



Heat Recovery from Waste-water in Buildings
- A System-Oriented Longitudinal Study
(Energimyndigheten Project-No. 41811-1)

Final Report
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2 Sammanfattning (Executive Summary/Swedish)

Projektet ”Värmeatervinning ur byggnaders spillvatten” genomfördes under perioden 160901-181231 med ekonomiskt stöd från Inex International Exergi AB och Energimyndigheten (Projekt-nr. 41811-1).

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2.1 Avgränsningar

Långsiktiga mätstudier är beroende av tillgången till långsiktiga (kvalitetssäkrade) mätdata. Svårigheterna och förseningarna vid genomförandet av detta projekt beror till stor del på

svårigheter med tillgången till pålitlig och långsiktig mätdata, samt det levererade datas genomgående bristande kvalitet och svårhanterlighet. Uppföljningen av energiprestanda har kantats av feldrabbad och utdragen idrifttagning vid alla tre tilltänkta testanläggningar (flerbostadshus i Lidingö, hotell i centrala Stockholm, Beckomberga-komplexet) omfattande fel på mätutrustning (t ex på spillvärmeåtervinningsbatterierna), förstört mätdata på grund av datafel på fastighetsförvaltningssidan (motsvarande nästan ett helt års mätvärden), avsaknad av viktiga mätdata (t ex spillvattenflöden) samt kommunikationssvårigheter med berörda aktörer (bl a mät-/förvaltningsbolag). Då den primära fokusen var att utvärdera spillvärmeåtervinnningen under uppvärmningssäsongen, resulterade detta i att (begränsat användbara) energimätdata fanns tillgängliga för Beckomberga –komplexet endast för perioden 171101-180331. Detta gjorde det dessvärre inte möjligt att genomföra några långtidsstudier (t ex omspannande ett helt kalenderår).

Olika tekniska problem med den förinstallerade mätutrustningen, men framförallt utdragna idrifttagnings-svårigheter fram till sommaren 2017 resulterade i att industridoktoranden aldrig fick tillgång till de utlovade mätdata innan föräldradedigheten påbörjades under juni 2017. Ihärdiga problem med idrifttagningen i hotellanläggningen (Stockholm) samt bostadshuset (Lidingö) ledde till att arbetet helt fick inriktas på Beckomberga-komplexet fom juni 2017. Industridoktoranden ägnade sina studier från projektstart i september 2016 till juni 2017 åt uppbyggnaden av en full-skale testrigg för mätning/kalibrering av spillvärmeväxlare, litteraturstudier, kurser, samt utveckling av en matematisk modell av spillvärmeåtervinnningssystemet. Privata omständigheter ledde till att industridoktoranden dessvärre inte kunde återvända till sitt arbete under den resterande delen av projektet. Rekryteringen av en ersättare för industridoktoranden resulterade först 170901 i att Dr Genku Kayo (Aalto Universitetet) kunde anställas som postdoktor (med övervägande finansiering via KTH-interna fakultetsmedel) och påbörja sitt arbete inom projektet. Han ansvarade för den operativa delen av arbetet fram till projektets slut (181231).

2.2 Mål

Målet med projektet var att ta fram ny kunskap om funktionen och prestandan hos olika system for värmeåtervinning ur byggnaders spillvärme under verkliga och simulerade driftförhållanden samt i ett långtids-, system- och livscykelperspektiv.

Den ursprungliga avsikten var att studien skulle omfatta en hotellanläggning i centrala Stockholm, ett flerbostadshus på Lidingö samt ett större flerbostadshusområde i Beckomberga. Utdragen och feldrabbad idrifttagning i alla tre testanläggningar samt begränsad tillgång till användbar mätdata ledde under projektets gång till att arbetet helt fick inriktas på Beckomberga komplexet (Kapitel 7).

Studiens syfte var att bidra till en bättre förståelse om:

- Metoder för mätning och utvärdering av värmeåtervinningsgraden hos olika typer av spillvattenvärmeväxlare
- Variationer i spillvärmeåtervinnings effektivitet över året (momentan- och säsongsvariationer)
- Skillnader i varmeväxlingseffektivitet och övergripande prestanda mellan olika typer av varmeväxlingssystem (för- och nackdelar med olika system)
 - Brine-baserad motströmsvarmeväxling i kombination med återladdning av bergvärmelager
 - Värmeväxling för direkt förvärmning av tappvarmvatten (med och utan pumpförstärkning under perioder med hög spolningsintensitet)
 - Kopplingar mellan varmvattenanvändning (bruksprofiler), byggnadsdrift, drift av värmeåtervinningsystem och varmeväxlingseffektivitet
- Driftekonomiska aspekter (lönsamhetsanalys) i relation till tidsvariabla energi- och effektkostnader (t ex fjärrvarme)
- Teknisk integration av värmeväxlare i olika byggnadstyper
- Driftsäkerhet, underhållsbehov- och kostnader hos olika varmeväxlingssystem
- Förutsättningar och kostnader för installation av spillvärmeväxlare vid nybyggnation och renovering
- Driftoptimering av spillvärmeväxlare i förhållande till energi-/exergieffektivitet på systemnivå och driftkostnad i livscykelperspektiv
- Energi-/exergieffektivitet på komponent- och systemnivå

Studien skulle även resultera i en state-of-the-art litteratursammanfattning om system/metoder för återvinning av värme från byggnaders spillvatten; en dynamisk modell och ett verktyg för simulering och utvärdering av värmeåtervinning från byggnaders spillvatten på komponent- och systemnivå; samt en modell för realtidsvisualisering av varmvattenvärmeflödena (tappvarmvatten, spillvatten), samt relaterade energikostnadsflöden (energi-/effektkostnader) i en byggnad.

2.3 Måluppfyllelse och slutsatser

- En state-of-the-art kunskapsynthes om spillvärmeåtervinning i byggnader har sammanställts (Kapitel 5).

- Värdefulla erfarenheter har samlats från samverkan med IEA EBC Annex 64 (LowEx Communities), IEA HPT Annex 52–(*Long-term measurements of GSHP system performance in commercial, institutional and multi-family buildings*), HÅVA-projektet (Hållbarhetsanalys av Värmeåtervinning ur Avloppsvatten) (Kapitel 6).
- En analys av spillvärmeåtervinningen i Beckomberga-komplexet har genomförts utifrån den begränsade mätdata som var tillgänglig (se Kapitel 2.1 samt Kapitel 7-8).
- En matematisk modell har utvecklats i samverkan med Tokyo City University (Professor Masanori Shukuya) för analys av exergieffektiviteten hos spillvattenvärmeväxlare, borrhålsvärmeväxlare och värmepumpar (Kapitel 9).
- En test-rigg i full skala för mätning och kalibrering av spillvärmeväxlarens energieffektivitet har byggts upp i samarbete med Inex International Exergi AB, som också stod för över 75% av tillhörande utrustnings- och arbetskostnader (Kapitel 10).
- Exergianalys: Exergianalysen visade att 12% (snittvärde, 3-24%) av spillvattens exergi kunde överföras till kallvattnet. 76% (snittvärde, 60-88%) av exergin förstördes inom värmeöverföringsprocessen. Exergieffektiviteten kan huvudsakligen förbättras genom en bättre värmeöverföring i systemet (optimering av vattenflöden, pumpar, dimensionering av värmewäxlare, kortare distributionsrör), (Kapitel 12).

2.4 Informationsspridning

Resultaten från denna studie kommer spridas enligt följande:

- En kortfilm om projektet är under produktion i samverkan med ”GrönBostad”. Filmen kommer finnas tillgänglig på: <https://gronbostadstockholm.se/kontakt/>
- Abstract till en konferensartikel med titeln “*Kayo, G., Shukuya, M. and Martinac, I.: Energy and exergy behaviour analysis on the heat recovery from a waste-water system*” har accepterats och arbetet med artikeln pågår. Artikeln är planerad att presenteras vid 10th Int. Conference on Indoor Air Quality, Ventilation and Energy Conservation in Buildings, IAQVEC, Bari/Italy, 5-7 September 2019.
- En utvidgad artikel som utgår ifrån resultaten i konferensartikeln ovan är planerad att publiceras i en vetenskaplig tidskrift.
- Projektteamet samverkar fortsatt med IEA HPT Annex 52 (som drivs av Svenskt Geoenergi centrum) och avsikten är att resultaten från det fortsatta arbetet med

långtidsuppföljningen av spillvärmeåtervinningen i Beckomberga komplexet ska spridas via annexets kanaler.

- Projektteamet samverkar fortsatt med referensgruppen för HÅVA projektet (Kapitel 6).
- Projektledaren för detta projekt deltar i referensgruppen för det vid KTH Water-Center nyligen påbörjade, Formas-finansierade projektet “Ensuring sustainability and equality of water and energy systems during actor-driven disruptive innovation (SEQWENS)” (2018-2020) där frågor rörande spillvärmeåtervinning diskuteras i ett bredare system- och livscykelperspektiv.
- Erfarenheterna från detta projekt kommer spridas genom CIEB-plattformens kanaler (Samverkansplattform för brukaranpassad, hållbar byggnadsdrift), se även (Martinac et al. 2017). I CIEB-samarbetet ingår för närvarande 6 universitet (KTH, Chalmers, LTH, Universitetet i Jönköping, Blekinge Tekniska högskola samt Malmö Universitet) och ett trettiotal ledande företag och organisationer från byggsektorn.
- En artikel om projektet avses publiceras i en branschjournal (t ex Energi och Miljö, Förvaltaren).

2.5 Framtida studier

Mot bakgrund av ett fortsatt starkt intresse från industrin (bland annat Inex International Exergi AB) är projektkonsortiets avsikt att fortsätta utforska effektiviteten hos olika typer av spillvattenvärmeåtervinningssystem. Medan denna studie fokuserade på horisontella värmeväxlare (och värmeväxlarpaket), är avsikten att framöver även studera olika typer av vertikala system. En fråga av primärt intresse är hur spillvärmeväxlare bör utformas för att öka värmeväxlningseffektiviteten (utifrån form och storlek, flödesregim mm).

Analysen av spillvärmeåtervinningen i Beckomberga komplexet är av fortsatt intresse. Där är en central fråga hur värmeåtervinningssystemen bör utformas, utrustas samt kopplas till övergripande styrsystem (smarta system) för att möjliggöra en pålitlig, kontinuerlig och användarvänlig drift- och prestandauppföljning. Fördjupade studier avses vidare genomföras rörande relaterade exergieffektivitetsfrågor, för att få en mer helhetlig förståelse och bedömning av den spillvärmeåtervinningens effektivitet och kvalitet.

3 Executive Summary (English)

3.1 Limitations

Longitudinal measurement studies crucially depend on the access to quality-assured longitudinal data. The difficulties and delays encountered over the duration of this project are to a large extent related to the lack of access to such data, as well as the sub-optimal quality of the data that was eventually made available to the research team. The performance evaluation of the Beckomberga complex was affected by a fault-ridden, extended commissioning process in all three designated test facilities (Lidingö residential building, hotel in central Stockholm and the Beckomberga residential complex). The work was further affected by loss of data (amounting to almost an entire year of data collection) caused by facility-management related IT-system faults, lack of key data (such as waste-water flow rates), as well as communication issues with stakeholders on the facility management side. As the primary goal was to evaluate the efficiency of heat recovery from waste-water during the heating season, the study ended up having to be based on a (limited-quality) measurement data set (Beckomberga complex, 1 November 2017 to 31 March 2018) eventually made available to the research team. This, unfortunately, did not make it possible to conduct a long-term or detailed system performance evaluation. The data-set obtained, lacked crucial data, such as as flow-rates in key portions of the system, and contained significant amounts of erroneous data (generated by faulty metering on the facility-management side).

Different technical problems, especially those related to commissioning from project start through the summer of 2017 resulted in the industrial PhD-student not being provided with access to any measurement data prior to commencing parental leave in June 2017. Persistent commissioning problems with the Lidingö residential facility and the hotel in central Stockholm resulted in the decision to entirely focus the study on the Beckomberga complex from June 2017 onwards. Due to private circumstances, the industrial PhD-student was unable to return to work throughout the remainder of the project. Dr Genku Kayo was eventually recruited as postdoctoral researcher to take over, starting 1 September 2018, the operational responsibility for the project. His employment was mainly funded with faculty (intra-mural) funding throughout the conclusion of the project.

3.2 Objectives

The aim of this project was to investigate the performance of the waste-water heat recovery systems installed in the Beckomberga multi-apartment building (Beckomberga complex). The project focused on:

- Performance of the heat recovery system during the heating season
- Performance of ground source heat storage (boreholes) in the heating season
- Developing a methodology for evaluating system performance in the case of limited data availability
- Discussing the requirements, and limitations of long-term monitoring research
-

The study intends to contribute to a better understanding of:

- 1) The methods for measuring and evaluating the heat recovery efficiency;
- 2) Different types of heat exchangers and their performance
- 3) Appropriate methods for the performance analysis of complex waste-water heat recovery systems
- 4) The real-life performance of heat recovery systems (Beckomberga complex).

#1 and #2 were carried out in the format of a literature review, stakeholder meetings and by exchange of expertise and experience with national and international research networks, while #3 and #4 were conducted through measurements on a full-scale test rig, as well as waste-water heat recovery analysis in a case study (Beckomberga complex).

3.3 Project outcomes and conclusions

- A state-of-the art knowledge synthesis (literature review) on waste-water heat recovery was conducted (Chapter 5).
- Valuable experiences have been collected and compiled through the collaboration with IEA EBC Annex 64 (LowEx Communities), IEA HPT Annex 52–(*Long-term measurements of GSHP system performance in commercial, institutional and multi-family buildings*), and the HÅVA-projektet (Hållbarhetsanalys av Värmeåtervinning ur Avloppsvatten) (Kapitel 6).

- An analysis was carried out (based on the limited amount of data that was made available) of the efficiency of heat recovery from waste-water at the Beckomberga complex (Chapter 2.1 and Chapters 7-8).
- A full-scale test-rig was designed and developed for measuring and calibrating the energy performance of heat exchangers for waste-water heat recovery. The rig was constructed in collaboration with Inex International Exergi AB, who also covered in excess of 75% of related costs (Chapter 10).

3.3.1 Exergy Analysis

An advanced exergy efficiency model was developed in collaboration with Tokyo City University (Professor Masanori Shukuya), (Chapter 9).

3.3.1.1 Waste-Water Heat-Exchanger

The exergy analysis showed that 12% (on average, range: 3 - 24%) of exergy contained in the waste-water was delivered to the cold water. 76% (on average, range: 60 - 88%) of exergy was consumed during the process. It was concluded that there are two ways to increase the exergy efficiency: Adjusting flow rates through the system, and reducing pump electricity use. Thus, optimizing the scale of waste-water heat recovery application is needed. The possible strategies are, for example, to reduce the capacity of the pump by optimizing the flow rate of the cold water or optimizing the scale of heat collection. In the case of the Beckomberga site, the cold-water circulation loop is too long.

The performance evaluation was conducted using a limited amount of measured data and assuming approximate values for the missing data. The temperature level of the waste-water was around 15 - 20 °C on average. The study showed that the heat collection from the waste-water can be a key factor which contributes to the source of heat supply.

The energy study showed that the flow rate of waste-water which passes through the heat exchanger is a key factor. Even when large amounts of waste-water are generated, the high flow rate doesn't allow enough for heat to be transferred from the warm waste-water side to the cold water side. Flow-rate optimization emerged as a parameter of key interest for future research work.

3.3.1.2 Borehole Heat Exchanger Performance

The study on the borehole heat exchanger showed that the temperature of the ground was very stable through the day, around 2.2–2.3°C on average. The energy gained by exchanging heat from the borehole was 247 kW/h on average with a maximum of 293 kW/h at 4 am.

The exergy performance analysis showed that 48% of exergy from the borehole ($X_{b.in}$) was delivered to the cold water side ($X_{c.out}$). 27% of $X_{b.in}$ was consumed through the process (X_{cons}). To extend the evaluation boundary, the exergy input to the pump (E_p) and exergy consumption at the pump ($X_{cons.ep}$) occupy the large part of the balance. The analysis suggests that the E_p and $X_{cons.ep}$ would be reduced if the capacity of the pump could be minimized. Future work should explore the optimal number of boreholes and the capacity of the circulation pump.

3.3.1.3 Heat Pump Performance

Through the analysis of the heat pump performance, the average balance of the temperatures around the heat pump were analysed. For the water at the supply side, incoming ($T_{hpc.in}$) was 3.7°C and out-going ($T_{hpc.out}$) was 1.0°C. For the water at the demand side, incoming ($T_{hph.in}$) was 46.9°C and out-going ($T_{hph.out}$) was 47.0°C. The trend of temperature changing was stable throughout the day.

The energy performance analysis showed that 29–40% of the heat supply was delivered by recovery from waste-water and 28–38% of the supply was covered by ground source heat from the boreholes. As a result, the partial load of the heat pump was 57–61% and the COP was 3.06–3.12 (3.09 on average). An additional scenario was explored in which the contribution by heat recovery was not included. For this case, the partial load of heat pump was increased by 77–86% and the COP was reduced by 1.39–1.62.

The exergy balance study showed that 41.2% of input was covered by the supply side and the rest was covered by electricity consumed by the compressor of the heat pump and consumed through the process. To extend the evaluation boundary, the result indicates that 5.6% of exergy input was delivered to the demand side (X_{cd}) and the rest was consumed. The exergy theory states that the electricity is high quality. Exergy efficiency could clearly be further increased by decreased electricity use in the system.

In closing, the various technical and logistical difficulties faced by the research team throughout this project, provide an example of how difficult (and frustrating) it can be to depend on third-party measurement data in conducting system performance studies, even in facilities equipped with advanced instrumentation and building management systems. Numerous studies have shown that this issue is, unfortunately, rather prevalent in the built environment, especially in the case of complex plants and facilities. Building system performance data is often incomplete, faulty or formatted in ways that make it difficult to use. Efforts are currently in progress in collaboration between six Swedish universities and key stakeholders from the private and the public sectors to establish a national innovation platform for user-adapted, building performance management (Martinac et al. 2017).

