UTILIZATION OF RES USING SEAWATER SOURCE HEAT PUMP WITH AND WITHOUT ENERGY STORAGE
Comparison of Thermal and Battery Energy Storage

by

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Heat and cooling stands out with the great potential in decarbonisation since they have a large share in the final energy consumption. Power-to-heat technologies may contribute to the heat sector decarbonisation as well as the integration of renewables if they are sufficiently flexible. They are also shown to have a good effect on the system costs. This work will analyse the potential of seawater heat pump system for the utilization of high share of electricity production from the renewables. The Old City of Dubrovnik is selected as a case study because of its specific situation. A large number of the outdoor units are not well approved by UNESCO since the Old City is under the protection of the UNESCO World Heritage Centre. The results of the study showed that the combination of wind and solar electricity production can cover 67% of load for stand-alone seawater heat pump system based on hourly time step. Utilization of renewable electricity generation, for this case, resulted in 433.71 tCO_2/y emission reduction. System based on 10 minutes time step gave poorer results by 6%. System with the additional energy storage gained best results in the case of combined wind and solar electricity generation, as well. It resulted in storage capacity reduction by 78% according to the case of solar electricity generation and by 60% according to the wind electricity generation. Battery energy storage resulted in 40 times lower volume and 13 times higher investment costs and levelised cost of heat in comparison to the thermal energy storage.

Keywords: *seawater source heat pump, renewable energy sources, thermal demand, thermal energy storage, battery energy storage*

Introduction

The European Union is aiming to develop a sustainable, competitive, secure and decarbonised energy system by 2050 according to the Directive 2012/27/EU [1]. The Energy Performance Building Directive [2] is focused in the building energy consumption as the most important sector where to act [3]. The EU 2030 objectives are the reduction of GHG emissions by at least 40%, increase in the use of RES by at least 32%, improvement of energy efficiency by at least 32.5% when compared with 1990, and to complete the internal energy

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market by reaching an electricity interconnection target of 15% between EU countries. The EU objectives by 2050 are to achieve an 80-95% reduction in GHG emissions when compared with 1990 levels. 2030 and 2050 scenarios focus on small or micro scale district heating (DH), electrification of the heating sector, primarily by using heat pump (HP) technology [4]. Heating and cooling demand within EU had a share of 49% in total final energy consumption in 2012, while RES provided 18% of the demand. The DH supply is still mostly based on fossil fuels, 90% in the world and 70% within EU. Replacing fossil fuels and increasing the combine heat and power (CHP) based DH system can decrease total primary energy consumption by 3.7% or 7.0% with DH market shares of 30% or 50%, respectively, as it has been shown in the case of EU [5]. The HP can provide a stable and efficient heat supply when integrated in DH systems, but their efficiency dependents on a heat source. Authors in [4] concluded that it is not possible to create a universal solution for all EU members of HP integration into DH and each EU country should be analysed individually. The HP have the potential to be a central part of the efficient, renewable and interconnected smart energy system when properly controlled using information and communication technologies [6].

The DH is currently moving towards implementation of the newest concept referred as 4th generation district heating (4GDH) which will be constructed during 2020-2050. The 4GDH systems might be used for stabilization of the electric power grid due to the increase of intermittent RES into the electric power systems, implementing integration of multiple energy systems [7]. Some of the recent researches have discussed HP technology as a key component of 4GDH systems. The HP enhance RES integration [8], affect the reduction of emissions [9] and draw benefit of low electric power prices during periods of high RES electricity production [5, 10]. Heat pump unit has shown to be financially preferred production unit than CHP unit [11]. Approximately 800000 electrically driven HP units have been sold in the EU per year during 2010-2015 period [6]. The HP is shown as better option both in terms of cost-efficiency and emission savings in comparison to the solar thermal collectors (TC) [5]. On the other hand, integration of HP into the solar DH system improves their energy efficiency, as shown in [12, 13], as well as results in a lifecycle cost reduction and primary energy savings [14]. Smart regulation of such systems can lead to an additional cost reduction, [15, 16] as well as reducing emissions [17].

The weather forecast, the self-consumption and the heat storage management also result in additional energy gain [18]. The volume of the thermal energy storage (TES) has a significant effect on the performance of the system [19], while the use of TES systems is crucial to reduce the need of fossils fuels in heating [12]. The HP is suggested as the best solution for lowering the DH temperature levels as well as primary energy consumption [20]. Analyses of different HP systems resulted in load mismatch during summer and winter months according to the grid interaction, as shown in [10, 21]. Load-shifting possibilities of HP in residential buildings, as well as its influencing and limiting factors, are displayed in study [22]. In [23] hourly analysis for the role of cool TES in the integration of RES and peak load reduction were studied on the level of building, while in [24] the role of different storage were analysed on level of city/state. Results of the study [25] showed that HP electricity consumption has a potential to follow wind power availability in hourly basis while TES might only offer little flexibility to the grid if controlled in an intelligent way.

