Available at: <<http://ec.europa.eu/eurostat>>, [accessed 10.2.2017]
- [24] Test reference year. Available at: <http://meteo.arso.gov.si/met/en/climate/tables/test_ref_year/>, [accessed 10.2.2017]
- [25] Poredoš, Primož, Tjaša Čož, Andrej Kitanovski, and Alojz Poredoš. 2017. "Thermo-economic and primary-energy-factor assessment based on the field test of an air-to-water heat pump." *International Journal of Refrigeration* 76:19-28. doi: <https://doi.org/10.1016/j.ijrefrig.2017.02.003>.
- [26] DIN e. V., DIN V 18599-5:2007-02. Energy efficiency of buildings — Calculation of the energy needs, delivered energy and primary energy for heating, cooling, ventilation, domestic hot water and lighting — Part 5: Delivered energy for heating systems. February 2007
- [27] [EN20] Cene energije. Available at: <http://kazalci.arso.gov.si/?data=indicator&ind_id=719>, [accessed 10.2.2017]
- [28] Poročilo o stanju na področju energetike v Sloveniji v letu 2015. Available at: <[27](http://</p></div><div data-bbox=)

www.energetika-portal.si/fileadmin/dokumenti/publikacije/agen_e/porae_2015.pdf>,

[accessed 27.10.2016]

[29] Bonin, J., 2015, Heat Pump Planning Handbook, New York, NY: Routledge, Chap. 4.

ISBN: 9781317483311

[30] CO₂ emissions from fuel combustion. Available at:

<<https://www.iea.org/publications/>

[freepublications/publication/CO2EmissionsfromFuelCombustion_Highlights_2016.pdf](https://www.iea.org/publications/freepublications/publication/CO2EmissionsfromFuelCombustion_Highlights_2016.pdf)>,

[accessed 10.2.2017]

Figure Captions List

Fig. 1: Schematic of the local heating unit used in a simulation with TRNSYS. This unit additionally heats the sanitary water, previously heated by the DH supply in the heat exchanger.

Fig. 2: External air and SCW temperature variations over a 1-year period in Ljubljana

Fig. 3: Weekday and weekend patterns of SHW usage, denoted as SHW load ratio. Note: cumulative SHW usage load ratio per day = 1.

Fig. 4: Simulation-based calculation of an AWHP's COP for 1 year with a 5-minute time step.

Fig. 5: Relative share of final costs based on a fixed EU-28 average gas price for domestic consumers at 0.0974 €/kWh for three different values of required additional heat: 1330, 1075 and 821 kWh/a. The analysis considered the lowest, average and highest electricity prices in the EU-28 for domestic consumers. Note: The EU-28's electricity and natural-gas prices are based on EUROSTAT and include all taxes and levies.

Fig. 6: Relative share of the final costs based on the fixed required additional heat for SHW at 1075 kWh/a for the EU-28's lowest, average and highest natural-gas prices for domestic consumers, based on EUROSTAT: 0.0272, 0.0974 and 0.2070 €/kWh, respectively. The analysis considered the EU-28's lowest, average and highest electricity prices for domestic consumers. Note: The EU-28's electricity and natural-gas prices are based on EUROSTAT and include all taxes and levies.

Fig. 7: Relative share of the final costs for the case of the Slovenian market for three different values of the required additional heat: 1330, 1075 and 821 kWh/a. Note: Electricity and natural-gas prices include all taxes and levies.

Fig. 8: Relative share of used primary energy for the NG boiler and ERH compared to the AWP. The analysis considered the lowest, average and highest PEFs of the EGM and natural gas in the EU-28. All the PEFs were based on the GEMIS model, version 4.95.

Fig. 9: Relative share of CO₂ (eq) emissions for the NG boiler and ERH compared to the AWP. The analysis considered the lowest, average and highest CO₂ (eq) EFs of the EGM and natural gas in the EU-28. All the CO₂ (eq) EFs were based on the GEMIS model, version 4.95.

Table Caption List

Table 1: Simulation results of the SPF factor for two hypothetical cases of the WWHP and AWHP with the heat source from the DH return pipe and the air inside the heating substation, respectively

	WWHP			AWHP		
DH supply temperature [°C]	35	40	45	35	40	45
DH return temperature [°C]	25	30	35			
Temperature of the heat source - WWHP	20	25	30	/	/	/
Air temperature inside heating substation - AWHP [°C]	/	/	/	20	20	20
SPF [/]	3.66	3.83	4.00	3.60	3.60	3.60

Table 2: Important simulation-based values. The additional required heat and SPF are later included in the TE, PEF and EF analyses.

DH supply temperature [°C]	35	40	45
SHW usage [m ³ /a]	46,033	46,033	46,033
Required heat for SHW [kWh/a]	2,526	2,526	2,526
Heat supplied by DH [kWh/a]	1,196	1,451	1,705
Required additional heat [kWh/a]	1,330	1,075	821
Sanitary hot-water-storage heat losses [kWh/a]	196	196	196
Heat for anti-legionella superheating program [kWh/a]	34	32	30
SPF [/]	3.28	3.28	3.28

Table 3: An example of the TE calculation for all three proposed local heating units

Local heating unit	Cost of energy source [€/kWh]	Boiler efficiency [%]	SPF factor [/]	Investment costs (VAT included) [€]	Average final costs for heat production [€/kWh]	Average annual final costs [€/a]	Relative share of final costs [/]
NG boiler	0.0974	90	/	280	123	163	0.96
AWHP	0.1999	/	3.28	1,180	128	171	1.00
ERH	0.1999	/	/	70	204	271	1.59

Table 4: An example of the PEF calculation for all three proposed local heating units

Local heating unit	PEF of heat source [/]	Boiler efficiency [%]	SPF factor [/]	PEF for heat production [/]	Annual consumed PE [kWh/a]	Relative share of consumed PE [/]
NG boiler	1.34	90	/	1.49	1,980	1.97
AWHP	2.48	/	3.28	0.76	1,006	1.00
ERH	2.48	/	/	2.48	3,298	3.28

Table 5: An example of the CO₂ (eq) EF calculation for all three proposed local heating units

Local heating unit	CO ₂ (eq) EF of heat source [kg CO ₂ (eq)/kWh]	Boiler efficiency [%]	SPF factor [/]	CO ₂ (eq) F for heat production [kg CO ₂ (eq)/kWh]	Annual emitted CO ₂ (eq) [kg CO ₂ (eq)/a]	Relative share of CO ₂ (eq) emissions[.]
NG boiler	0.285	90	/	0.317	421	2.94
AWHP	0.354	/	3.28	0.108	143	1.00
ERH	0.354	/	/	0.354	470	3.28