3.4 Information Dissemination

The results from this study will be disseminated through the following channels:

- In collaboration with the “GrönBostad” project, a short film about this study is currently being produced and will become available at (<https://gronbostadstockholm.se/kontakt/>).
- A conference paper abstract, entitled “*Kayo, G., Shukuya, M. and Martinac, I.: Energy and exergy behaviour analysis on the heat recovery from a waste-water system*” has been accepted towards preparation of a full paper to be presented at the conference: 10th Int. Conference on Indoor Air Quality, Ventilation and Energy Conservation in Buildings, IAQVEC, Bari/Italy, 5-7 September 2019.
- An extended paper, partly based on the above conference paper will be submitted to a scientific journal.
- The project team continues to collaborate with IEA HPT Annex 52 (operated by Svenskt Geoenergi-centrum) and participates in related information dissemination.
- The project team continues to contribute to the reference group work for the HÅVA project.
- The Principal Investigator for this project is a member of the newly initiated Formas-funded project “Ensuring sustainability and equality of water and energy systems during actor-driven disruptive innovation” where issues related to the management of water and energy resources will continue to be discussed.
- Experiences from this project will be shared with and disseminated through the extensive CIEB-consortium (Samverkansplattform för brukaranpassad, hållbar byggnadsdrift), see also (Martinac et al. 2017).
- A paper is intended to be submitted to at least one professional journal (such as Energy och Miljö, Förvaltaren, etc.).

3.5 Further Studies

Building on strong, continued industrial interest, the research partnership is currently exploring how the continued performance of waste-water heat-recovery systems, (such as those in the Beckomberga complex, but also in other facilities) can be evaluated in a follow-up study, to provide a better understanding of the long-term performance and potential benefits of low-exergy residual heat.

4 Introduction

4.1 Background

Waste-water heat recovery has been shown to reduce heating costs and energy utilization in several studies. Studies on heat exchangers that function without external power input are rarer, but the temperature efficiencies of some models have been evaluated. Temperature efficiencies of up to 72.2% have been reported for vertical waste-water heat exchangers using the effect that occurs when water falls next to a surface under the influence of gravity when used with shower drainwater (Collins, 2009). McNabola and Shields (2013) reported efficiencies of up to 26.5% for a horizontal shower heat exchanger and tests by Nordling (2014) showed a temperature efficiency of up to 37.9% for another horizontal shower heat exchanger model. Studying the effects on a whole system with these passive heat exchange techniques could provide a better understanding of the possibilities for energy savings in buildings.

4.2 Project Objectives

The aim of this project was to investigate the performance of the waste-water heat recovery systems installed in the Beckomberga multi-apartment building (Beckomberga complex). The project focused on:

- Performance of the heat recovery system during the heating season
- Performance of ground source heat storage (boreholes) in the heating season
- Developing a methodology for evaluating system performance in the case of limited data availability
- Discussing the requirements, and limitations of long-term monitoring research

The study intends to contribute to a better understanding of:

- 5) The methods for measuring and evaluating the heat recovery efficiency;
- 6) Different types of heat exchangers and their performance
- 7) Appropriate methods for the performance analysis of complex waste-water heat recovery systems
- 8) The real-life performance of heat recovery systems (Beckomberga complex).

#1 and #2 were carried out in the format of a literature review, stakeholder meetings and by exchange of expertise and experience with national and international research networks, while #3 and #4 were conducted through measurements on a full-scale test rig, as well as waste-water heat recovery analysis in a case study (Beckomberga complex).

4.3 Research Team

The research/project team included:

Professor Ivo Martinac, Principal Investigator, Building Services and Energy Services (IES)/KTH

Sofia Korpar Malmström, Industrial PhD-Student/INEX

Dr Genku Kayo, Researcher, IES/KTH

Professor Masanori Shukuya, Tokyo City University, Yokohama, Japan

Hossein Rahimbaroughi, MSc-Thesis Candidate, IES/KTH

4.4 Project Limitations

Longitudinal measurement studies crucially depend on the access to quality-assured longitudinal data. The difficulties and delays encountered over the duration of this project are to a large extent related to the lack of access to such data, as well as the sub-optimal quality of the data that was eventually made available to the research team. The performance evaluation of the Beckomberga complex was affected by a fault-ridden, extended commissioning process in all three designated test facilities (Lidingö residential building, hotel in central Stockholm and the Beckomberga residential complex). The work was further affected by loss of data (amounting to almost an entire year of data collection) caused by facility-management related IT-system faults, lack of key data (such as waste-water flow rates), as well as communication issues with stakeholders on the facility management side. As the primary goal was to evaluate the efficiency of heat recovery from waste-water during the heating season, the study ended up having to be based on a (limited-quality) measurement data set (Beckomberga complex, 1 November 2017 to 31 March 2018) eventually made available to the research team. This, unfortunately, did not make it possible to conduct a long-term or detailed system performance evaluation. The data-set obtained, lacked crucial data, such as as flow-rates in key portions of the system, and contained significant amounts of erroneous data (generated by faulty metering on the facility-management side).

Different technical problems, especially those related to commissioning from project start through the summer of 2017 resulted in the industrial PhD-student not being provided with access to any measurement data prior to commencing parental leave in June 2017. Persistent commissioning problems with the Lidingö residential facility and the hotel in central Stockholm resulted in the decision to entirely focus the study on the Beckomberga complex from June 2017 onwards. Due to private circumstances, the industrial PhD-student was unable to return to work throughout the remainder of the project. Dr Genku Kayo was eventually recruited as postdoctoral researcher to take over, starting 1 September 2018, the operational

responsibility for the project. His employment was mainly funded with faculty (intra-mural) funding throughout the conclusion of the project.

5 Literature Review

5.1 Heat Exchangers

5.1.1 Classification of Heat Exchangers

Heat exchangers can be classified based on their construction and flow arrangements (Shah, K, Sekulić, & P., Classification of Heat Exchangers, 2003). Heat exchangers can also be classified according to heat transfer processes or number of fluids involved, as well as heat transfer mechanisms (Shah, K, Sekulić, & P., Classification of Heat Exchangers, 2003).

- *Transfer Processes*

By considering transfer process, heat exchangers can be classified into direct and indirect contact types. In direct contact type two fluids are separated from each other with the heat transfer surface without any mix and leak (Shah, K, Sekulić, & P., Classification of Heat Exchangers, 2003). On the other hand, in indirect contact type there is no thermally contact and interacting between two fluids and intermittent heat exchange between the hot and cold via thermal energy storage and release through the exchanger surface or matrix (Shah, K, Sekulić, & P., Classification of Heat Exchangers, 2003). And this type of heat exchanger, also referred to as a surface heat exchanger (Shah, K, Sekulić, & P., Classification of Heat Exchangers, 2003).

- *Number of fluids*

Two-fluid heat exchangers are the conventional type in this category but in some cases, such as in chemical processes, we can find up to 12-fluids flows (Shah, K, Sekulić, & P., Classification of Heat Exchangers, 2003).

- *Heat transfer mechanism*

In this category heat exchangers are mainly classified into four types based on the internal heat transfer mechanism involved (Shah, K, Sekulić, & P., Classification of Heat Exchangers, 2003):

1. Single-phase convection on both sides
2. Single-phase convection on one side-two phase convection on other side
3. Two phase convection on both sides
4. Combined convection and radiative heat transfer

5.1.2 Heat Energy Recovery from Waste-water Systems

The waste water heat recovery through heat exchangers in the buildings is one of the solutions as the alternative heat source to reduce the energy consumption for preheating water, heat the buildings and chilling for air conditioning (Niewitecka, 2018). To utilize this kind of energy source via grey water in the building section we need to separate the sewage system into grey water and black water (Niewitecka, 2018). The grey water is defined as the outflow of water from showers, bathtubs, washbasins and automatic washing machines or dishwashers with the low pollutant load and the temperature around 30°C (Niewitecka, 2018). On the other hand, the black water is called to the water discharged from toilet bowls and urinals with the high pollutant load and the temperature around 10°C (Niewitecka, 2018).

The critical factors to evaluate the energy potential of waste water are temperature and quantity, and the second priorities are the quality, technical condition of the sewers, the distance between the heat recovery system and the customers, as well as the type of customers and their energy needs (Niewitecka, 2018).

By installing the heat exchanger at the nearest place which the grey water will be discharged the much of this source of heat can be recovered, this system is called Drain Water Heat Recovery (DWHR) (Niewitecka, 2018). The DWHR heat exchangers can be in horizontal and vertical types in the forms of spiral, pipe-in-pipe, based on the conditions that will be implemented (Niewitecka, 2018).

5.1.3 Heat Exchanger Applications for Waste-Water Heat Recovery

The important issue for designing a waste-water heat exchanger (WWHEX) is to find an optimal design to facilitate the heat exchange efficiently between two fluids without mixing and exposing them to a direct contact (Culha, Gunerhan, Biyik, Ekren, & Hepbasli, 2015). WWHEX are mainly classified in two different categories such as utilization and construction of WWHEX (Culha, Gunerhan, Biyik, Ekren, & Hepbasli, 2015). There are three different situations for utilization of WWHEX such as domestic, sewage and after treatment and also the construction section consists of material and type (Culha, Gunerhan, Biyik, Ekren, & Hepbasli, 2015).

In the domestic utilization the recovered heat mainly used to preheat the supply water (Culha, Gunerhan, Biyik, Ekren, & Hepbasli, 2015). The advantages of this implication are high water temperature, and short heat transport distance but the disadvantages can be fluctuation of flow rate, distortion caused by the materials inside the waste-water and high operational cost in decentralized systems (Culha, Gunerhan, Biyik, Ekren, & Hepbasli, 2015). In the sewage system utilization this system can be installed in sewer network regarding of high heat potential energy, availability of adequate flow rate in any time and capability of monitoring (Culha, Gunerhan, Biyik, Ekren, & Hepbasli, 2015). On the other hand, main the disadvantage of this system is it can impact the treatment of waste-water (Culha, Gunerhan, Biyik, Ekren, & Hepbasli, 2015). The final utilization category is implementing this system after sewage treatment plant. The advantages of this system are no impact on waste-water treatment, sizeable

constant flow rate, largest heat supply, and waste-water are purified but the disadvantage of this system is relatively high heat transport route to the consumers cause the heat loss in the process (Culha, Gunerhan, Biyik, Ekren, & Hepbasli, 2015).

5.1.4 Efficiency Analysis of Heat Exchangers and Heat Exchanger Networks

The concept of heat exchanger efficiency provides a new and more convenient way for the design and analysis of heat exchangers and heat exchanger networks (Fakheri, Efficiency analysis of heat exchangers and heat exchanger networks, 2014). The heat exchanger is sized and selected to meet the thermal requirements of the system, which includes the design heat transfer rate at a true mean temperature difference across the heat exchanger (Jeff, 2017). The Thermal Capacity (UA) represents the heat exchanger's ability to transfer heat and has a maximum value based on the heat transfer surface area (A) and the maximum possible value of the heat transfer coefficient (U); which depends on both fluids convection heat transfer coefficients, tube wall thickness, material conduction heat transfer coefficient, and fouling factors (Jeff, 2017).

The author recently proposed a third method for analyzing heat exchangers by defining the concept of heat exchanger efficiency (Fakheri, Efficiency analysis of heat exchangers and heat exchanger networks, 2014). Heat exchanger efficiency can be used to conveniently analyze different heat exchanger design problems, including the network of heat exchangers without the need for charts, or complicated performance expressions (Fakheri, Efficiency analysis of heat exchangers and heat exchanger networks, 2014). The Author presents a new methodology for analyzing the network of heat exchangers connected in series, which allows the direct determination of the size of individual heat exchangers, and the rate of heat transfer in them, which shows the heat transfer rate in consecutive heat exchangers connected in series increases geometrically (Fakheri, Efficiency analysis of heat exchangers and heat exchanger networks, 2014).

Basically, there are two methods for analyzing heat exchangers: The Log Mean Temperature Difference (LMTD) and ϵ -NTU approach (Fakheri, Heat Exchanger Efficiency, 2007). To calculate the efficiency based on the LMTD method the inlet and outlet temperatures are known, and the size of the heat exchanger needs to be specified, and it is called a sizing problem (Fakheri, Efficiency analysis of heat exchangers and heat exchanger networks, 2014). On the other hand, in ϵ -NTU approach the size of the heat exchanger and the inlet temperatures are known, and the heat transfer rate and the fluid exit temperatures are to be determined, which is called rating problem (Fakheri, Efficiency analysis of heat exchangers and heat exchanger networks, 2014).

When one heat exchanger will not be able to meet the design specifications the minimum number of heat exchangers needed to have a feasible design which is the next integer higher than the value of N in Eq.1 and for designed temperatures in Eq.2. additionally, the overall efficiency of the system is defined in Eq.3 (Fakheri, Efficiency analysis of heat exchangers and heat exchanger networks, 2014).

Table. 2.1.6.1 The methodology for rating and sizing problems (Fakheri, Efficiency analysis of heat exchangers and heat exchanger networks, 2014)

Rating known	Sizing known
$Cr = \frac{C_{min}}{C_{max}}$	$\Delta T_{min} = \min[(t_2 - t_1), (T_1 - T_2)]$
$NTU = \frac{UA}{C_{min}}$	$\Delta T_{max} = \max[(t_2 - t_1), (T_1 - T_2)]$
$Fa = NTU \frac{(1 + mCr^n)^{\frac{1}{n}}}{2}$	$Fa = \tanh^{-1} \left[\frac{(\Delta T_{max}^n + m\Delta T_{min}^n)^{\frac{1}{n}}}{2(\bar{T} - \bar{t})} \right]$
$\eta = \frac{\tanh(Fa)}{Fa}$	$\eta = \frac{\tanh(Fa)}{Fa}$
$\bar{T} - \bar{t} = \frac{T_1 - t_1}{1 + NTU\eta \frac{(1+Cr)}{2}}$	$\bar{T} - \bar{t} = \frac{T_1 + T_2}{2} - \frac{t_1 + t_2}{2}$
$q = \eta UA(\bar{T} - \bar{t})$	$q = C_h(T_1 - T_2) = C_c(t_2 - t_1)$
$T_2 = T_1 - \frac{q}{C_h}$ & $t_2 = t_1 + \frac{q}{C_c}$	$UA = \frac{q}{\eta(\bar{T} - \bar{t})}$

Table 2.1.6.2. The Fin analogy number parameters m, n for different heat exchangers and nomenclature (Fakheri, Efficiency analysis of heat exchangers and heat exchanger networks, 2014)

HX type	m	n
Counter flow	-1	1
Parallel	1	1
Single stream ($C_r = 0$)	1	1
Single shell and tube	1	2
Cross flow, C_{max} unmixed, C_{min} mixed	1.2	4.4
Cross flow, C_{max} mixed, C_{min} unmixed	1.35	4.02
Cross flow, both mixed	1.2	2
Cross flow, both unmixed	-0.1	0.37

Table 2.1.6.3 The heat exchanger networks equations (Fakheri, Efficiency analysis of heat exchangers and heat exchanger networks, 2014)

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$N > \frac{Fa}{NTU} \frac{2}{(1 - C_r)} \tanh^{-1} \left[\frac{\Delta T_{max}}{T - t} \frac{(1 - C_r)}{2} \right]$	Eq.1
$N > \frac{(\Delta T_{max}^n + m \Delta T_{min}^n)^{\frac{1}{n}}}{\Delta T_{max} - \Delta T_{min}} \tanh^{-1} \left[\frac{\Delta T_{max} - \Delta T_{min}}{2(T - t)} \right]$	Eq.2
$N > \frac{\text{Tanh} \left[\frac{NTU (1 - C_r)}{2} \eta_1 \right]}{\frac{NTU (1 - C_r)}{2}}$	Eq.3

Table 2.1.6.4 The nomenclature (Fakheri, Efficiency analysis of heat exchangers and heat exchanger networks, 2014)

A	surface area, m²	T₁ hot fluid inlet temperature
AMTD	Arithmetic Mean Temperature Difference $AMTD = \left(\frac{T_1 + T_2}{2} - \frac{t_1 + t_2}{2} \right) = (\bar{T} - \bar{t})$	T₂ hot fluid exit temperature
C_c	heat capacity of the cold fluid; $C_c = (m C_p)_c$	t₁ cold fluid inlet temperature
C_h	heat capacity of the hot fluid; $C_h = (m C_p)_h$	t₂ cold fluid exit temperature
C_{min.}	= min [C_h, C_c]	T average temperature of the hot fluid

		$T = 0.5(T_1 + T_2)$
C_{max}	$= \max [C_h, C_c]$	t average temperature of the cold fluid $t = 0.5(t_1 + t_2)$
C_r	capacity ratio; $C_r = \frac{C_{min}}{C_{max}}$	$\Delta T = T_1 - T_2$
F_a	Fin analogy number	$\Delta t = t_2 - t_1$
N	number of shells	$\Delta T_{max} = \max [\Delta T, \Delta t]$
NTU	number of transfer units; $NTU = \frac{UA}{C_{min}}$	$\Delta T_{min} = \min [\Delta T, \Delta t]$
q $(\bar{T} - \bar{t})$	rate of heat transfer; $q = UA \eta$	U overall heat transfer coefficient, $W/m^2 K$
q_{opt} $q_{opt} = UA (\bar{T} - \bar{t})$	optimum heat transfer rate	η heat exchanger efficiency

5.1.5 Energy Recovery System from Waste-water for Heat Pumps in Residential Buildings

As far as a lot of researchers have investigated the waste-water heat recovery coupled to heat pumps in terms of recovering heat from particular appliances, this experimental study has introduced to examine the performance of the recovery system by the heat pump and the possibility of working with the storage tank and standard external heat exchanger (Postrioti, o.a., 2016). The summer and winter compatible heat pump is implemented and optimized to supply hot water for domestic users. The heat supply circuit was designed to allow the evaluation of the heat pump system performance with and without the contribution of the energy recovery from the sewer (Partial recovery operation.PRO). In this study (Postrioti, o.a., 2016), the hourly temperatures and mass flow rates of each component were calculated based on the Building America Research–Benchmark Definition 2009. The twelve thermocouples, two flowmeter transducers and two voltammetry transducers were installed on the heat supply circuit prototype to extract the data for further analysis.

The results of the prototype indicated that by reducing the contribution of the storage tank to the plant the COP of the system decreased significantly (values around 3.00) (Postrioti, o.a., 2016). Moreover, the results of hourly COP of the plant showed that the average of COP is much higher than the value of the COP 3.3 for the standard layout operation (SLO) (Postrioti, o.a., 2016). All in all, the overall results of the COP in two different strategies, partial recovery operation (PRO) and standard layout operation (SLO) indicated that the average of the COP in PRO is continuously higher than in the SLO configuration 3.72 against 3.3 (Postrioti, o.a., 2016).

5.1.6 Experimental Evaluation, Parametric Analysis for Recovering Heat from Hot Drain Water

In this study (Ramadan, Lemenand, & Khaled, 2016) the experimental method and parametric analysis were applied in the heat recovery systems which can be utilized as the system performance development and optimization procedure. The basic prototype was designed which consists of water supply tank, water pump, drain box, electric heater, and coiled heat exchanger (Ramadan, Lemenand, & Khaled, 2016).