Previous studies mostly analysed the potential of HP for the integration of solar and wind generation individually. Most of the studies are done for microgrid systems, like buildings, where seawater is poorly represented as HP source. This study gives some new approaches, according to the previous studies, dealing with RES electricity generation, short term step calculations, increase in system size and opportunities for the electric batteries. Study analyses the potential of seawater source heat pump (SWHP) system for utilization of solar and wind generation, individually and in the combination. It provides comparison of the SWHP systems, based on hourly and 10 minute time step, for the Old City of Dubrovnik, Croatia within the energy system of the Dubrovnik region. Energy storage opportunities are also analysed comparing thermal and battery energy storage (BES). As there are many similar protected old cites near coastline that need heating and cooling, especially in the Mediterranean, the study can provide guidelines for general application of SWHP in combination with solar, wind and energy storage.

Seawater source heat pump

Seawater source HP DH system is a renewable energy utilization system as it can utilize the sensible heat energy contained in the seawater. It is a good solution to cover heating and cooling demand of buildings in coastal areas. Seawater has very good characteristics as a heat source for the HP. It has less seasonal temperature variation and lower freezing temperature (about –2 °C) than river water, and also maintains 5-10 °C temperature difference from the atmosphere, which is ideal for heating and cooling [26]. The HP is used as chiller in the summer and seawater is used as heat sink, and in winter seawater is used as heat source. In comparison to the conventional system, SWHP system is generally higher in initial investment and lower in operation costs [27].

The use of air conditioning in the residential sector is increasing due to the average income growth and thermal comfort in dwellings. A great effort has been made, especially in Europe and China, to study and deploy technologies driven by RES [28-30]. North European countries, like Norway and Sweden, take a lead in the engineering application of the SWHP heating and cooling system, using seawater heat as a heat source for DH since 1982 [26, 31]. The largest SWHP facility is Värtan Ropsten with 180 MW total capacity in Sweden [27]. Areas in Japan have also used SWHP for DH and cooling since 1993. There have been several related research and application cases in Korea [26]. China has been using seawater as a heat source for DH since early 2000, and SWHP has a large popularizing and utilizing value in cold areas [32]. Study [33] showed that seawater most likely will have to play a substantial role as a heat source in future energy systems in Denmark. The energy-saving potential of the SWHP DH system is significantly underestimated in comparison to the conventional boiler house DH system [34]. Analysis of the SWHP system in Korea showed the improvement in annual heating performance of 8-14% [26]. Studies [32, 35] showed that the beach well infiltration intake system effectively improves the stability, reliability and energy efficiency of SWHP systems.

This work will analyse the implementation of SWHP in the Old city of Dubrovnik, Croatia for heating and cooling purposes by integration of intermittent RES electricity generation in wider urban Dubrovnik region. Dubrovnik is well known touristic destination placed in south of Croatia on the coastline of the Adriatic Sea. The entire Old city of Dubrovnik has been part of UNESCO World heritage since 1979. The largest part of heating and cooling demand of the Old city is covered with air conditioning units which results in negative visual impact of building facades. The Conservation Department in Dubrovnik, in cooperation with the institute Hrvoje Požar, started a project with the aim to reduce and eventually eliminate all of the external air conditioning units from building facades in the Old city. Hrvoje Požar made the study [36] done for this purpose suggesting SWHP as the best solution to cover heating and cooling demand of the Old city of Dubrovnik. Since the Dubrovnik is a part of

UNESCO World heritage, renewable systems like photovoltaics (PV) and TC are forbidden. Same problem exists in Venice, so study [37] analysed a lagoon water coupled HP installed in the retrofit of the Crucifers Convent, a historical building in Venice. The results showed significantly higher saving on the energy consumption than the required 20% and thus a consequently reduction in the emission of GHG in comparison to traditional plant. The SWHP system was analysed for the important port in China, Dalian, with marine climate, which is also an industrial, trade and tourism city, similar to Dubrovnik. The results of the study [38] showed energy efficiency enhancement potential of the HP units, while the investment in a SWHP system is generally profitable [27]. Seawater source HP is not a new thing in the Old city. Rectors palace has been using SWHP since 1980's, and the old system has now been replaced with the new one.

Methods

Dubrovnik region has a high potential of RES, mostly wind and Sun, which is why they are selected as a sources of electricity generation within this study. As shown in the previous study [39] done for Dubrovnik region, air temperature could be taken as reliable factor used to forecast solar radiation and energy demand, even on a short-term scale of 10 minutes. Wind speed and solar radiation based on the mean monthly values have shown good correlation meaning these two RES give good combination in electricity generation. The 10 minutes time scale showed poorer results meaning higher needs for flexibility in order to utilize intermittent RES on a short-term scale. The potential of SWHP system to utilize RES electricity generation is provided for the system based on hourly and 10 min time step. The needs for energy storage (ES) within the SWHP system are also analysed and the comparison is done for BES and TES. The calculations are done according to three different scenarios:

- Scenario 1: SWHP and RES electricity generation, calculations based on 1 hour and 10 minutes time step.
- Scenario 2: SWHP + BES and RES electricity generation, calculations based on 1 hour time step.
- Scenario 3: SWHP + TES and RES electricity generation, calculations based on 1 hour time step.