Three different scenarios were applied in this experiment which in the first, the inlet cold temperatures varying from 3.2°C to 22.4°C, the hot inlet temperature of 70°C and cold flow rate of 0.146 kg/s. The second is accomplished for different cold-water flow rates varying from 0.058 kg/s to 0.146 kg/s and the third is performed for different hot inlet temperatures ranging from 40°C to 80°C.

Analyzing the results of the first scenario revealed that by increasing the cold-water temperature from 3.2°C to 24°C the recovered heat, efficiency and effectiveness of the system decreased significantly from 8.24 kW to 2.62 kW, around 100% to 47% and 26% to 12% respectively (Ramadan, Lemenand, & Khaled, 2016). Moreover, the results of the second and the third scenario revealed that by increasing the temperature and flow rate the recovered heat will highly increase but when the flow rate increases from 0.097 kg/s the recovered heat seems to reach a plateau beyond this value (Ramadan, Lemenand, & Khaled, 2016). In respect of effectiveness analysis by increasing the temperature the effectiveness dramatically increased (Ramadan, Lemenand, & Khaled, 2016). On the other hand, the effectiveness increases when the water flow rate changes from 0.058 kg/s to 0.097 kg/s and then decreases when the cold flow rate increases from 0.097 kg/s to 0.146 kg/s (Ramadan, Lemenand, & Khaled, 2016).

5.1.7 Localized Residential Waste-water Energy Recovery System (Feasibility Study)

In order to analyze and calculate the efficiency of waste-water heat recovery system with the affiliate of multiple-function heat pumps to utilize in domestic water heating, space heating and cooling of buildings, the feasibility study has been done by researches to evaluate the overall source energy consumption and potable water consumption (Ni, o.a., 2012). This numerical study tested the single-family house with four members and the approximate size of 220 m² excluding the floor area of the basement, gross wall area is 380m², and the window-wall ratio is 12.65% in 15 cities with the various climate in the United States (Ni, o.a., 2012).

This study investigates the potential saving of incorporating condenser heat recovery using the heat pump to reclaim heat from residential waste-water for space heating, space cooling, and domestic water heating (Ni, o.a., 2012). The waste-water is used in this study, for heat recovery and reused as the water supply for irrigation purpose. When the waste-water is not sufficient for irrigation, the potable water will compensate it as the additional solution.

This numerical study investigated in the flexible design that allows several strategies to meet the required loads of space heating, space cooling, and hot water heating. To investigate the system, the statistical prediction models of residential end-use water, the hourly supplied hot water flow rate, calculation of the temperature of water in the waste-water tank, annual fuel utilization efficiencies and the efficiency of the heat pump are developed and discussed (Ni, o.a., 2012).

The simulation results of this of this study indicated that this localized waste-water heat recovery with cooperating the heat pump has high energy savings and potable water savings, especially in moderate outdoor temperature (Ni, o.a., 2012). Moreover, source energy consumptions decrease 23.5%, 2.7% and 76.0% for space heating, cooling, and hot water heating, respectively. The potable water consumption also reduced by 27.2% or 72.9% for outdoor water use (Ni, o.a., 2012).

In summary the total source energy savings for all 15 cities had a range of 17%-57.9% (Ni, o.a., 2012). Furthermore, hot water heating has the most significant energy savings with over 60% reduction (Ni, o.a., 2012). In addition, the results illustrated the potable water savings had a range of 15%-34.1%. The higher water savings can be observed in the hot climate (Ni, o.a., 2012).

5.1.8 Drain Water Heat Recovery in Horizontal Domestic Shower Drains

In this paper the authors outlined the development and analysis of a horizontal drain water heat recovery system for domestic showers (McNabola & Shields, 2013).

Based on the nature of flow rate in the pipes, utilizing the drain water heat recovery (DWHR) in domestic shower drains by the vertical orientation heat exchangers have implemented in many buildings (McNabola & Shields, 2013). The vertical heat exchangers need the sufficient space to apply which is not possible for many dwellings to utilize. However, horizontal installation of the device would undoubtedly facilitate greater penetration of this technology and optimize its potential impact on energy efficiency in the sector (McNabola & Shields, 2013). Therefore, the researchers in this study provide the developments and analysis of the horizontal drain water heat exchangers that can mainly use for shower drains.

Based on the differentiation in waste-water flow around the entire boundary of the pipe wall in horizontal and vertical pipes the prototype of drain water heat recovery with the 40 mm diameter PVC for waste water pipe and the 12.7 mm diameter copper for water supply was designed (McNabola & Shields, 2013).

The experimental analysis, numerical models and CFD predictions were performed in three different properties of cold-water output temperature, drain water input temperature, drain water flow rate and transition time (McNabola & Shields, 2013).

The experimental results illustrated that effectiveness of the standard test condition is 23%, and by increasing the drain water temperature to 65°C and reducing the drain water flow rate to 6 l/min, the effectiveness of the system will improve slightly (McNabola A. a., 2013). Moreover, the effect of varying the thickness of the copper cold water pipe was also examined. Surprisingly, by reducing the thickness to 0.79mm, the effectiveness reached to 50% while, by increasing it to 2.38mm the effectiveness decreased dramatically to 38% (McNabola A. a., 2013).

5.2 Ground Source Heat Pump (GSHP)

5.2.1 Heat Pumps

Heat pumps are devices which by consuming electricity can transfer heat from a low-temperature medium to a high-temperature medium (Rosen & Koohi-Fayegh, Background and Technologies, 2016). The heat pumps consist of a condenser, the expansion device, the evaporator, and compressor (Rosen & Koohi-Fayegh, Background and Technologies, 2016).

The intention of the heat pump in heating mode is to provide heat from the low-temperature environment to heat the space and in contrast, in cooling mode is to remove heat from the cooled space to the high-temperature environment to provide cooling demand (Rosen & Koohi-Fayegh, Background and Technologies, 2016). Heat pumps have the significant energy savings since they can transfer more energy than they consume (Rosen & Koohi-Fayegh, Background and Technologies, 2016). Coefficient of performance (COP) is the factor which can be evaluate the efficiency of heat pumps. The higher COP is considered as the higher efficiency (Rosen & Koohi-Fayegh, Background and Technologies, 2016). The COP in heating mode is defined by the ratio of the heat provided to heated space to the electricity consumption but, in cooling mode is defined as the ratio of the heat removed from cooled space to the electricity consumption (Rosen & Koohi-Fayegh, Background and Technologies, 2016). Heat pumps which are applied for heating and cooling spaces have the space as their high-temperature and low-temperature medium, respectively (Rosen & Koohi-Fayegh, Background and Technologies, 2016). A variety of choice such as air, water, and ground stand for the other medium from/to which heat is transferred.

5.2.2 Underground Thermal Energy Storage

The thermal energy storage (TES) is the storage of thermal energy (heat or cold) for a period in a storage medium and also mainly categorized in the three different type such as sensible, latent and thermochemical which all of them are practical (Rosen & Koohi-Fayegh, Underground Thermal Energy Storage, 2016). The thermochemical energy storage is relatively

new and in development (Rosen & Koohi-Fayegh, Underground Thermal Energy Storage, 2016). Energy is stored by raising the temperature of a storage medium in sensible heat storage, changing the phase of a storage medium in latent heat storage, and chemically reacting a storage medium in thermochemical storage (Rosen & Koohi-Fayegh, Underground Thermal Energy Storage, 2016). The components of the TES systems are storage medium, a container, and equipment for injecting and recovering thermal energy (Rosen & Koohi-Fayegh, Underground Thermal Energy Storage, 2016).

TES system provides the situation to compensate the periods when thermal energy (heat or cold) is available and in demand and also, by storing thermal energy for later use in its original form, or in conversion to electricity or other energy products (Rosen & Koohi-Fayegh, Underground Thermal Energy Storage, 2016). The application, the storage period required, economics, and operating conditions are the crucial factors to design the proper TES system (Rosen & Koohi-Fayegh, Underground Thermal Energy Storage, 2016).

TES systems are generally designed to operate on a cyclical phase, and according to storage duration are mainly categorized in daily, weekly, or seasonally (Rosen & Koohi-Fayegh, Underground Thermal Energy Storage, 2016). In the long-term application, the system gains the advantages from seasonal climatic change, but the thermal losses are significant (Rosen & Koohi-Fayegh, Underground Thermal Energy Storage, 2016). Additionally, the daily use TES allows electricity consumption costs to be reduced by shifting electrical heating and cooling loads to periods when electricity prices are lower, usually during the night (Rosen & Koohi-Fayegh, Underground Thermal Energy Storage, 2016).

There are several strategies for charging and discharging in the cooling demand during peak hours which the two main types are full storage which capable to shifts the entire peak cooling load to off-peak hours, and with partial storage the chiller operates to meet part of the peak-period cooling load, and the rest is achieved by drawing from storage (Rosen & Koohi-Fayegh, Underground Thermal Energy Storage, 2016).

The performance of the TES system also depends on various factors such as storage design capacity configuration, storage temperature, balance of system and environment, storage operation, storage material, thermal stratification and thermal charging and recovery rate (Rosen & Koohi-Fayegh, Underground Thermal Energy Storage, 2016).

In insensible TES systems the fundamental characteristics related to the medium are high specific heat capacity, long-term stability under repeated charging and discharging cycles, compatibility between the storage medium and its containment and low cost (Rosen & Koohi-Fayegh, Underground Thermal Energy Storage, 2016). Moreover, the sensible TES types are rock cavern, aquifer, container tank, deep ground borehole, ground shallow and solar pond. But the two main vital types are underground and container tank (Rosen & Koohi-Fayegh, Underground Thermal Energy Storage, 2016). Sensible TES can be applied in the wide range of storage durations. In short-term (daily to weekly) systems often use crushed rock beds, earth beds, water tanks, ceramic brick, and building mass and in the Long-term type (annual or seasonal) TES systems often utilize rock beds, earth beds, and water tanks and also aquifer TES

can be used for all storage periods (Rosen & Koohi-Fayegh, *Underground Thermal Energy Storage*, 2016).

In the latent TES system, the heat transferred by the phase change of the materials, for instance, solid to liquid. Latent heat TES can be used to store hot or cold. Phase-change materials (PCMs) provide greater energy storage capacity with smaller temperature fluctuations compared with sensible storage (Rosen & Koohi-Fayegh, *Underground Thermal Energy Storage*, 2016). PCMs also are potentially advantageous for use in solar walls (Rosen & Koohi-Fayegh, *Underground Thermal Energy Storage*, 2016).

5.2.3 Borehole Thermal Energy Storage

The general definition of borehole thermal energy storage (BTES) is the systems which can store sensible heat or cold in the ground surrounding of each borehole (Gehlin, 2016). In the case of utilizing heat pumps the system specified as geothermal heat pump systems, ground-coupled heat pump (GCHP) systems, ground-source heat pump (GSHP) systems or geo-exchange systems (Gehlin, 2016). The BTES is the typical type in underground thermal energy storage system with the high efficiency for large energy load have the low changes over the time (Gehlin, 2016).

The boreholes perforating the ground volume are pipes fitted with circulating a heat carrier fluid and serve as heat exchangers between heat carrier and ground. Heat transport between the heat exchanger and the ground takes place primarily by conduction (Gehlin, 2016). Thermal energy is stored in the ground between the borehole heat exchangers. The ground is an inexpensive storage medium and enables large amounts of heat and cold to be stored over short- or long-term periods at relatively low cost (Gehlin, 2016). To attain the efficient heat transfer between the ground and ground heat exchangers the high thermal conductivity is favorable (Gehlin, 2016).

The ground heat exchangers (GHE) is installed in the BTES systems by drilling in a specified depth and then fitted with collector pipes. The depth for shallow installation is around 10 to 40 meters and the typical depth of the boreholes is around 100 to 200 meters (Gehlin, 2016). In most countries, boreholes are backfilled or grouted (Gehlin, 2016). The grout performs as the stabilizer and seal the boreholes and to provide the good thermal contact between the ground material and the collector pipes (Gehlin, 2016). Moreover, in the case of existing the groundwater in underground level the groundwater offers superior thermal contact between borehole wall and collector pipe and increase the heat transfer due to natural convection (Gehlin, 2016).

The geometry of the BTES system is the fundamental factor in heat loss (Gehlin, 2016). While storage capacity is linked to storage volume, and heat losses are proportional to surface area (Gehlin, 2016). The relative heat loss decreases with increasing storage volume (Gehlin, 2016). Thermal conditions and distance to, the ground surface are also crucial factors for the operational heat loss (Gehlin, 2016). Accordingly, the most commonly used storage geometries are the cylinder or parallelepiped (box) shapes (Gehlin, 2016). Consequently, in the

experimental measurement of thermal efficiency of a BHE with three drill hole diameters: 121 mm, 165 mm and 180 mm which the BHE was installed in a GSHP system of an office building, the author is proposed that the BHE with a bigger drill hole diameter has a better thermal performance and also the difference of cooling performance among the three drill hole diameters significantly related on the subterranean borehole temperature which the lower the subterranean borehole temperature provide the better BHE cooling performance with the bigger drill hole diameter (Luo, Rohn, Bayer, & Priess, 2013).

Another essential factor in the design and operation of BTES systems is the average storage temperature in relation to the average temperature of the surrounding ground (Gehlin, 2016). In steady-state heat loss the temperature difference between the annual average storage temperature and the undisturbed ground temperature is fundamental issue (Gehlin, 2016) and on the sizing process of GHE design the ground thermal properties, the thermal resistance of the borehole and the characteristics of the heat pump are the serious factors which to be considered. (Spitler & Bernier, 2016).

Analysis of heat transfer in ground (or geothermal) heat exchangers is essential to their design and integration within ground-source heat pump (GSHP) systems and the analytical models are classified in terms of the underlying thermal processes and are evaluated in a time-scale framework (Li, Zhu, & Fang, 2016).

In one case study the authors have been specified the efficiency of vertical geothermal heat exchanger by analyzed the quasi three-dimensional model, via the fluid temperature response in depth of a borehole (Zeng, Diao, & Fang, 2003). The shortcomings of two-dimensional model have been revealed the quasi three-dimensional provides better understanding of the thermal processes in GHE, and is highly recommended for design and thermal analysis of ground heat exchangers and also can serve as the useful tools in design and simulation of their performance as well (Zeng, Diao, & Fang, 2003).

5.2.4 Sustainability and Efficiency of Borehole Heat Exchanger Coupled Ground Source Heat Pump Systems

In this study a numerical model with different scenarios were simulated to evaluate the BHE outflow and soil temperatures (Hein, Kolditz, Görke, Bucher, & Shao, 2016). The model includes flow and heat transport processes with the dynamics of heat pump efficiency (Hein, Kolditz, Görke, Bucher, & Shao, 2016). The methodology which is adopted in this study is the dual-continuum approach by utilizing the open-source finite element code OpenGeoSys (OGS) (Hein, Kolditz, Görke, Bucher, & Shao, 2016).

In system modeling, two scenarios were analyzed base on comparison between system with or without heat pump. The results are shown that in the system without the heat pump, the soil temperature is moving slowly towards the quasi-steady-state, the subsurface temperature is approximately 1.3 °C lower than in the system with the heat pump and also the outlet temperature is 4.5°C lower than that in the heat pump system (Hein, Kolditz, Görke, Bucher, & Shao, 2016).

In the case of subsurface characteristics, the impact of heat capacity on the recovery of the subsurface and the performance of the heat pump was insignificant and also, the thermal conductivity has only a small impact on subsurface recovery and insignificant influence on outlet temperatures. Accordingly, temperature of the BHE decreased but the COP increased with increasing groundwater flow velocity (Hein, Kolditz, Görke, Bucher, & Shao, 2016).

In the system which the heat pump utilized both in cooling and heating mode the recovery of the subsurface is enhanced, the quasi-steady-state is reached faster and also the higher BHE outlet temperature caused the slightly better performance of the heat pump (Hein, Kolditz, Görke, Bucher, & Shao, 2016).

In summary, thermal conductivity of grout, the soil temperature is not affected by the thermal conductivity of grout while the outlet temperature increases with thermal conductivity of the ground. And also, the results indicated the BHE outlet temperature and COP will not change when the grout thermal conductivity is higher than $2.4\text{Wm}^{-1}\text{K}^{-1}$ (Hein, Kolditz, Görke, Bucher, & Shao, 2016).

5.2.5 Environmental Benefits, Renewability and Sustainability of GSHP

One of the essential environmental advantages of utilizing the ground-source heat pump (GSHP) systems is their low wastes/emissions (Rosen & Koohi-Fayegh, Environmental Factors; Renewability and Sustainability, 2016). The risk of transportation, storage, operation, and groundwater contamination in the GSHP systems is not the same as petroleum-based energy systems (Rosen & Koohi-Fayegh, Environmental Factors; Renewability and Sustainability, 2016). Implementing the GSHP has the lower CO₂ emission in comparison to the other conventional heating and cooling systems in the building sectors (Rosen & Koohi-Fayegh, Environmental Factors; Renewability and Sustainability, 2016). The CO₂ emissions and impact of GSHP systems on the environment are directly dependent on the source of their electricity supply (Rosen & Koohi-Fayegh, Environmental Factors; Renewability and Sustainability, 2016). The COP of the heat pump and the number of hours that a GSHP system operates are the critical factors to evaluate the emission of the GSHP system (Rosen & Koohi-Fayegh, Environmental Factors; Renewability and Sustainability, 2016). The complete simulations and analyses of single buildings and their heating and cooling loads via regional weather data, are the key factors to predict the emission reductions from executing GSHP systems (Rosen & Koohi-Fayegh, Environmental Factors; Renewability and Sustainability, 2016).

The recent study in 10 Indian states with populations ranging from 0.6 to 12.5 million indicated that by using GSHP beside typical electric heaters and air conditioners, the CO₂ emission is reduced around 24–54% per year (Rosen & Koohi-Fayegh, Environmental Factors; Renewability and Sustainability, 2016). Moreover, when the electricity for the GSHP operation is generated from renewable energies, the notable CO₂ emission reduction will occur (Rosen & Koohi-Fayegh, Environmental Factors; Renewability and Sustainability, 2016). In Germany, by assuming the conventional energy heating with the mix of 53% natural gas, 42% heating oil,

4% electricity, and 1% coal as the base for the comparative case study, the implementing of GSHP has resulted to reduction of 35% in CO₂ emissions (Rosen & Koohi-Fayegh, Environmental Factors; Renewability and Sustainability, 2016).

The essential factors regarding environmental impacts, include heat pump manufacturing, leakage of the heat carrier fluids to the ground, groundwater and aquifers, and thermal and chemical contamination of natural water resources and temperature-sensitive underground ecosystems (Rosen & Koohi-Fayegh, Environmental Factors; Renewability and Sustainability, 2016). The temperature turbulences in the ground caused by the operation of GSHP systems may result in disruption to sensitive life stages of aquatic organisms and reduce reproduction rates (Rosen & Koohi-Fayegh, Environmental Factors; Renewability and Sustainability, 2016). Accordingly, due to the thermal imbalances in the cooling and heating demand of the GSHP, the significant temperature rises in the region where the system is installed and can cause to significant problems with a heat pump's long-term performance (Rosen & Koohi-Fayegh, Environmental Factors; Renewability and Sustainability, 2016).

As a renewable energy source, geothermal energy is a significant contributor to sustainable development and, more broadly, sustainability (Rosen & Koohi-Fayegh, Environmental Factors; Renewability and Sustainability, 2016). The sustainability of GSHPs depends on the type of systems utilizing energy at various parts of the ground like horizontal heat exchangers versus vertical and the kind of utilization such as heating only versus heating and cooling (Rosen & Koohi-Fayegh, Environmental Factors; Renewability and Sustainability, 2016).

5.3 Large-Scale Energy Management Monitoring

5.3.1 Solving a Real-Life, Large-Scale Energy Management Problem

In the provided paper the researchers proposed three-phase hybrid approaches for a large-scale energy management to deal with scheduled maintenance periods and refueling amounts for nuclear power plants and also outlines for future demand and cost (Godskesen, Jensen, Kjeldsen, & Larsen, 2013).

The critical parts of the presented procedure are an initial solution construction and a two-part solution improvement phase. The initial solution consists of a constraint programming (CP) model for the complex scheduling problem which is utilized approximated constraints for production levels and fuel consumption (Godskesen, Jensen, Kjeldsen, & Larsen, 2013). The stochastic local search (SLS) algorithm based on a simple neighborhood structure were applied for the first schedule. In the local search part, the very fast feasibility check and a quick but approximated evaluation of the change in solution cost were applied and finally, the last phase was the greedy algorithm to eliminate any overproduction (Godskesen, Jensen, Kjeldsen, & Larsen, 2013).

In the field of search strategy, the CP solver by searching a tree has found the solution to optimize the problem. The variable and value selection are the two essential factors to optimize the pruning in a productive way (Godskesen, Jensen, Kjeldsen, & Larsen, 2013).

In compactional analysis section by introducing the Problem instances, the computational test algorithm on ten real-life instances was applied (Godskesen, Jensen, Kjeldsen, & Larsen, 2013). Moreover, in implementation details part, the algorithms are implemented in Java, and CP solver solved the scheduling problem (Godskesen, Jensen, Kjeldsen, & Larsen, 2013). Finally, in time allocation chapter the how much time is spent in different components were analyzed and the elementary test demonstrate that the ten minutes for the CP solver and the remaining 50 minutes for local search and other tasks is a reasonable distribution of the one hour available (Godskesen, Jensen, Kjeldsen, & Larsen, 2013).

By implementing the method were provided above the model always able to find a feasible solution, and by considering the overall score, ranked the first in the assessment procedure in the final evaluation of the ROADEF/EURO Challenge 2010.

5.3.2 Creating a Digital Environment for Large-Scale Energy Management at Homes(DEHEMS):

In this paper, the authors present a domestic energy management system (DEHEMS), which deploys electricity and gas monitoring in European-wide homes (Qi Liu, Cooper, Linge, Takruri, & Sowden, 2013).

In this study, the researchers created the digital techniques via smart devices to energy monitoring and management systems to persuade users to energy saving and efficiency (Qi Liu, Cooper, Linge, Takruri, & Sowden, 2013). The provided system introduced three iterative cycles based on User-Driven Innovation (UDI) method with specific technical development and behavioral change objectives described for each cycle. And over 250 houses in 5 different cities in the UK and Bulgaria were investigated. Moreover, this system provided the online explore and monitor the energy for users, context-aware recommendations and also application to share the consumption in their community for comparison and competition.

The collected data were analyzed in both qualitative and quantitative methods (Qi Liu, Cooper, Linge, Takruri, & Sowden, 2013). In the qualitative approach, the data analysis was applied based on five different categories which consist of motivations to save energy, system usability – infrastructure, system usability – dashboard, social aspects and impact on behavior change (Qi Liu, Cooper, Linge, Takruri, & Sowden, 2013). On the other hand, the quantitative data analysis was applied under two categories: overall energy consumption and impact of appliance monitoring and social network application (Qi Liu, Cooper, Linge, Takruri, & Sowden, 2013).

The results of this system revealed that users had consumed less energy during the experimental cycle, especially with the monitoring device and the social networking application (Qi Liu, Cooper, Linge, Takruri, & Sowden, 2013). Furthermore, 92% of participating users

have remarked positive behavior changes in energy consumption throughout the project (Qi Liu, Cooper, Linge, Takruri, & Sowden, 2013).

5.3.3 An Urban-Scale Method for The Characterization of Water Streams and The Assessment of Energy Savings and Costs:

In this article the authors proposed a method to quantify the building-specific energy cost and energy saving potentials, based on pinch analysis, at the urban scale (Bertrand, Aggoune, & Maréchal, 2017).

in this study the scholars, based on pinch analysis via waste water streams characterization, thermal load calculation method, number of occupants, the number of households, the appliance occurrences, the building type and the waste water heat recovery configuration, discussed a new approach for the detailed energy saving and cost assessments of grey water heat recovery systems from the building level and, by date aggregation, to the urban scale (Bertrand, Aggoune, & Maréchal, 2017).

The pinch analysis and its algorithmic formulation assess the heat recovery potential from cooling down hot streams in order to preheat cold streams (Bertrand, Aggoune, & Maréchal, 2017). The thermal load start and end temperatures of hot and waste water streams are the required input data (Bertrand, Aggoune, & Maréchal, 2017). To analyze the heat recovery potential of grey water streams for residential DHW users heating, mass flow, duration, and frequency of use per capita for each contribution waste water parts such as bathroom, kitchen and laundry must be characterized to calculate their thermal load (Bertrand, Aggoune, & Maréchal, 2017). Moreover, to define common temperature levels utilizing Geographical Information System (GIS) data information on occupant and household numbers for each building is necessary (Bertrand, Aggoune, & Maréchal, 2017).

Two case studies, with different scenarios to evaluate different configurations and their impact on the total heating demand, were investigate in this study. The first case consists of the characterization as well as energy savings, and cost calculation methods are applied to the existing residential buildings of the city and the second case was potential energy saving of the low energy, passive and high-efficiency residential buildings which the heating demands are not available (Bertrand, Aggoune, & Maréchal, 2017).

The results illustrated that, by horizontal heat exchangers and grey water heat recovery for hot water preheating, energy saving in single-family buildings, multifamily, and mixed-use buildings significantly reduced (Bertrand, Aggoune, & Maréchal, 2017). And also, the payback time for the assessed heat recovery systems and the average household (three inhabitants), is almost 18 years, besides for six inhabitants, the payback time falls below ten years (Bertrand, Aggoune, & Maréchal, 2017). In summary, the aggregation of the energy savings and costs from the single buildings to the urban scale also allows improving the results of large-scale energy assessments by grey water heat recovery (Bertrand, Aggoune, & Maréchal, 2017). The presented study thus contributes to the EU greenhouse gas emission reduction as well as energy

efficiency improvement targets, especially concerning near-zero energy buildings (Bertrand A. a., 2017).

5.4 Energy Retrofitting

5.4.1 Effective Ways of Building Energy Retrofitting

In this study, the authors by introducing the several scenarios regarding building envelope, building services (HVAC), various energy supply equipment and staff satisfactory demand, have discussed the performance of building retrofitting (Zhou, o.a., 2016). The drawings, intranet notification system, energy consumption monitoring, and design simulations are the essential documents to review in this study and also the method is considered effective ways to transform the existing building to the green buildings (Zhou, o.a., 2016).

The procedure of retrofitting the envelope in this study was defining the best scheme of retrofitting approach by changing the windows to wall ratio, external wall, door and roofs materials via simulating the annual energy consumption and also considering the payback period (Zhou, o.a., 2016). Moreover, in the HVAC system, the critical retrofitting process consists of changing the cold sources, heat sources and other indoor terminal units and systems (Zhou, o.a., 2016).

The final results of this study indicated that conventional energy retrofitting approach has an enormous impact on capitalizing the benefits of building energy efficient retrofitting, the staff satisfaction of indoor environment have met, heating, cooling, and annual electricity consumption is reduced significantly by 47%, 36%, and 43% respectively in corresponding value of the office buildings with the similar scale (Zhou, o.a., 2016).

In summary, the authors mentioned implementing conventional technologies in buildings retrofitting can help to achieve green building certification via appropriate strategy besides, executing expensive renewable energy technologies (Zhou, o.a., 2016).

5.4.2 Defining and Developing an Energy Retrofitting Approach:

Nowadays there are the plenty of researches have been studied in the field of energy retrofitting in buildings. But the rate of development and retrofitting existing buildings is meager in comparison to the reasonable level of retrofitting in building stocks (Luther & Rajagopalan, 2014). The suggested studies indicated that the reasons behind this shortcoming are risks of failure, overestimation of energy savings, increased payback period, and interruptions to operations (Luther & Rajagopalan, 2014).

In this study the authors introduced the methodology to saving energy considerably in the field of building operation by identifying a decision-making process for energy retrofitting and the missing stage viewed as the integrity audit which is focused on identifying energy waste first, reducing the overall peak electrical demand and then retrofitting for energy-efficiency (Luther & Rajagopalan, 2014). The initial purpose of the integrity audit is to identify the area

that energy may waste by indicating the several measures at this stage and the results outcome is defined as the Building Control Diagnostics (Luther & Rajagopalan, 2014).

The results and process analyzing of this methodology on several Australian buildings by focusing on identifying energy waste first, reducing the overall peak electrical demand load and then retrofitting for energy efficiency revealed that although this methodology has limitations with respect to a total life cycle cost but have the potential to reduce peak demand load and to reduce the pressure on the power supply infrastructure (Luther & Rajagopalan, 2014).

5.4.3 Cost-Effective Energy-Efficient Building Retrofitting

The European Energy Performance of Buildings Directive (EPBD) established the article which by December 31, 2020, all new constructions have to be nearly zero-energy buildings and also the deadline for new public buildings, is the end of 2018 (Torgal, 2017). Besides, the EU regulation provided two methodologies which are the cost-effective method with the considerable degree of flexibility through the input data for the calculation and also cost optimality which is the particular case of the cost-effective (Torgal, 2017).

Since the most buildings stock in the Europe had been built before introducing the first code in buildings energy performance in the 1970s thus, the significant portion of this section has not energy efficiency performance (Torgal, 2017). Accordingly, the existing buildings are the best opportunity for energy efficiency improvement (Torgal, 2017). The building energy retrofitting have a beneficial impact on economic recovery by stimulating the economy, put the alternatives like cutting the value-added tax (VAT) or investing in capital infrastructure projects. Energy retrofitting in the EU is the win-win approach to meet the EU 2020 goals, economic growth, jobs, energy, climate, and cohesion policies (Torgal, 2017).

The deep buildings retrofitting not only need technological innovation but also, by transparency in cost should be economically viable (Torgal, 2017). Another critical issue in retrofitting buildings which always disregarded and often act as the barrier is Socioeconomic aspects (Torgal, 2017). The decision process of energy-retrofitting is impressed by, the household size, household income, age composition of the household members and members education level (Torgal, 2017). The homeowners are not yet aware of the benefits of energy-efficiency improvements which need to the administration of coordinated campaigns at the local level with participating energy agencies, consultants, tradesmen, the local authorities, and the local press (Torgal, 2017).

Another crucial social issue regarding energy retrofitting is the rebound effect (Torgal, 2017). The rebound effect is used for the situation when the saved money from energy efficient technology is then used to heat more floor space and also to extend the heating period (Torgal, 2017). Moreover, the recent investigation indicated that the homeowner behaviors have a significant impact on building energy efficiency even the best-designed building in the world can consume more than a conventional building if users are not informed and supported in the use of the building (Torgal, 2017).

6 Research Collaboration & Stakeholder Meetings

Within the context of this project, collaboration was established with national and international research communities working in a number of areas, including heat recovery, low-exergy systems, and long-term system performance monitoring.

6.1 IEA EBC Annex 64

EBC Annex 64 was a three-year international research project, which was initiated in an international definition workshop in September 2012 in Munich and started after a one-year preparation phase with a working phase in mid-2014, ending in mid-2017. The project was closed after the reporting in mid-2018.

The IEA EBC Annex 64 – LowEx Communities (<https://www.annex64.org/>) aimed to demonstrate the potential of low exergy thinking on a community level as ways to achieve 100% renewable and GHG emission-free energy systems. Central challenges were the identification of promising and efficient technical solutions for practical implementation. Aspects of future network management, new business models for distribution and operation, as well as aspects of transition management and policy were also considered.

Within the project, a discussion on appropriate additional indicators, supplementing the exergy assessment was initialized and finalized to obtain a common understanding of local potentials and supply options under the preconditions of local availability. In this context, the application of exergy analysis provides the necessary basis for greater local energy autonomy and impulses for local economy.

The main objective of the annex was to demonstrate the potential of low exergy thinking on a community level as a means of achieving 100% renewable and GHG emission-free energy systems. The intention was to reach these goals by providing and collecting suitable assessment methods (e.g., holistic balancing methods). Furthermore, the intention was to provide guidelines, recommendations, best-practice examples and background material for designers and decision makers in the fields of building, energy production/supply and politics.

Specific objectives were:

- to develop and improve means for increasing the overall energy and exergy efficiency of communities through demand-adapted supply and inclusion of renewable energy sources.
- to initialize a discussion on how to weigh high-exergy electricity for heating and cooling purposes under the preconditions of local availability.

- to identify the most promising and efficient technical solutions for practical implementation and aspects of future network management and business models for distribution and operation.

Countries which participated in the IEA EBC Annex 64: Austria, Denmark, Germany, Italy, the Netherlands, Sweden, USA, and Turkey as an observer.

The work within Annex 64 was focused on both the theoretical and methodological tools as well as on modelling and on practical implementation. The scope is clearly to evaluate the practical application of low-exergy approaches on a community scale. Thereby, the Annex gave input to further technology development, the understanding of system synergies, and existing implementation barriers.

With this basis and to accomplish the above-mentioned objectives, participants researched developments within the general framework of four fields.

- On the one hand, optimization of the energy demand profiles and the resulting business models for such activities has a focus on the users and the energy utilization within the built environment.
- On the other hand, the optimized utilization of (renewable) energy sources and optimized supply structures are focusing on the structure of the energy supply and the management of the involved infrastructure. For an optimized system, both need to be regarded as an integral energy system.
- To visualize the possibilities and challenges from this approach, as well as the possible implementation of technologies, the realization and the development of model cities, of realized cases, was an important part in the project.
- Finally, for an assessment of both the technologies and case studies, calculation methods and developed tools are further developed and evaluated based on an exergy assessment methodology description.

The knowledge transfer and dissemination activities of the project were focused on the collection and spreading of information on ongoing and finished work of the Annex.

Further information about the project can be found on the internet under:

www.annex64.org or <http://www.iea-ebc.org/projects/project?AnnexID=64>

6.2 IEA HPT Annex 52

Measured long-term performance data for ground-source heat pump systems serving commercial, institutional, and multi-family buildings are rarely reported in the literature. Energy use intensity figures are occasionally published, but as they necessarily lump the

building loads and the system performance together, they are of limited usefulness in understanding real-world system performance.

IEA HPT Annex 52 (2018-2021) – *Long-term measurements of GSHP system performance in commercial, institutional and multi-family buildings* (<http://geoenergicentrum.se/geoenergi-2/iea-hpt-annex-52/>) started its operation in 2018 (operating agent Svenskt Geoenergicentrum). The work within Annex 52 is intended to bridge the gap between those who see the heat pump system as a complex environment and the ground source as a black box, and those who see the ground source as a complex environment and the heat pump system as a black box.

6.2.1 Objective

The Annex 52 aims to survey and create a library of quality long-term measurements of GSHP system performance for commercial, institutional and multi-family buildings. All types of ground sources (rock, soil, groundwater, surface water) are included in the scope. While previous work will be surveyed, the emphasis of the annex will be on recent and current measurements. The annex also aims to refine and extend current methodology to better characterize GSHP system performance serving commercial, institutional and multi-family buildings with the full range of features shown on the market, and to provide a set of benchmarks for comparisons of such GSHP systems around the world.

Analysis procedures that help diagnose poor performance and opportunities for system improvements will be investigated. Multiple case studies featuring GSHP performance measurements for systems around the world will be included and these case studies will serve as reference sets for future benchmarking.

6.2.2 Tasks

Task 1. Long-term measurement case studies – new and previous

- An annotated bibliography covering past GSHP system performance studies will be prepared. As part of this work, a summary of benchmarking results will be developed.
- A report covering case studies of GSHP performance monitoring projects will be prepared. It is expected that each participant will provide at least one case study and some participants will provide more than one. As the projects will be at various stages of completion at the beginning of the annex, it is expected that the more complete projects will provide useful lessons learned and suggested improvements for the newer projects.

Task 2. Guide for instrumentation and measurement of GSHP systems

- A consensus on necessary instrumentation and monitoring (parameters, frequency, instrument quality, etc.) will be reached by the participants.

- A report (guideline document) on instrumentation and measurement of GSHP system performance will be published.

Task 3. Guide for analysis and reporting of GSHP system performance data

- A consensus on key parameters and analysis procedures for GSHP system performance monitoring will be reached.
- A report (guideline document) on analysis and evaluation reporting of GSHP system long-term performance will be published.

6.2.3 1st Annex 52 Kick-off Meeting

This meeting was held on 24-25 May 2018 in Malmö, Sweden, with 24 experts from eight countries (Sweden 15, Germany 1, Finland 3, the Netherlands 1, USA 2, UK 1, Belgium 1, and Denmark 1). Swedish members were the Swedish Geoenergy Center, Geostrata HB, RISE, KTH, Malmberg, ClimaCheck, Xylem, IKEA, EON, EnergyMachines, Geotec, HP Borrningar, LTH/Chalmers. Within this annex, entitled Long-term measurements of GSHP system performance in commercial, institutional and multi-family buildings, a large number of ground source heat pump systems, as well as a couple of ground source systems that do not include a heat pump unit, will be monitored and analyzed from a long-term performance perspective, using and developing the system boundaries presented by the SEPEMO EU-project.

At the meeting, some 35 GSHP long-term monitoring projects in nine countries were presented. Twenty GSHP performance monitoring case studies, located in Sweden, the Netherlands, and the USA, were confirmed as part of the Annex 52 work. Of these case studies, 17 are located in Sweden and cover a range of building types, system applications, and ground sources. The Dutch case studies are mainly groundwater systems and the US case study is a high-profile office building with a distributed GSHP system. Another 15 case studies in Europe were presented at the meeting by the countries that have yet to formally join the annex.