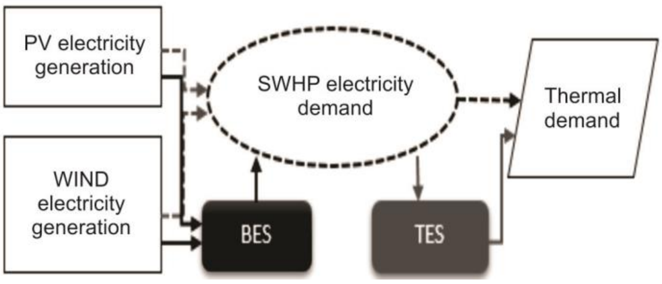

Figure 1. Model of the scenarios

First scenario included standalone SWHP system. Two other scenarios included SWHP combined with BES and TES and were calculated only on hourly time step. Model for selected scenarios is provided in fig. 1. Dashed line presents the model of Scenario 1, black line is for Scenario 2 and grey line for Scenario 3. The study analysed three different cases for each of the scenarios. Cases differ in renewable electricity generation:

- CASE A: PV electricity generation.
- CASE B: WIND electricity generation.
- CASE C: RES (PV + WIND) electricity generation.

The SWHP system in the Old city of Dubrovnik

Input data of SWHP system for this study are taken from the study done by the institute Hrvoje Požar [36]. In present situation, air conditioning covers most of the heating demand and total cooling demand of the Old city. Heating and cooling demand in the study [36] are calculated according to HRN EN ISO 13790 standard. Study [36] did not consider domestic hot water demand, only space heating and cooling demand. According to the calculations it is estimated that the total installed capacity of SWHP should be 11 MW. Two-step HP would be the best option for this location using R134a as a working substance. The optimal solution would be installation of higher number of aggregates with lower capacities in order to ensure higher flexibility of the system as well as proper distribution and pipe diameters of smaller dimension. Seawater intake should be done at depths below 15 m. Thermodynamic magnitudes of the SWHP in the Old city of Dubrovnik are shown in tab. 1. The scheme of the SWHP heating process is provided in fig. 2. Hourly values of COP are calculated according to the EN 15316-4-2:2017 standard, with seasonal COP (SCOP) given in tab. 2. The seasonal energy efficiency ratio (SEER) value is selected according to the available values provided by the manufacturer on the efficiency of the HP in cooling mode, because the hourly values of the EER could not be calculated. The values provided by the manufacturer are Eurovent-certified values in compliance with standard EN14511-3:2013.

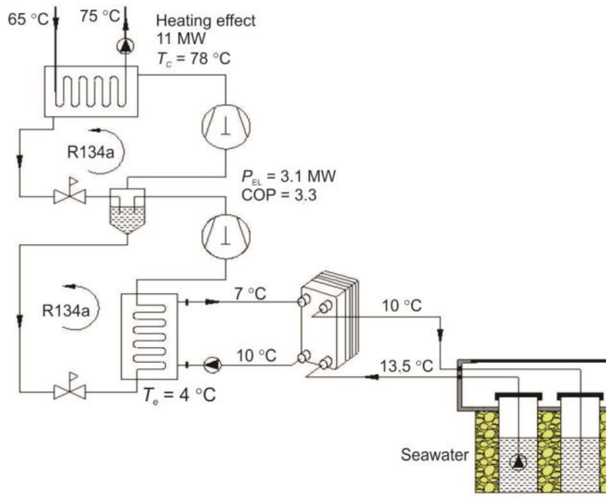

Figure 2. Seawater source HP heating process scheme

Table 1. Thermodynamic magnitudes of the SWHP in the Old city of Dubrovnik

Thermodynamic magnitudes	Value [°C]
Sea temperature – heating period	13.5
Sea temperature – cooling period	16
Evaporation temperature – heating period	4
Evaporation temperature – cooling period	3
Condensing temperature – heating period	78
Condensing temperature – cooling period	22
Energy carrier flow temperature – heating period	75
Energy carrier flow temperature – cooling period	7

Table 2. Input data

Heating demand [MWh/year]	10179
Cooling demand [MWh/year]	8107
COP [–]	3.3
EER [–]	6.3
Electricity heating demand [MWh/year]	3089.18
Electricity cooling demand [MWh/year]	1286.83
Installed capacity of PV power plant [MW]	18
Installed capacity of wind power plant [MW]	160

Calculations

Calculations are done based on the hourly and 10 minutes data set. Cooling season is considered to be from May 1th till October 1th and heating season is considered to be rest of the year. During the heating season HP is working when the air temperature is lower than 15 °C. Hourly and 10 minutes thermal demand, *STP*, is calculated according to the eqs. (1) and (2), in order to get hourly and 10 minutes thermal demand distributions:

$$STP_i = \left(\frac{THP}{\sum_i^{8760} DD_i} \right) DD_i \tag{1}$$

$$DD_i = T_{\mathrm{p},i} - T_{\mathrm{v},i} \tag{2}$$

Degree hour *DD* stands for the degree hour or 10 minutes, where subscript *i* stands for hourly or 10 minutes time step. It is calculated according to the eq. (2), as a difference between inside, T_p , and outside, T_v, temperature for hourly or 10 minutes time step. T_p is set to 22 °C during the cooling season and during the heating season to 20 °C. Data for T_v are provided by Croatian Meteorological and Hydrological Service, based on the 10 minutes time step for the year 2014. The hourly T_v values are gained as an average values of each hour. The hourly DD distributions and the total heating and cooling demand, THP, provided in tab. 2, are used to calculate the distribution of heating and cooling demand based on hourly and 10 minutes time step, STP, eq. (1). In the case of 1 hour time step there are 8760 data and in the case of 10 minutes time step there are 52560 data.

Electricity generation from wind and sun was calculated according to the data of wind speed and solar radiation provided by Croatian Meteorological and Hydrological Service, based on the 10 minutes time step. Measured data of 2014 were selected for the calculations. Since some of the measurements were missing, we had to combine measurements from 2014 with ones from 2013, in order to gain a complete yearly data. According to the gained data based on 10 minutes time step, we calculate the hourly values. Renewable electricity production is calculated according to the study [40] done for the Dubrovnik region. Installed capacities were set based on the energy plan for 2030 for the Dubrovnik region [40] and provided in tab. 2. Mean monthly values of wind speed and solar radiation measured data are given in tab. 3. Distributions of renewable electricity generation are shown in diagrams in fig. 3.

Table 3. Mean monthly values of wind speed and solar radiation for 2014 for Dubrovnik region

2014	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Wind speed [ms^{-1}]	5.28	5.42	4.00	3.52	3.03	3.32	2.98	2.79	3.07	3.24	4.71	5.03
Solar radiation, [Whm^{-2}]	133.12	194.55	360.72	324.83	420.60	511.35	482.41	544.62	369.06	273.55	199.13	165.27

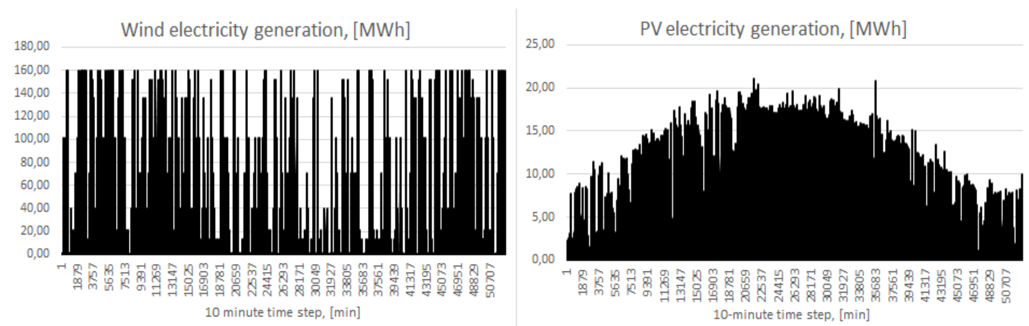

Figure 3. The 10 minute time step distribution of yearly wind and solar electricity generation for the Dubrovnik region for 2030

Scenario 2 and 3 included ES in the model so the calculations are done in order to define ES needs in the case of BES and TES on hourly basis. Calculations are provide in the eq. (3)-(5):

$$E_{\text{ES},i} = E_{\text{ES},i-1} - E_{\text{SWHP},i} + E_{\text{RES},i} \tag{3}$$

$$0 \le E_{\text{ES},i} \le E_{\text{ES,max}} \tag{4}$$

$$E_{\text{SWHP},i} \ge 0 \tag{5}$$

Stored energy in every hour, $E_{\text{ES},i}$, is calculated according to the eq. (3). It takes into a consideration stored energy form the previous hour, $E_{\text{ES},i-1}$, SWHP electricity demand, $E_{\text{SWHP},i}$, and RES electricity production, $E_{\text{RES},i}$. Some constraints are taken into a consideration for $E_{\text{ES},i}$ and $E_{\text{SWHP},i}$. Stored energy in each hour $E_{\text{ES},i}$ cannot go beyond its maximum capacity, as shown in the eq. (4). It is also considered that the thermal demand will be covered in every given hour throughout the year, using only RES electricity production, directly with a SWHP or energy stored in ES. This is insured with a constraint given in the eq. (5). Efficiency of BES and TES charging and discharging are not taken into a consideration in this work, so the results might vary from the ones in reality. The BES is storing electricity which is used to cover SWHP electricity demand in the time of lack of RES electricity production. The TES is storing thermal energy to cover thermal demand in the time of lack of RES generation. The TES is charged using SWHP, so the difference between TES thermal capacity and BES electricity capacity is given with SCOP and SEER of SWHP.

Results

Results of the study are given for three different scenarios and each of the scenarios is modelled for three different cases. The results of the scenarios show the difference between the system using only SWHP and the one with ES, BES and TES. They also provide a comparison of technical and financial aspects of BES and TES. The results of the cases show the variations in the system according to the changes in electricity supply. Results of the Scenario 1 also show the comparison of the system based on hourly and 10 minutes time step. Yearly distribution curves of SWHP electricity demand, based on hourly and 10 minutes time step provided in fig. 4. It can be seen that a heating demand is represented during higher period of the year with a higher demand in comparison to the cooling period. Hourly load has higher peak demand by 500 kW in comparison to the 10 minutes time step load.