HPT Annex 52 is open to participation from countries that belong to IEA Technology Collaboration Programs HPT, ECES and Geothermal, and the deadline for joining the annex is October 2019.

The Annex 52 categorizes three stages regarding the status of data collection at buildings. According to the level of stages, the approach of data analysis in the project will be modified.

Stage III:

- Project instrumentation, data collection, and analysis are essentially complete. Some further analysis may be done, but the primary contribution of these projects will be to provide benchmarking data, lessons learned, and a case study chapter.

Stage II:

- Project instrumentation is complete, data collection has begun, but analysis has not been completed and additional data collection may be needed.

Stage I:

- Project instrumentation is underway, data collection has not begun.

6.2.4 Case Study (Site visits)

Technical tour 1: Bunkeflostrand, Residential apartment block in Malmö

- GSHP for 220 flats
- 24 boreholes + 160kW HP/plot
- Supply space heating and domestic hot water
- No district heating connection
- 5 years after operation with data collection



Fig. 3.2

Technical tour 2: IKEA Hubhult, Office building in Malmö

- Ground water heat exchange + HP
- Space heating/cooling and domestic hot water
- Electricity consumption of office: 26 kWh/m²a



Fig. 3.3

6.3 On-going Heat-Recovery Projects (HÅVA, KTH)

6.3.1 HÅVA-Project

The HÅVA project (Hållbarhetsanalys av Värmeåtervinning ur Avloppsvatten) focuses on evaluation of heat recovery systems from waste-water and impacts on waste-water treatment. The project partners include, among others, Lund University, RISE, Stångåstaden, Käppala, Tekniska Verken and Sweden Water Research. HÅVA is funded by Formas and runs until early 2020. New dynamic models are created based on simulations combined with three case studies. A literature review has been compiled and the report is available for all participants.

6.3.2 HÅVA Stakeholder Meeting

The meeting held on 13 June 2018, at Käppala WWTP (Lidingö, Sweden) was attended by participants from Lund University, RISE, Käppalaförbundet, KTH and KTH Water Center.

Project Summary

Adnan Ploskic (KTH) gave an overview of the project on efficient heat recovery systems from waste heat in multi-family buildings. Project partners were KTH, SBUF, Bravida, Stockholmshem, etc., with financing by STEM. Key members are Adnan, Qian Wang and Behrouz Nourozi. The project runs until the end of 2018. Recovered heat from waste-water is used for incoming ventilation, but may also be used for defrosting heat exchangers during winter. The use of recovered energy for warm water is becoming a dominating factor for energy-efficient houses. Several papers have been published and submitted to Journal of Applied Thermal Engineering. The project is mainly based on simulations.

Jörgen Wallin (KTH) informed the group about an upcoming project for heat recovery from waste-water at Fältöversten (shopping center in Stockholm) where a new type of heat exchanger was going to be installed. BELOK is running the project.

David Nilsson (Centrumföreståndare WaterCenter, KTH) discussed the potential conflict between stakeholders/operators of different parts of the infrastructure in a city or on a regional level. What is beneficial for one operator may be bad for another one. Consequently, analysis on a high system level is required.

Reference Group Collaboration

The participants decided to continue collaborating by inviting project representatives to attend reference groups meetings for the different projects.

Exchange of Data

The possibility to exchange data between the projects was discussed. HÅVA especially was hoping for data from the existing case studies carried out in the two KTH projects, in order to validate models on building level (production of waste-water flow and temperature, as well as heat exchanger efficiencies, etc.). However, much data is not properly logged for easy use in analysis and requires quite some hands-on work to get it into a proper format for use in other software. Moreover, the data from, e.g., the Beckomberga complex is not the property of KTH and it turned out to be difficult to get permission to provide that data to other projects, like HÅVA. The data that will be generated within HÅVA will most likely be accessible for the KTH projects, although most will be related to measurements in the sewer system and WWTP and therefore of limited use. The possibility to exchange data between the projects was found to be somewhat limited.

Exchange of Modelling/Simulation Experience

The HÅVA project uses MatLab as its main software platform. In the present project R, IBA and to some extent MatLab were used. In Adnan Ploskic's (KTH) project, MatLab and Transient were used. Existing models in Transient are normally used for heat exchangers, heat pumps, etc. HÅVA will not model heat exchangers, etc., in detail and would benefit from access to some simple models. As the meeting ran out of time, there was no possibility to show some modelling examples from HÅVA; they are, however, included here. Christoffer Wärrff is developing a stochastic model (in MatLab) to describe the dynamic generation of waste-water and associated temperature on a detailed level (from each individual appliance—washing machine, dishwasher, toilet, shower, etc.), thereby creating distributions of data with regard to flow and temperature (see Wärrff_Käppala meeting 20180613.pdf). From a single household, the models are then expanded into buildings, and different types of behavior, equipment, etc., can easily be studied. The model will also be expanded to include the pollutants (organics, nitrogen, phosphorus, etc.). Such a model could also be used by the KTH projects to generate very realistic data distributions of waste-water input to heat exchangers on building level. Ramesh Saagi is modelling the sewer and piping system (MatLab) so that various parts of the sewer system can be added together and describe the changes in temperature throughout (Saagi_Käppala meeting 20180613.pdf). Numerous model parameters are needed and the results will be validated using data from the HÅVA case studies. Also, the “famous” Käppala tunnel will be modelled.

Käppalaförbundet and the Käppala WWTP

Stefan presented the main facts and key numbers for Käppalaförbundet and the waste-water treatment plant (WWTP) layout and principle functions (see Erikstam_Käppala meeting 20180613.pdf). Also, special focus was given to the issues related to the temperature of the waste-water, its variation, and impact on the treatment processes. An interesting fact is that Boverket does not issue any rules about how much heat can be removed from the outgoing waste-water from buildings (i.e., minimum outgoing temperature). It states that this is a decision by the individual water and waste-water organizations (VA huvudmannen).

6.4 On-going MSc-Thesis Project (KTH)

An MSc-thesis, entitled “Methodology for Performance Assessment of Waste-Water Heat Recovery System using Big Data” is currently under way and expected to be completed in early Spring 2019. The project includes a knowledge synthesis on heat-recovery from waste-water and focuses on the analysis of 1) heat-recovery from waste-water, and 2) bore-hole heat-exchange in different type of plants.

7 Description of Study Case

7.1 Project Site

The district of Beckomberga is located in Västra Bromma, within the municipality of Stockholm. Beckomberga is today a residential area. In the district, new residential buildings are constructed and old buildings are being converted into apartments and student housing, senior housing, and condominiums. The houses are located around the old hospital park, Klockhusparken. In the middle of the area, there is a heritage-listed pavilion previously used for various joint activities and now a cultural center. Klockhuset, the former administration building, is under remodelling.

There are several landowners in the Beckomberga area and the respective property owners are responsible for operation and maintenance, as well as for the management of streets and squares within each area. Bonava, Veidekke and Besqab developed 241 homes in the southern part of Beckomberga. Wåhlin Real Estate built an eight-story house near Bromma Hospital with 32 rental homes. Riksbyggen built student housing and condominiums in and around the old hospital buildings and Klockhusparken (completed in autumn 2017). And Locum owns Bromma Hospital and part of the field around. The refurbishment of Follingbogatan took place in autumn 2016.

Beckomberga Hospital, the original building, was built in the early 1930s and was once Sweden's largest mental hospital. The management of the park facility was an important part of the patient's treatment. The hospital was wound down after the psychiatric reform in the middle of 1990s when the idea was that mental illness would be integrated with the rest of society instead of sitting at healthcare facilities.

7.2 Project Focus

The residential apartments (316 flats converted from the mental hospital building and 106 residential apartment flats as new construction) developed by Riksbyggen were selected for the study in this project. The project was completed and implemented in 2017.

7.2.1 Space Heating, Ventilation

The energy for heating is delivered by combining geothermal heat from boreholes in the central park, heat recovery from waste-water at every building, and heat pumps at the energy centre. The heating demand of the building blocks is estimated at 2.1 GWh/year. The peak heat demand is redundant by the district heating network.

7.2.2 Domestic Hot Water

The building blocks are connected to the district heating network to supply heat for domestic hot water. The domestic hot water demand including VVC losses is estimated as 1 GWh/year.

7.2.3 Heat Production

There are two types of heating energy solutions, geothermal heat application and heat recovery from waste-water. The operation of the energy system is monitored, and long-term energy monitoring is implemented.

7.3 Heat Generation and Storage

7.3.1 Heat Pump System

Two HPs in the heat center (Bergvärme Center) generate heat and deliver it to five building blocks. The specification is shown in the Table 4.1.

Table 4.1 Specification of HP

Product 30HXC175-PH3 opt150	
Series 30HXC Phase3 Option150 (High Condensing)	Number of compressors 2
Total power 322 kW	Compressor type screw
Supply power 197 kW	Compressor speed 49 r / s
Compressor power output 197 kW	Starting equipment type WYE / DELTA
C.O.P. 1.64	Volt / Phase / Hertz 400-3-50
Number of power stages 6	Power factor (0.87)
Minimum step 21%	Full load current 377 A (U nom.)
Refrigerant R134a	Maximum starting current 576 A
Expansion valve EXV	Voltage limits 360/440 V
	Operating weight 3,083 kg
	Refrigerant filling 104 kg
	L/ W/ H: 3275/ 980/ 1,940.5 mm
Evaporator	Condenser
Propylene Glycol 25%	Liquid Water
Outbound temperature 2 ° C	Initial temperature 57 ° C
Delta T. 4K	Delta T. 6K
Initial temperature 6 ° C	Outbound temperature 63 ° C
Flow 20 L / s	Flow 20.3 L / s
Vapor pressure drop 39 kPa	Pressure drop 20 kPa
Försmuts. factor 0.04403 m ² -K / kW	Försmuts. factor 0.04403 m ² -K / kW
Max. Water pressure 1000 kPa	Max. Water pressure 1000 kPa

7.3.2 Waste-Water Heat Exchanger (Spillvattenvärmeväxlare, S01, S02, S03)

Heat from of the circulated water is recovered by exchangers which collect from waste-water. Heat recovery from waste-water is estimated as 0.6 GWh / year in total.

- P1 starts and SV41 opens when the temperature at-GT51 exceeds the value at 17-GT41 more than set value. P1 stops and SV41 switches the temperature difference -GT51 - 17-GT41 below the set stop value.
- P1 stops and SV41 closes even if the temperature difference S01 / S02 / S03-GT41 - 17-GT41 is below the set limit time delayed 5 min (adjustable). Restart after 10 min (adjustable).

7.3.3 Ground Source Heat Storage

After circulating five building blocks, the heat of the circulated water is charged or discharged at boreholes, which is located in the central yard. There are 10 wells, 90 boreholes in total, 220m depth.

7.3.4 Air Handling Units (VÅ)

At every building block, heated circulated water is delivered to the air handling unit for ventilation and space heating. It is activated in case the air temperature of the attic space is higher than the temperature of the circulated water. The operation is as follows:

- FF01 and P1 start and SV41 opens when the temperature in the room at-GT51 exceeds the value at 17-GT41 more than set value. FF01 and P1 stop and SV41 switches the temperature difference -GT51 - 17-GT41 below the set stop value.
- FF01 and P1 stop and SV41 closes even if the temperature difference VÅ01 / VÅ02-GT41 - 17-GT41 is below the set limit time delayed 5 min (adjustable). Start-up after 10 minutes (adjustable).
- Anti-freezing mode: When the temperature in the room at-GT51 falls below the set value, P1 starts and SV41 opens and is in operation or open intermittent with the set time interval until the room temperature has risen above the value.

- **Table 4.2** Specification of AHU

VÅ01-FF1-ÅL1

Manufacturer AIA Battery Type 35x30, 3.

Propylene glycol 40%.

Airflow: 5.0 m³ / s

Temp in / out: 25/16° C

Pressure drop: 46 Pa

Power: 60 kW

Liquid flow: 3.58 l / s

Temp in / out: 12/16° C

Pressure drop: 27 kPa

Dimension B = 1,400 mm H = 1,700 mm D = 300 mm.

Pipe connection DN76. Complete with drip tray.

7.4 Delivery Process

The heat generated by HPs at Bergvärme Center is circulated in the district, starting from Granngården, through Klockhuset, Trädgården, Borggården, and Vingården, and back to Bergvärme Center.

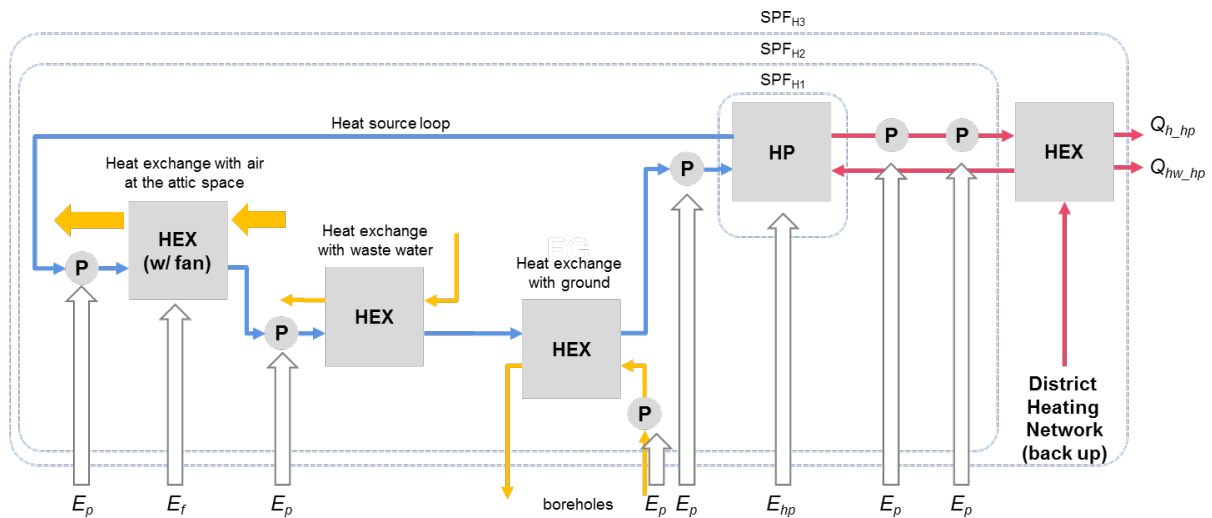


Fig. 4.1

7.5 Pump System

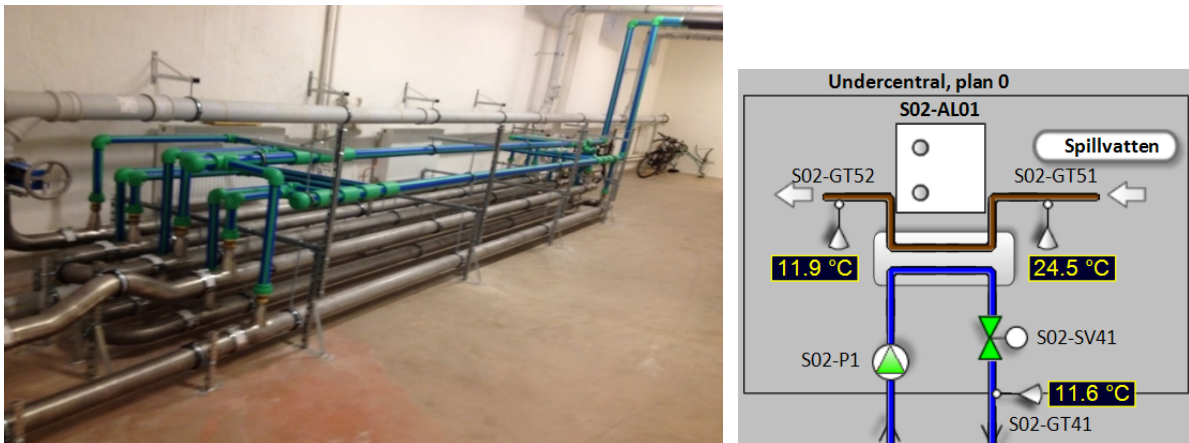
The specification of pumps installed in the heat system are shown in Table 4.3. KB01-P1 is the pump for circulating cold water, and KM-1-P1 is the pump for the circulation between boreholes and heat exchanger.

Table 4.3 Specification of pump

KB01-P1 1 ST	KM01-P1 1 ST
Manufacturer: Grundfos	Manufacturer: Grundfos
Type: TPE 100-360 / 2	Type: TPE 100-360 / 2
Flow: 47.6 l / s	Flow: 47.6 l / s
Pressure increase: 133 kPa	Pressure increase: 210 kPa
Pump media propylene glycol 40%.	Pump media bioethanol 18% Control:
Electricity: 3x400V, 18 kW	Electricity: 3x400V, 18.5 kW

7.6 Waste-water Heat Exchanger

The installed heat exchanger is counter current flow (CCF). CCF installed in Beckomberga site is via horizontal heat exchangers, which are based on the model “CCF Spillvattenväxlare”. Its temperature efficiencies vary between 15% and 40% (Engelholm, 2015), and the modelled heat exchanger was assumed to work at an average efficiency of 20%.

**Fig. 4.2** Heat recovery system**Table 4.4** Specification of pumps at AHU and VXX

<i>024-S01-P1, 024-S02-P1</i>	<i>024-VÅ01-P1</i>
Propylene glycol 25%	Propylene glycol 25%.
Manufacturer: Wilo,	Manufacturer: Wilo,
Type Stratos 50 / 1-12	Type Stratos 65 / 1-12
Flow: 5.5 l / s	Flow: 5 l / s
Pressure increase: 50 kPa	Pressure increase: 65 kPa
E1: 1x230V, 25-590W	E1: 1x230V, 25-590W

8 Data Collection

8.1 Monitoring System

The energy system at Beckomberga site is monitored by a building management system (BMS). The operation status of the system can be monitored remotely. The project accessed the BMS system and downloaded the all data relating to the heating supply system, including heat recovery from waste-water, ground source heat exchanger, and HP.