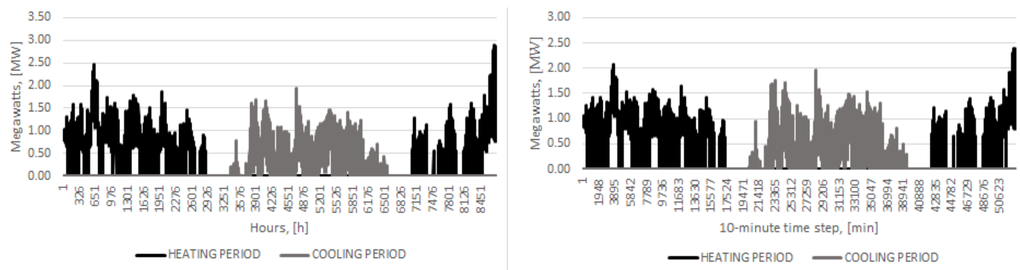

Figure 4. Distribution of electricity demand for SWHP based on hourly and 10 minutes time step

Results of the Scenario 1

Figure 5. shows one specific day during heating and cooling season. Third Wednesday of January was selected as a specific date for heating season and third Wednesday of July

for cooling season. Table 4. shows peak values of wind and solar electricity generation and SWHP electricity demand for each of the specific days. As it can be seen from fig. 5, during the cooling period PV electricity production can cover most of the SWHP cooling demand. During the heating season heat demand is higher during the evening when there is no RES electricity generation. Some of the heating demand during rest of the day can be supplied mostly from wind. The rest of the RES production, which appears in the time when there is no higher need for thermal demand, can be stored in additional storage and used afterwards. Probably this electricity from RES generation will be cheaper so the SWHP system could benefit in this way using the additional storage which will be charged with low cost electricity. On the other hand, storage will provide additional flexibility to the system. When we compare hourly and short-term distribution curves, we can see that short-term distribution of wind and PV electricity production has much more fluctuations meaning higher needs for flexibility. There are many short time peaks during the day, especially from wind electricity generation. They can be utilized by charging batteries during 10 minutes time period, demanding high electricity capacity in a short period of time.

Table 4. Maximum values of RES electricity generation and SWHP electricity demand for one specific day during heating and cooling season

Time step	1 hour		10 minutes	
Period	Heating period	Cooling period	Heating period	Cooling period
Unit	MWh	MWh	MW×10 min	MW×10 min
Wind electricity generation	158.67	10.13	160	40
PV electricity generation	2.96	17.08	4.62	17.22
Heating demand	1 24	–	1,23	–
Cooling demand	–	1.93	–	1.97

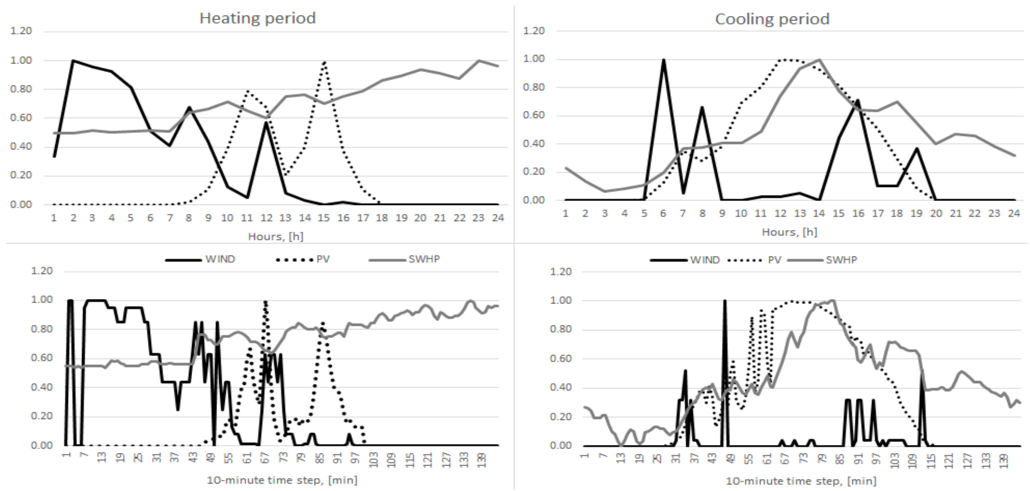

Figure 5. Comparison of normalized values of RES electricity production with SWHP demand for one specific day during heating and cooling season based on hourly and 10 minutes time step

Figure 6. shows the results of the Scenario 1 for three different cases based on the calculations for hourly and 10 minutes time step. Columns in the diagram show total yearly SWHP electricity demand, where light grey represents the demand which has been supplied by RES generation and the rest is the SWHP demand that needs to be covered with the additional ES, marked as dark green. Total yearly SWHP electricity demand is 4376 MWh per ye-

ar. The amount of SWHP electricity demand, that is covered with RES electricity production, is given in the percentages as well, as RES utilization. It can be seen from the results that there is a need for ES if the SWHP system will be supplied only by RES generation. Case C, on both sides, gives the best results, meaning that the combination of wind and PV production is a good option for renewable systems. Case C has the lowest ES needs and highest RES utilization. The 67% of SWHP demand can be supplied by the electricity generated from RES. Generally, 10 minutes calculations gave poorer results, by 6% in case C and 8% in case B, while for the case A the results are almost the same.

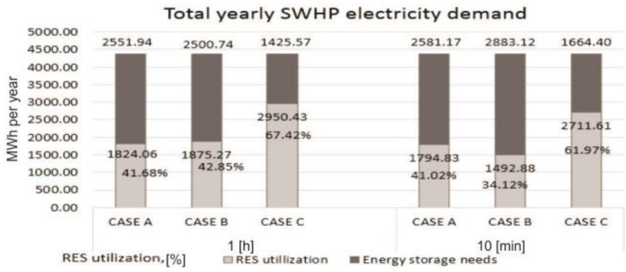

Figure 6. Results of the scenario 1

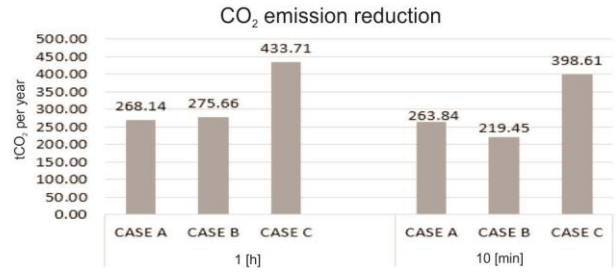

Figure 7. The CO_2 emission reduction by RES utilization

The SWHP system, with the integration of RES, has a great impact on the emission reduction. This study provided a short review on the CO_2 emission reduction by SWHP utilization of wind and solar electricity generation. Emission reduction is calculated according to the data of CO_2 emission factor taken for Croatia for 2018, which was 147 gCO_2/kWh [41]. The CO_2 emission reduction for all cases of the Scenario 1 is provided fig. 7. Higher RES utilization means higher emission reduction.

Results of the Scenarios 2 and 3

Scenarios 2 and 3 analysed SWHP system with BES and TES. It is assumed that the total yearly thermal demand will be supplied using RES electricity generation directly from SWHP or with energy stored in BES or TES. Study calculated the capacity of BES and TES needed to cover total yearly thermal demand in the time of lack of RES electricity production. Based on the technical and financial characteristics of BES and TES, given in tab. 5 and the eq. (3)-(5), we gained the results provided in tab. 6. The comparison between BES and TES is not done for the optimal storage since the aim of this study is to show the comparison for the different sources of RES electricity generation used for the system supply. It can be seen from the results that TES capacity is much higher than BES due to the SCOP and SEER values of the SWHP. Capacity of BES is given for the electric energy while TES is given for thermal energy. The results also showed that the investment costs are 13 times higher for BES while its volume is 20 times lower for each case, when compared to TES. The combination of wind and sun electricity generation in case C gained best results in comparison to the case A and B. Capacity, investment costs and volume of TES and BES in case C were reduced by 78% according to case A and by 60% according to case B.

Table 5. Financial and technical characteristics of TES and BES

	TES	BES
Investment cost	200 €/m^3	200 €/kWh_{el}
Capacity	80 kWh/m^3	500 kWh/m^3

Table 6. Results of the Scenarios 2 and 3

CASE	BES capacity [MWh]	TES capacity [MWh]	Investment cost BES [€]	Investment cost TES [€]	BES volume [m^3]	TES volume [m^3]
A	127	800	25400.00	2000000	254	10
B	94	592	18800.000	1480000	188	7400
C	28	176	5600.000	440	56	2200

Levelised cost of heat (LCOH) are done for the case C in order to compare BES and TES. Discount rate is taken to be 5% with a lifetime of 20 years. The LCOH for BES are almost 13 times higher, with the amount of 24.57 €/MWh, while for TES are 1.93 €/MWh. LCOH analysis for case C did not considered all of the system components, like SWHP, pipelines nor electricity prices, which should be taken into a consideration to do the complete LCOH analysis.

Conclusion

This work provides the results of the ability of SWHP system to utilize RES generation as a stand-alone system and using ES. Previous studies have not done much in the field of SWHP system. They mostly analysed HP for other sources. The integration of HP into renewable systems was mostly analysed for solar systems. Only few studies analysed wind electricity production in combination with HP systems. This study analyses the integration of wind and solar electricity generation using SWHP, both together and separately. Three scenarios are set. Scenario 1 considered SWHP stand-alone system to supply thermal demand of the Old City of Dubrovnik. Scenario 2 considered additional BES and Scenario 3 additional TES in thermal energy system. All of the scenarios are compared for three cases in order to show the difference between the sources of electricity production.

Results of the Scenario 1 showed that 67% of SWHP demand is covered by RES electricity production in case C, for the system based on hourly time step, providing better results than case A and B. The results of the calculations done in 10 minutes time step gained poorer results, by 6% for case C and by 8% for case B, while for the case A results were almost the same. It can be concluded that the system based on a short term scale has higher requirements for flexibility in the power system.