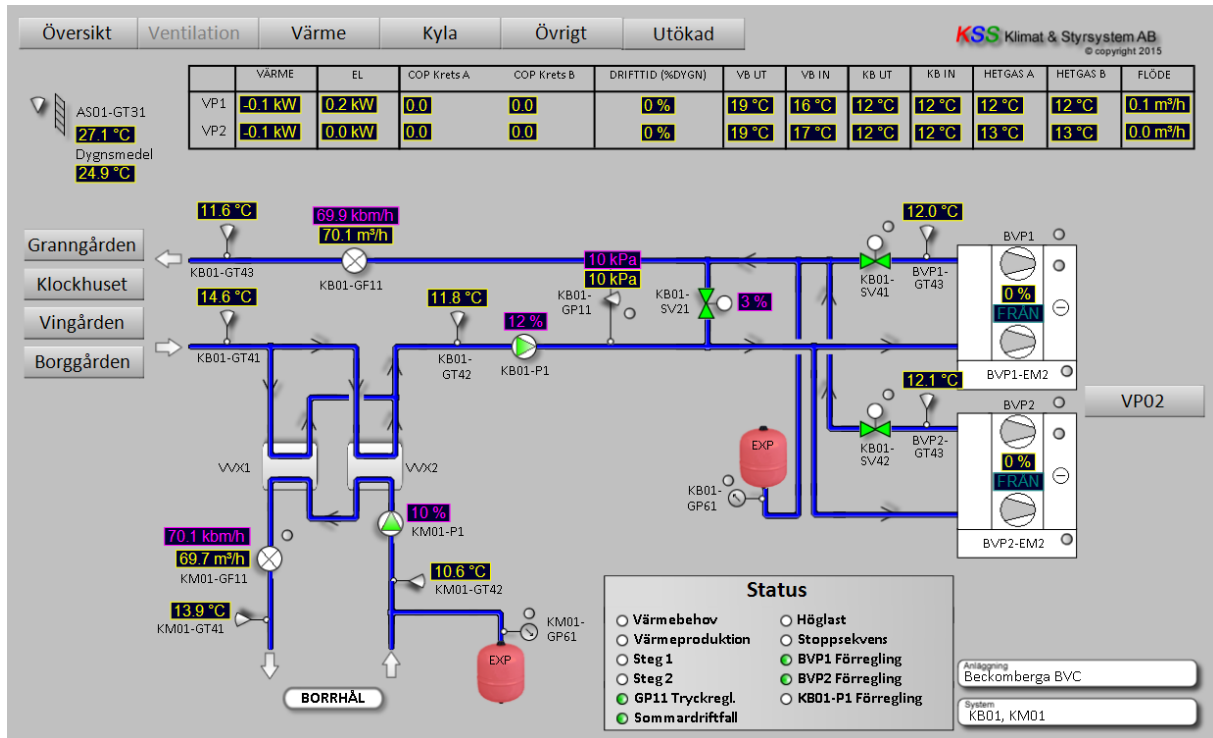


Fig. 5.1 GUI of the monitoring system

Due to technical problems at the site, the recorded data was damaged several times when the energy system malfunctioned. Because of this, the BMS was rebooted and all recorded data was lost. The collected data, which is available for the post-processing analysis in this project, covers 5 months from 1-11-2017 to 31-3-2018. Thus, this project utilized the available 5 months' measured data.

8.2 Limitations

8.2.1 Data Access

The status of system operations and the values of measurement points were monitored remotely (on-line). The original function of the BMS is to check the status of system operation. This is the reason why the preparation for data management as post-processing analysis is not established at all and limits the research. It is necessary to design and install BMS to be able to assess system performance.

Related to the reason above, the project had difficulty communicating with the contact persons from the industry who deal with on-site monitoring of the facility. Collecting the preliminary data sets from the BMS server was very time-consuming.

In addition, the collected data were in an unusable format. The problem was solved and the analysis process could be launched. However, key data needed for the performance analysis was lacking, and an alternative approach to analysing the system performance methodology needed to be developed.

Table 5.1 Status of data accessibility

<i>Values</i>	<i>Heat recovery system</i>	<i>Borehole heat storage</i>
Temperature of water	Almost available	Available
Flow rate	Partially available	Partially available
Pressure	Not available	Not available
Secondary system	Not available	-
Energy use of the system	Not available	Not available
Input from district heating	Not available	-

8.2.2 Quality of Data

Unreliable data were found in the temperature values of the circulated cold water, mainly due to poor sensor quality. The analysis began with checking the temperature levels of the process and utilized the data set.

Table 5.2 shows the list of data quality of the heat exchangers. Only three of ten heat exchangers offered reliable datasets, which are logically correct based on the basic law of thermodynamics.

Table 5.2 Status of data quality

No.	Building	System name	The quality of data
1	Granngården	S01-AL01	Logically correct
2		S02-AL01	Uncertain data are included in the value Tc.in
3		S03-AL01	Logically correct
4	Klockhuset	S01-AL01	Uncertain data are included in the value Tc.in
5	Tradgården	S01-AL01	Uncertain data are included in the value Tc.in
6	Borggården	S01-AL01	Uncertain data are included in the value Tc.in
7		S02-AL01	Uncertain data are included in the value Tc.in
8	Vingården	S01-AL01	Logically correct
9		S02-AL01	Uncertain data are included in the value Tc.in
10		S03-AL01	Uncertain data are included in the value Tc.in

9 Methodology for System Performance Analysis

9.1 Models

In this study, the different heat exchangers' performance is evaluated based on previously measured or assumed temperature efficiencies of the models. Temperature efficiency η_{temp} is defined as:

$$\eta_{temp} = \frac{T_{c.out} - T_{c.in}}{T_{w.in} - T_{c.in}} \quad (\text{eq 6.1})$$

Where η_{temp} is temperature efficiency [-], $T_{c.out}$ as temperature of preheated cold water leaving the heat exchanger [°C], $T_{c.in}$ as the temperature of cold water entering the heat exchanger [°C], and $T_{w.in}$ as the temperature of waste-water entering the heat exchanger [°C].

9.1.1 Logarithmic Mean Temperature Difference (LMTD)

The other theory, which is applied widely in heat transfer analysis, is LMTD (Logarithmic Mean Temperature Difference). This model is the case of countercurrent flow.

$$LMTD = \frac{(T_{c.out} - T_{w.in}) - (T_{w.out} - T_{c.in})}{\ln\left(\frac{T_{c.out} - T_{w.in}}{T_{w.out} - T_{c.in}}\right)} \quad (\text{eq 6.2})$$

The recovered heat, efficiency and effectiveness of the system were calculated based on the following equations.

The recovered heat

$$\dot{Q}_R = \dot{m}_c C_{p,c} (T_{c,o} - T_{c,i}) \quad (\text{eq 6.3})$$

The efficiency

$$\eta = \frac{\dot{Q}_R}{\dot{m}_h C_{p,h} (T_{h,i} - T_{h,o})} \quad (\text{eq 6.4})$$

The effectiveness

$$\varepsilon = \frac{\dot{Q}_R}{\dot{m}_h C_{p,h} (T_{h,i} - T_{c,i})} \quad (\text{eq 6.5})$$

In addition, the \dot{m}_c and $C_{p,c}$ are, respectively, the mass flow rate and specific heat of the cold water. \dot{m}_h and $C_{p,h}$ are, respectively, the mass flow rate and specific heat of hot water. $T_{c,i}$ and $T_{c,o}$ are the inlet and outlet of the coiled supply pipe (cold side of the heat exchanger),

respectively, and $T_{h,i}$ and $T_{h,o}$ are, respectively, the inlet and outlet of the drainage pipe (hot side of the exchanger).

9.1.2 Exergy Analysis

An exergy analysis was carried out To this end the first step is to define the energy balance between incoming energy (E_{in}) and out-going (E_{out}). In the case of this project, delivered heat energy from waste-water to the cold water, and it is assumed that no energy is stored (E_{store}) in the study boundary.

$$E_{in} = E_{store} + E_{out} \quad (\text{eq 6.6})$$

Second, entropy (S) is determined by considering reference temperature T_{ref} [K]. In this study, the outdoor temperature (T_o , [K]) is applied. In the balance of entropy, the value of generated entropy (S_g) is always positive.

$$S_{in} + S_g = S_{out} \quad (\text{eq 6.7})$$

$$S = C\rho V \ln \frac{T}{T_{ref}} \quad (\text{eq 6.8})$$

In the third step, eq 6.7 and eq 6.8 are combined as eq 6.9. Thus, exergy is calculated as eq 6.10.

$$E_{in} - (S_{in} + S_g)T_o = E_{out} - S_{out}T_o \quad (\text{eq 6.9})$$

$$X = C\rho V \left\{ (T - T_o) - T_o \ln \frac{T}{T_o} \right\} \quad (\text{eq 6.10})$$

$$X_{in} + X_c = X_{out} \quad (\text{eq 6.11})$$

Where X_c is the consumed exergy through the process of heat exchange. The exergy models are developed for analyzing the behavior of exergy consumption within the boundary of 1) Heat exchanger at waste-water, and 2) Heat exchanger at borehole.

9.2 Mathematical Model Development

For the analysis, the mathematical models are developed under the platform of R. Based on analysis, methodologies which are studied in the previous chapter clarify the performance regarding target parameters. All collected data were treated and managed at the R environment. In addition, energy and exergy models were developed and the performance of the target systems were evaluated.

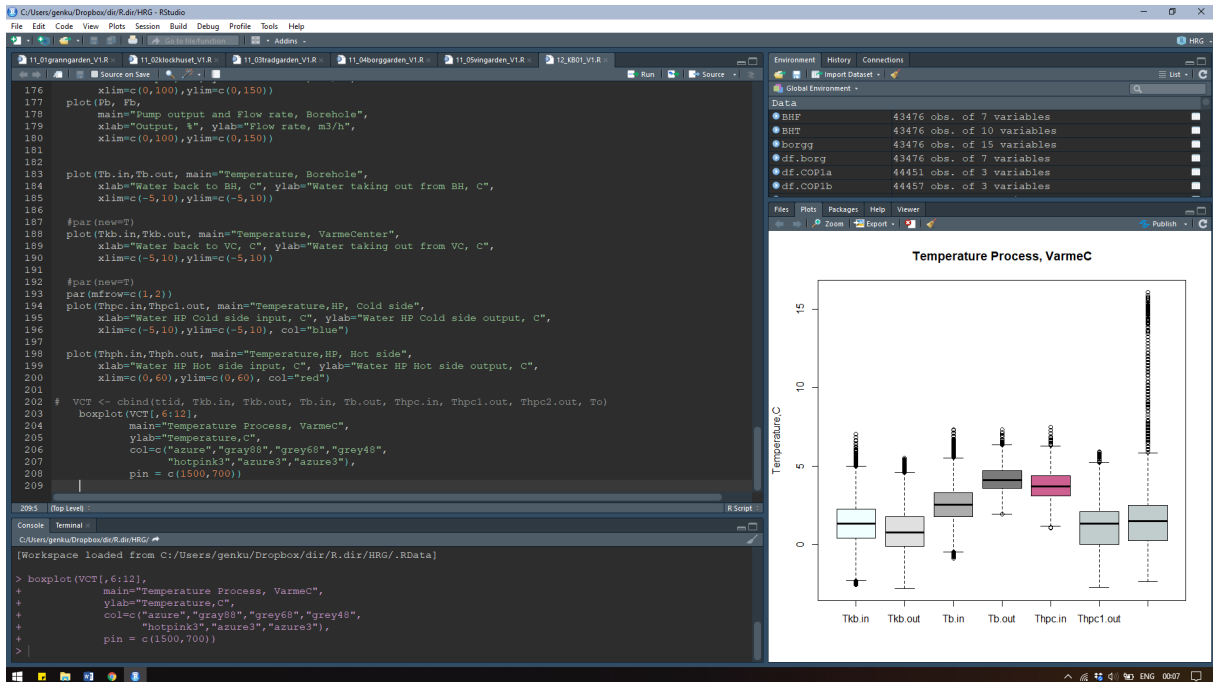


Fig. 6.1

10 Experimental Study using the Test Rig

10.1 System Description

Fig. 7.1a-c shows the test rig and its system flow chart. The test rig was designed and constructed to test waste-water heat exchanger systems at different water temperatures. A heat pump of 25 kW heating power produces both cold as “main water” and warm as “waste-water”. Clean water is used on both sides since raw sewage is neither chemically nor mechanically stable over time. There is also a possibility to run the cold side with propylene glycol or other common heat pump cooling brines.



Fig. 7.1a Test rig



Fig. 7.1b Test rig

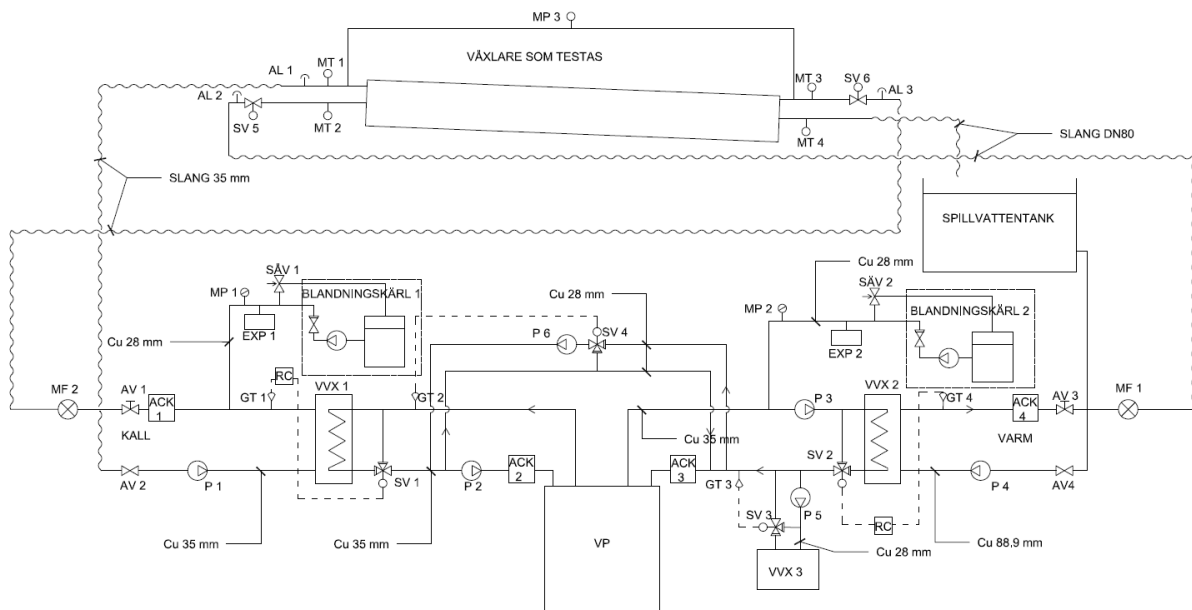


Fig. 7.1c Test rig system flow chart

The temperatures are measured at the center of the stream using submerged Pt100 sensors. The heat pump producing the hot and cold water for the test rig is I/O controlled (Fig 7.2). In order to regulate the temperatures of the incoming water quickly, the length between hot and cold sides of the heat pump can be shortened by opening the valve SV4.

The volume flows of the hot and cold side are measured using inductive flow meters (MF1, MF2). These flow meters also provide input to the variable-frequency driven pumps. The volume flow is assumed to uniform in the whole circuit at all times.

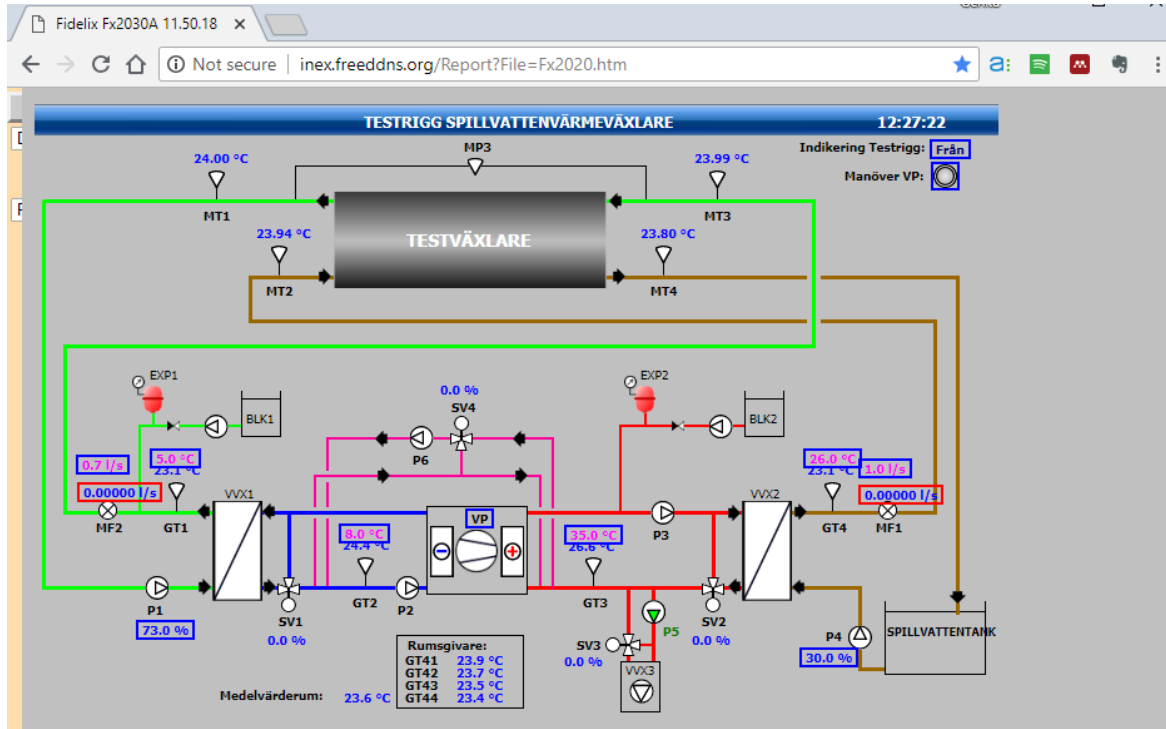


Fig. 7.2 Screen-shot from test rig control monitor

10.2 Heat Exchanger Validation

A methodology for testing waste-water heat exchangers and prediction of their performance within systems is the outcome of these experiments. A proposed validation algorithm for lab experiments is:

- Log incoming and outgoing temperatures of the water at steady-state heat transfer, using average temperatures of waste-water and cold water. Use a volume flow rate corresponding to the mean of the most frequently occurring volume flows, chosen from a duration diagram or expected flow profiles.
- Calculate the effectiveness and NTU for the flows above. This will serve as an average for the time of the duration diagram used. Yearly averages should be supported by monthly averages.

- Test the reaction time of the heat exchanger by starting at a steady state, then abruptly change the volume flow and measure the elapsed time until a new steady state is reached.

10.3 Purpose

Using the test rig, the sensitivity analysis to collect the performance data of the heat exchanger was conducted. Since the waste-water flow is often not measured, as was the case at the Beckomberga complex, it is not possible to apply common performance evaluation methods for the heat exchanger. Thus, the main aim of this study is to understand the relationship of water flow volumes of cold water and waste-water.