The results of the Scenarios 2 and 3 for all three cases showed that BES has 13 times higher investment cost but 20 times lower volume in comparison to TES. The BES requires smaller area for its installation which, in this case, would be a better option for the Old City of Dubrovnik due to the lack of area required for the ES placement. On the other hand, it requires higher investment costs. Case C provided even better results than case A and B. The combination of PV and wind in RES electricity production in case C reduces capacity, investment costs and volume of TES and BES by 78% according to the case A and by 60% according to the case B. Case C provided better results for all three scenarios.

The BES, although having 13 times higher investment costs and LCOH, has 40 times lower volume in comparison to TES. The BES is also more interesting option for future smart energy system because, besides of storing electricity, it can provide electricity to the grid in the of lack of electricity production and other ancillary services. Today's electric batteries have the ability to be fully charged in just 10 minutes, requiring higher energy capacity for charging. Although system, based on 10 minutes time step, is shown to have higher requirements for flexibility in the system, fast charging batteries could provide additional flexibility being able to store higher amount of energy in a short period of time. These options will be analysed and discussed in one of our future work.

Nomenclature

$E_{ES,I}$ – stored energy in each hour, [MWh]
$E_{ES,I-1}$ – stored energy from the previous hour, [MWh]
$E_{RES,I}$ – RES electricity production [MWh]
$E_{SWHP,i}$ – seawater source HP electricity demand [MWh]
T_p – inside air temperature [°C]
T_v – outside air temperature [°C]
DD – degree hour or 10 min [°C]
STP – thermal demand [MWh]
THP – total heat production [MWh]

Abreviations

4GDH – 4th generation district heating
BES – battery energy storage
CHP – combine heat and power
DH – district heating
EER – energy efficiency ratio
ES – energy storage
HP – heat pump
LCOH – levelised cost of heat
PV – photovoltaic
SCOP – seasonal coefficient of performance
SEER – seasonal energy efficiency ratio
SWHP – seawater source HP
TC – thermal collector
TES – thermal energy storage
UNESCO – United Nations Educational, Scientific and Cultural Organization

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References

[1] ***, European Parlament/European Directive 2012/27 EU, https://eur-lex.europa.eu
[2] ***, EU, Energy performance of buildings and Directive 2012/27/EU on energy efficiency (Text with EEA relevance), *Official Journal of the European Union*, *156* (2018), 75, pp. 1–17
[3] Popa, V., *et al.*, Thermo-Economic Analysis of an Air-to-Water Heat Pump, *Energy Procedia*, *85* (2016), Jan., pp. 408-415
[4] Sayegh, M. A., *et al*., Heat Pump Placement, Connection and Operational Modes in European District Heating, *Energy Build.*, *166* (2018), May, pp. 122-144
[5] Rama, M., Wahlroos, M., Introduction of New Decentralised Renewable Heat Supply in an Existing District Heating System, *Energy*, *154* (2018), July, pp. 68-79
[6] Fischer, D., Madani, H., On Heat Pumps in Smart Grids: A review, *Renew. Sust. Energ. Rev.*, *70* (2017), Apr., pp. 342-357
[7] Lund, H., *et al*., 4th Generation District Heating (4GDH). Integrating Smart Thermal Grids Into Future Sustainable Energy Systems, *Energy*, *68* (2014), Apr., pp. 1-11
[8] Baccino, G., *et al*., Energy and Environmental Analysis of an Open-Loop Ground-Water Heat Pump System in an Urban Area, *Thermal Science*, *14* (2010), 3, pp. 693-706
[9] Gong, Y., *et al*., Development of a Compression-Absorption Heat Pump System for Utilizing Low Temperature, *Thermal Science*, *23* (2019), 2, pp. 791-799
[10] Levihn, F., CHP and Heat Pumps to Balance Renewable Power Production: Lessons from the District Heating Network in Stockholm, *Energy*, *137* (2017), Oct., pp. 670-678
[11] Blarke, M. B., Lund, H., Large-Scale Heat Pumps in Sustainable Energy Systems : System and Project Perspectives, *Thermal Science*, *11* (2007), 3, pp. 143-152
[12] Lauka, D., *et al.*, Heat Pumps Integration Trends in District Heating Networks of the Baltic States, *Procedia Comput. Sci.*, *52* (2015), 1, pp. 835-842
[13] Shakir, Y., *et al.*, Numerical Simulation of a Heat Pump Assisted Regenerative Solar Still with PCM Heat Storage, *Thermal Science*, *21* (2017), pp. 411-418
[14] Testi, D., *et al*., Cost-Optimal Sizing of Solar Thermal and Photovoltaic Systems for the Heating and Cooling Needs of a Nearly Zero-Energy Building: The Case Study of a Farm Hostel in Italy, *Energy Procedia*, *91* (2016), June, pp. 528–-536
[15] Niederhauser, E. L., *et al*., Novel Approach for Heating/Cooling Systems for Buildings Based on Photovoltaic-heat Pump: Concept and Evaluation, *Energy Procedia*, *70* (2015), May, pp. 480-485
[16] Di Liddo, P., *et al*., Application of Optimization Procedure to the Management of Renewable Based Household Heating and Cooling Systems, *Energy Procedia*, *62* (2014), Dec., pp. 329-336

[17] Schellenberg, C., *et al*., Operational Optimisation of a Heat Pump System with Sensible Thermal Energy Storage Using Genetic Algorithm, *Thermal Science*, *22* (2020), 5, pp. 2189-2202
[18] Niederhauser, E.L., *et al*., New Innovative Solar Heating System (Cooling/Heating) Production, *Energy Procedia*, *70* (2015), May, pp. 293-299
[19] Guo, X., *et al*., Volume Design of the Heat Storage Tank of Solar Assisted Water-Source Heat Pump Space Heating System, *Procedia Eng.*, *205* (2017), Dec., pp. 2691-2697
[20] Ostergaard, P. A., Andersen, A. N., Economic Feasibility of Booster Heat Pumps in Heat Pump-Based District Heating Systems, *Energy*, *155* (2018), July, pp. 921-929
[21] Tamasauskas, J., *et al*., An Analysis of the Impact of Heat Pump Systems on Load Matching and Grid Interaction in the Canadian Context, *Energy Procedia*, *78* (2015), Nov., pp. 2124-2129
[22] Ellerbrok, C., Potentials of Demand Side Management Using Heat Pumps with Building Mass as a Thermal Storage, *Energy Procedia*, *46* (2014), Dec., pp. 214-219
[23] Ban, M., *et al*., The Role of Cool Thermal Energy Storage (CTES) in the Integration of Renewable Energy Sources (RES) and Peak Load Reduction, *Energy*, *48* (2012), 1, pp. 108-117
[24] Dominković, D. F., Krajačić, G., District Cooling Versus Individual Cooling in Urban Energy Systems: The Impact of District Energy Share in Cities on the Optimal Storage Sizing, *Energies*, *12* (2019), 3, 407
[25] Carmo, C., *et al*., Smart Grid Enabled Heat Pumps: An Empirical Platform for Investigating How Residential Heat Pumps Can Support Largescale Integration of Intermittent Renewables, *Energy Procedia*, *61* (2014), Dec., pp. 1695-1698
[26] Baik, Y. J., *et al*., Potential to Enhance Performance of Seawater-Source Heat Pump by Series Operation, *Renew. Energ.*, *65* (2014), May, pp. 236-244
[27] Zhen, L., *et al*., District Cooling and Heating with Seawater as Heat Source and Sink in Dalian, China, *Renew. Energ.*, *32* (2007), 15, pp. 2603-2616
[28] Marques, A. C. V., Dos Santos Oliveira, W., Technological Forecasting: Heat Pumps and the Synergy with Renewable Energy, *Energy Procedia*, *48* (2014), Dec., pp. 1650-1657
[29] ***, International Energy Agency/The Future of Cooling, http//www.iea.org
[30] ***, International Energy Agency/The Future of Cooling in China Suistainable Sir Conditioning, http//www.iea.org
[31] Averfalk, H., *et al*., Large Heat Pumps in Swedish District Heating Systems, *Renew. Sust. Energ. Rev.*, *79* (2017), Nov., pp. 1275-1284
[32] Jia, X., *et al.*, Multifactor Analysis on Beach Well Infiltration Intake System for Seawater Source Heat Pump, *Energy Build.*, *154* (2017), Nov., pp. 244-253
[33] Lund, R., Persson, U., Mapping of Potential Heat Sources for Heat Pumps for District Heating in Denmark, *Energy*, *110* (2016), Sept., pp. 129-138
[34] Haiwen, S., *et al*., Quasi-Dynamic Energy-Saving Judgment of Electric-Driven Seawater Source Heat Pump District Heating System Over Boiler House District Heating System, *Energy Build.*, *42* (2010), 12, pp. 2424-2430
[35] Zheng, X., *et al*., Seepage and Heat Transfer Modeling on Beach Well Infiltration Intake System in Seawater Source Heat Pump, *Energy Build.*, *68* (2014), Part A, pp. 147-155
[36] Krstulović, V., et al., *Study of the Optimal Solution of the Cooling and Heating System in the Old City of Dubrovnik*, Institute Hrvoje Požar, Zagreb, Croatia, 2018
[37] Schibuola, L., Scarpa, M., Experimental Analysis of the Performances of a Surface Water Source Heat Pump, *Energy Build.*, *113* (2016), Feb., pp. 182-188
[38] Hiawen, S., *et al.*, Energy Efficiency Enhancement Potential of the Heat Pump Unit in a Seawater Source Heat Pump District Heating System, *Procedia Eng*., *146* (2016), Dec., pp. 134-138
[39] Falkoni, A., Krajačić, G., Linear Correlation and Regression Between the Meteorological Data and the Electricity Demand of the Dubrovnik Region in a Short-Term Scale, *Thermal Science, 20* (2016), 4, pp. 1073-1089
[40] Šare, A., *et al*., The Integration of Renewable Energy Sources and Electric Vehicles Into the Power System of the Dubrovnik region, *Energy Sustain. Soc.*, *5* (2015), Sept., 27
[41] ***, Ministry of Environment and Energy/Energy in Croatia - Annual Energy Report 2018, http://www.eihp.hr/wp-content/uploads/2020/04/Energija2018.pdf

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