10.4 Test Conditions

The experimental test setting is shown in Table 7.1. The output of the pump at the cold-water side (P1) is fixed in three steps. At each P1 setting, the output of the pump at the waste-water side (P4) is changed between 16% and 40% in a 2% interval. Temperatures of cold water ($T_{c.in}$) and waste-water ($T_{c.out}$) are fixed at 5°C in cold water and 28°C in waste-water. The temperatures affect the influences from the flow rate, so the error range is accepted in this experiment.

Table 7.1 Setting of test

Parameter	Setting	Remark
V_c	0.5, 0.6, and 0.7 l/s	Output of pump at cold water supply (P1)
$T_{c.in}$	5°C, constant	Temperature of cold water
V_w	16 - 40%, 2% steps	Output of pump at waste-water supply (P4)
$T_{w.in}$	28°C, constant	Temperature of waste-water

11 Results and Discussion

11.1 Waste-water Heat Exchanger

Fig. 8.1 shows the model of the waste-water heat exchanger. The flow rate of waste-water (V_w) is the unknown value in this model.

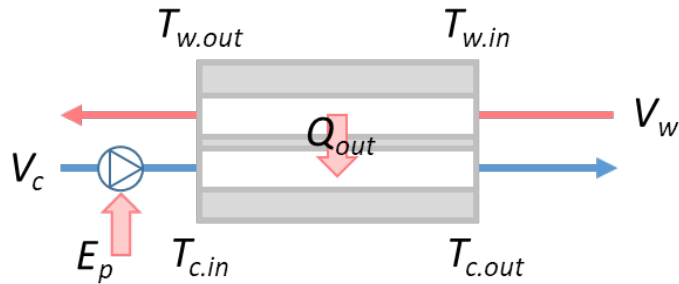


Fig. 8.1 model of waste-water heat exchanger

11.1.1 Water Flow Rate

The water flow rate for each heat exchanger is 0.4 l/s per one heat exchanger component, thus 3.2 l/s in total. The pump (capacity 5.5 l/s) is installed to get the constant cold water flow.

11.1.2 Temperature

Fig 8.2 shows the heatmap of waste-water at the input side ($T_{w.in}$) and the output side ($T_{w.out}$) during the period from January to the middle of May. Since the heating period ended at the beginning of April, the temperature decrease ended at the same time. Generated waste-water temperature was almost the same between heating and non-heating period.

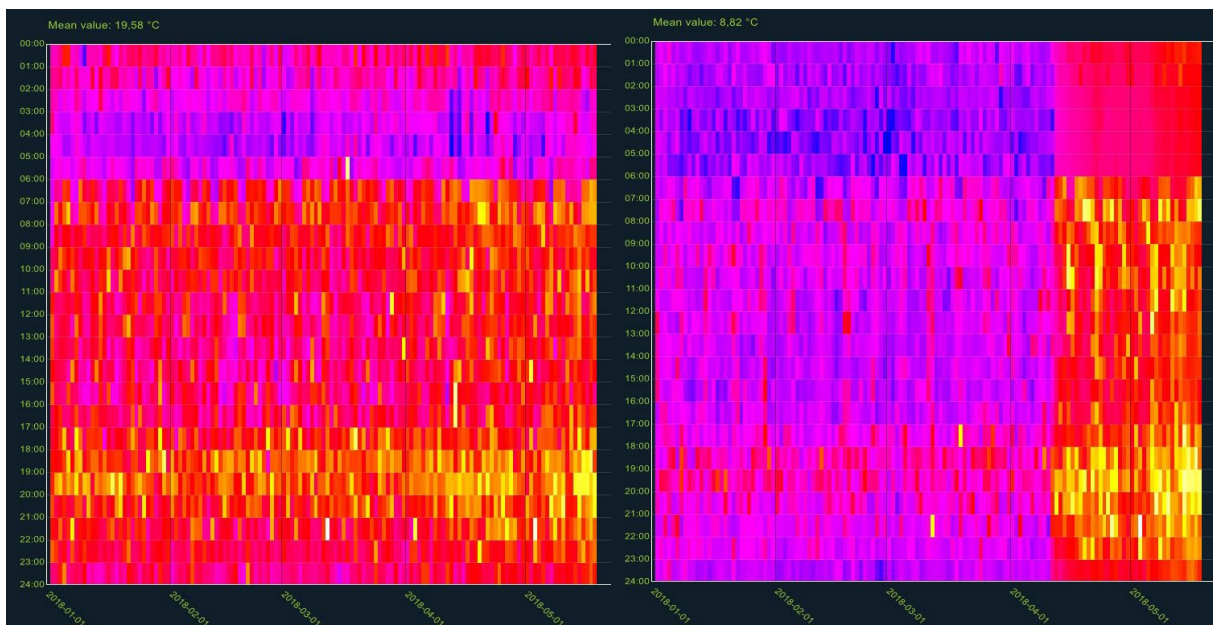


Fig. 8.2 Heat map of waste-water at input side ($T_{w.in}$, left) and output side ($T_{w.out}$, right)

Fig. 8.3 shows the waste-water temperature around the heat exchangers in the building Granngården. The temperature of the waste-water was around 20°C through the day (left row of Fig. 8.3). Temperature gaps before and after the heat exchangers were around 10–13°C through the day (right row of Fig. 8.3). The potential heat contained in the waste-water was as expected and the heat from waste-water was transferred to the circulated water. The temperature of the waste-water was around 15–20 °C on average. The temperature was high at 6–7 am and at around 6–7 pm. The temperature overnight was lower than other periods. The temperature gap was 10–13 °C on average. From the temperature analysis, the potential of the heat source is estimated for a 24-hour period.

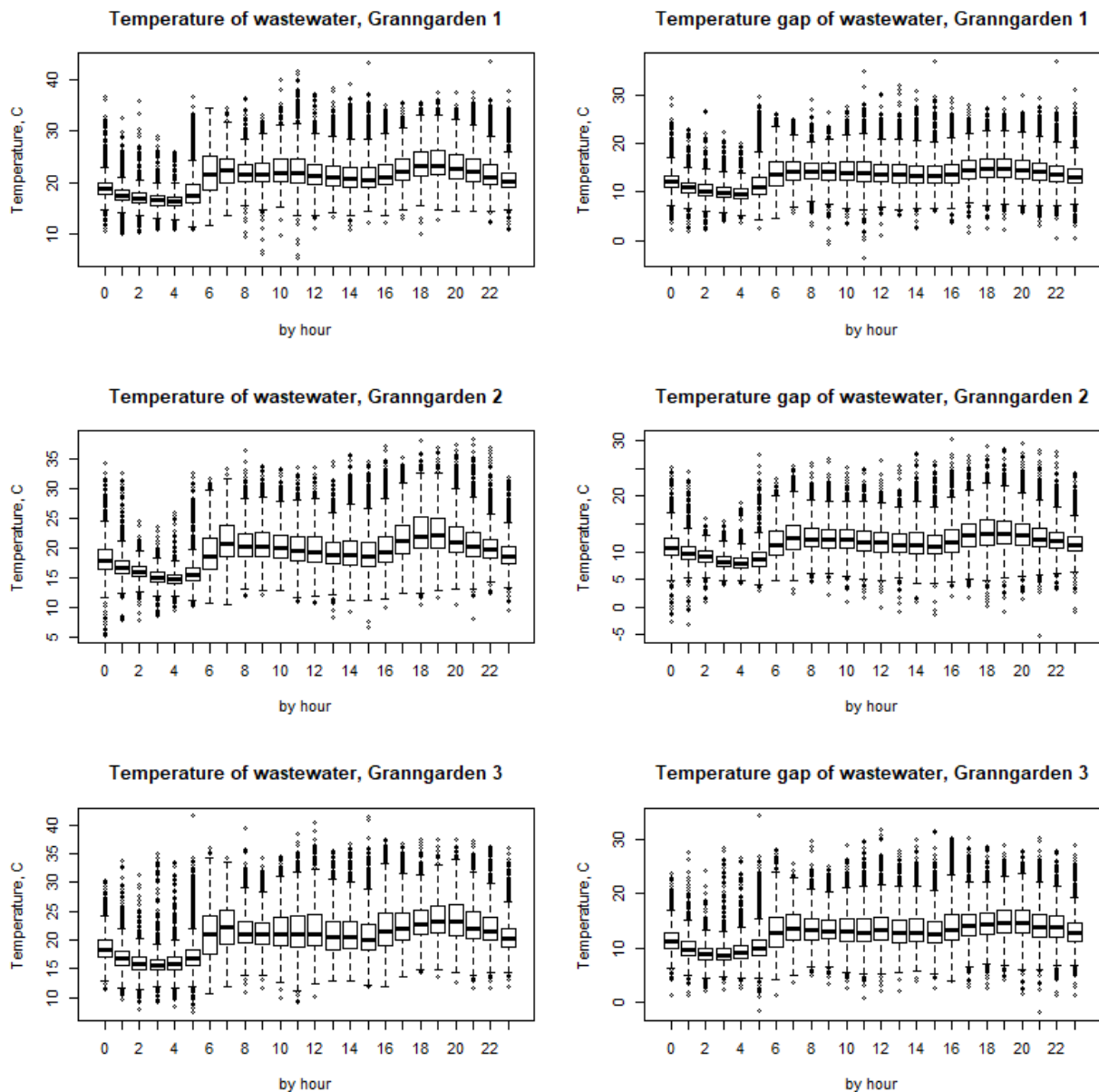


Fig. 8.3 Waste-water temperature around the heat exchangers in the Granngården building.

11.1.3 Logarithmic Mean Temperature Difference, LMTD

Fig. 8.4 shows the trends of LMTD values in each heat exchanger at the apartment Granngården. LMTD values were calculated using all hourly data, and the figure shows the average at each hour. The LMTD averaged 10°C. The value was basically constant, but dropped slightly overnight.

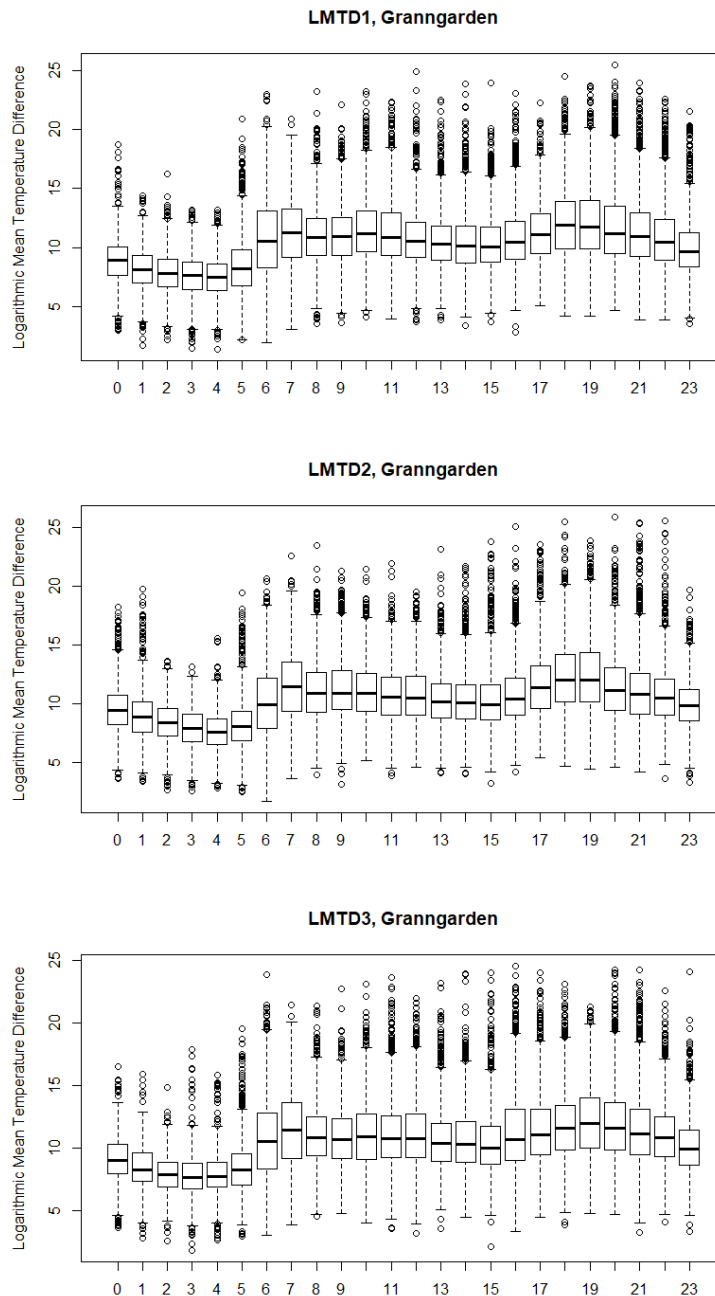


Fig. 8.4 LMTD at the heat exchangers for Granngården (S01-AL01, S02-AL01, S03-AL01)

11.1.4 Energy Balance

Fig. 8.5 shows the trend of energy from waste-water (Q_{out}) and electricity input to the pump (E_p). The result of two heat exchangers (upper: S01-AL01, lower: S03-AL01) in Granngården were applied in the study. Since the flow rate of waste-water (V_w) is not measured, the delivered energy was estimated with the temperatures of cold water (T_c), waste-water (T_w) and the flow rate of cold water (V_c). The amount of generated waste-water and its flow rate affect the deliverable energy. The result showed that energy delivery overnight was high through the day. The flow rate of waste-water decreased because of low activity and it resulted that there was enough time to transfer the heat to the cold water. Consequently, there is a tradeoff relationship between the amount of generated waste-water and delivered heat energy, making moderated waste-water generation a key focus of the next coming study. Energy study clarified that 10.7kW (on average, 1.1 - 38.7kW) of heat from waste-water was delivered to the cold water side.

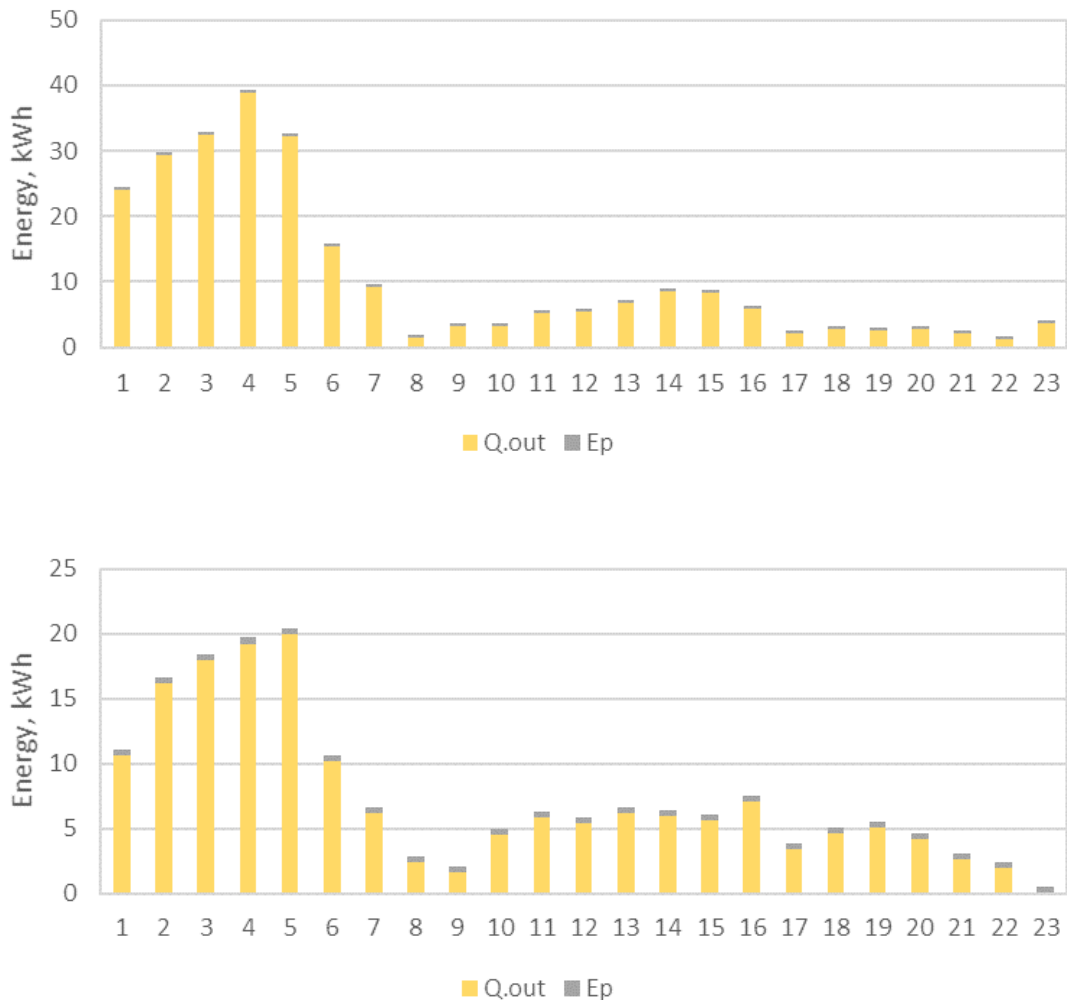


Fig. 8.5 Exergy balance (upper: S01-AL01, lower: S03-AL01)

11.1.5 Exergy Balance

Fig. 8.6 shows the exergy balance of two different heat exchangers (upper: S01-AL01, lower: S03-AL01) in Granngården. The positive side of the Y-axis indicates the incoming exergy into the system, and the negative side indicates the amount of outgoing exergy. The exergy of incoming cold water ($X_{c.in}$, light blue) increased after exchanging heat ($X_{c.out}$, dark blue). The exergy of incoming waste-water ($X_{w.in}$, dark orange) decreased ($X_{w.out}$, light orange) because some parts were delivered to the cold water and other parts were consumed (X_{cons} , green). The exergy input (E_p , grey) and consumption ($X_{cons.ep}$, light green) at the pump were included in this balance. In both cases, the waste-water overnight has more exergy than at other times. The energy and exergy analysis brought the understanding of actual system performance and practical knowledge when applying values from BMS. Exergy analysis clarified that 12% (on average, 3–24%) of exergy contained in the waste-water was delivered to the cold water and 76% (on average, 60–88%) was consumed during the process.

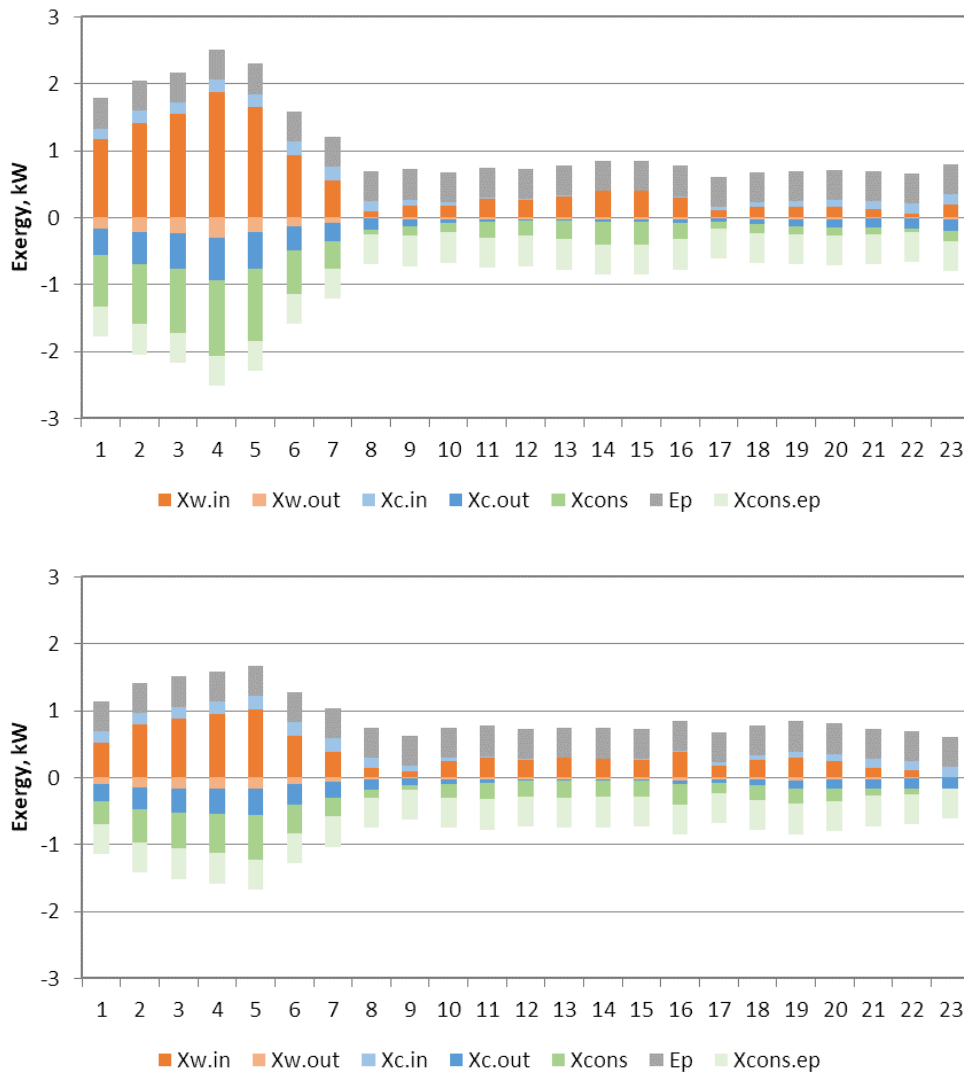


Fig. 8.6 Exergy balance (S01-AL01, S03-AL01)

11.2 Borehole Heat Exchanger

Fig. 8.7 is the model of borehole heat exchanger. In the model, V_c is an unknown value.

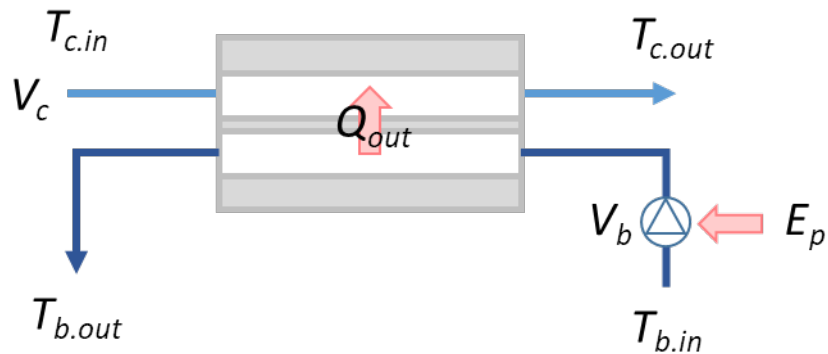


Fig. 8.7 model of borehole heat exchanger

11.2.1 Water Flow Rate

Fig. 8.8 shows the water flow rate (V_b) at the circulation between borehole and heat exchanger. The water flow is constant at $70\text{m}^3/\text{h}$ in November and $140\text{m}^3/\text{h}$ in other months.

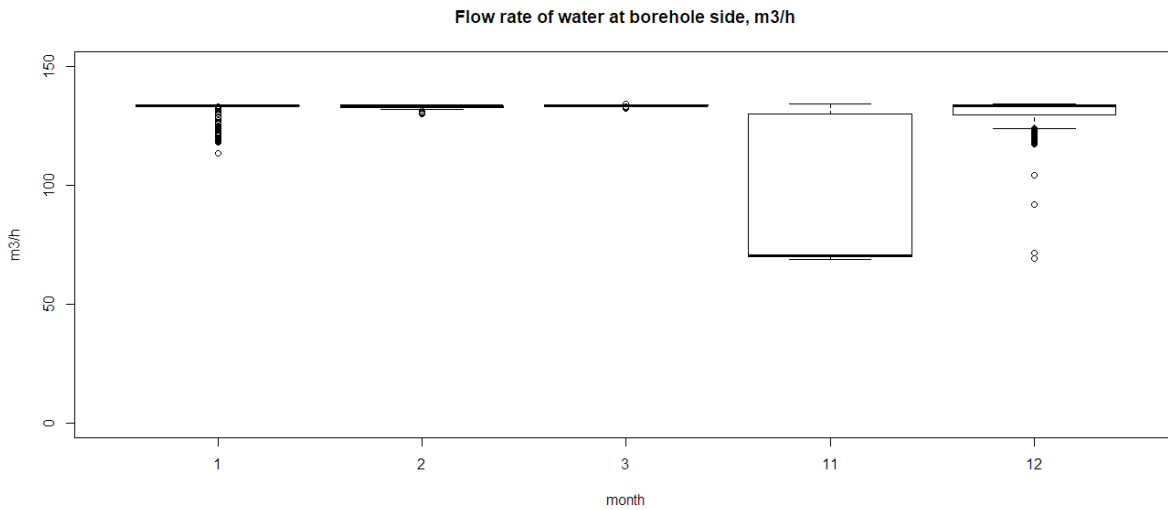


Fig. 8.8 Water flow rate of borehole side (monthly)

11.2.2 Temperature

Fig. 8.9 shows the temperature of the water pumped up from boreholes and entering the heat exchanger ($V_{b.in}$). The temperature was almost constant around 2.2–2.3°C throughout the day. The result means that the temperature of the ground was very stable through the day without any destruction of a thermal condition under the ground in this case.

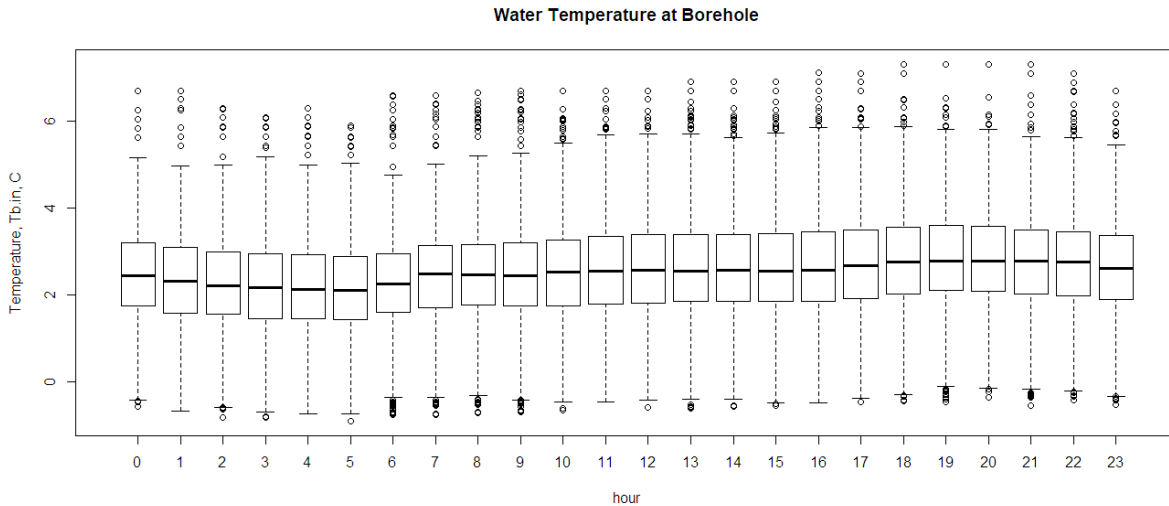


Fig. 8.9 Water temperature at borehole side (hourly)

11.2.3 LMTD

Fig. 8.10 shows the LMTD around the heat exchanger at the borehole. LMTD is 2.2°C on average. The result of LMTD also means that the operation of discharging heat from the ground is stable.

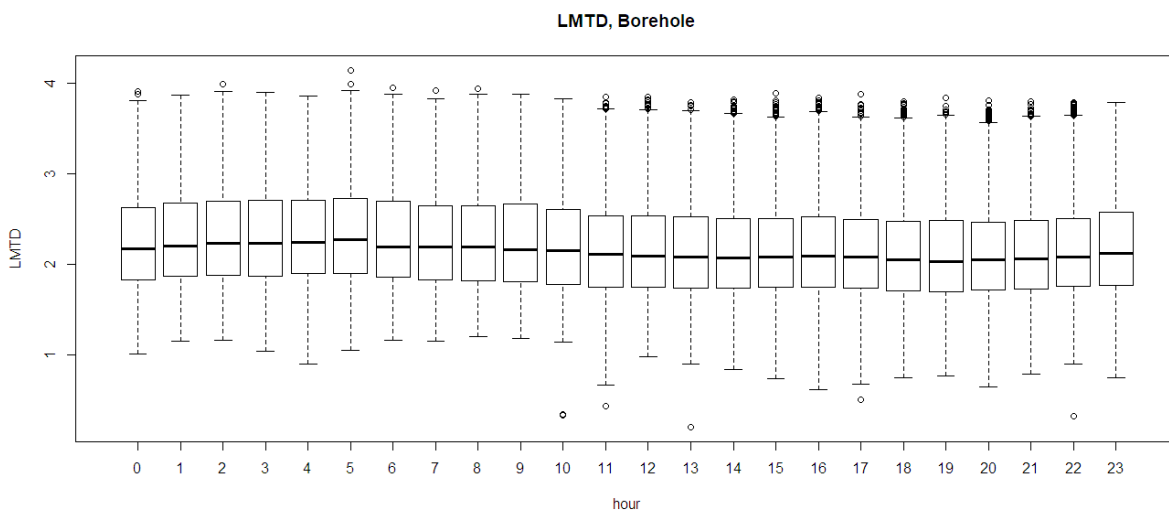


Fig. 8.10 LMTD around heat exchanger at borehole (hourly)

11.2.4 Energy Balance

Fig. 8.11 shows the trend of energy gain by exchanging heat from the borehole (Q_{out}), and electricity use at the pump (E_p). Q_{out} is 247kW on average and 293kW at maximum at 4 am. Since the pump worked at a constant output, E_p is always 18.5kW. The energy gain from the borehole was high overnight and constant during the day. The ratio of E_p occupied only 7% (on average) of total energy. Because the available data for analysis are only for the winter, the behavior of discharging heat from the borehole can be analyzed. To study the behavior of charging heat to the borehole will be a future research focus.

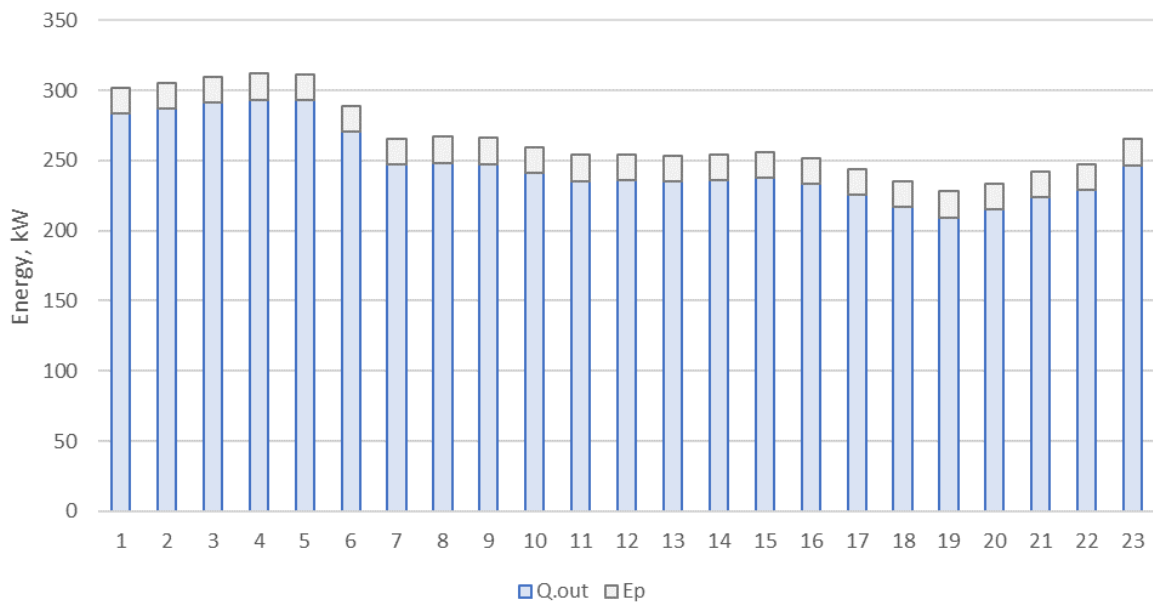


Fig. 8.11 Energy balance at the borehole heat exchanger

11.2.5 Exergy Balance

Fig. 8.12 shows the exergy balance at the heat exchanger at the borehole; the upper bar plot figure shows the exergy balance heat delivery process, and the lower one indicates the exergy balance including pump input. E_p is added in the input side and the exergy consumption at the pump ($X_{cons,p}$) is added in the output side. The positive side of the Y-axis is the input into the boundary and negative side indicates the output from the boundary. The exergy balance increases from 2 pm to 7 am, and the period during 12pm and 1 pm is the minimum balance. 48% of exergy from the borehole ($X_{b,in}$) is delivered to the cold water side ($X_{c,out}$), and 27% is consumed through the process (X_{cons}). The result shows the exergy input to the pump (E_p); exergy consumption at the pump ($X_{cons,ep}$) occupies the large part of the balance. If the capacity of the pump could be minimized, E_p and $X_{cons,ep}$ would be reduced. That is a further research question to optimize the number of boreholes and the capacity of the circulation pump.



Fig. 8.12 Exergy balance at the heat exchanger at the borehole

11.3 Heat Pump

Fig. 8.13 shows the model of the heat pump. Incoming water temperature of demand side ($T_{hph.in}$) is an unknown value.

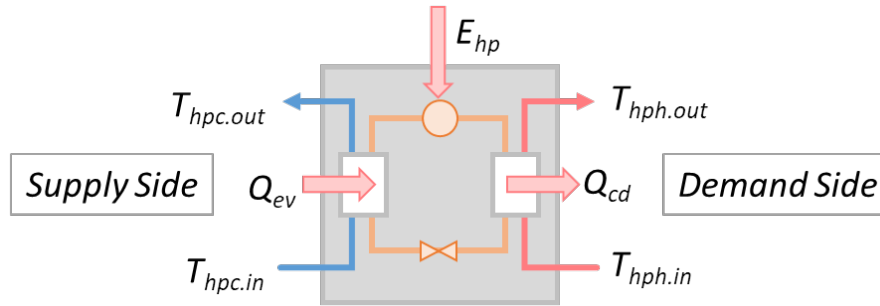


Fig. 8.13 model of heat pump

11.3.1 Water flow rate

Fig. 8.14 shows the water flow rate of the circulated water, monthly and hourly. There are two statuses of water flow operation, 70 m³/h in November and 130 m³/h in other months. The flow rate was constant throughout the day. This means the water flow rate is generally balanced as the same rate.

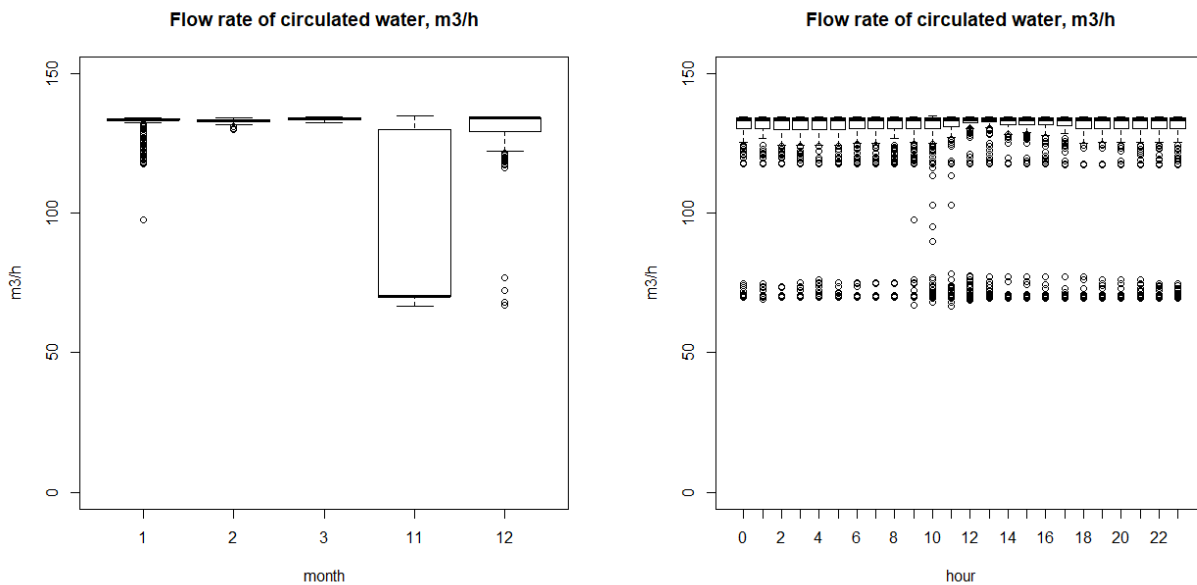


Fig. 8.14 Water flow rate of the circulated water (monthly, hourly)

11.3.2 Temperature

Fig. 8.15 shows the temperatures around the heat pump, incoming ($T_{hpc.in}$) and outgoing ($T_{hpc.out}$) water at the supply side, and Fig. 8.16 shows the incoming ($T_{hph.in}$) and outgoing ($T_{hph.out}$) water at the demand side. $T_{hpc.in}$ is 3.7°C on average and $T_{hpc.out}$ is 1.0°C on average. The temperature at the demand side increased from 46.9°C to 47.0°C . The trend of temperature was constant.

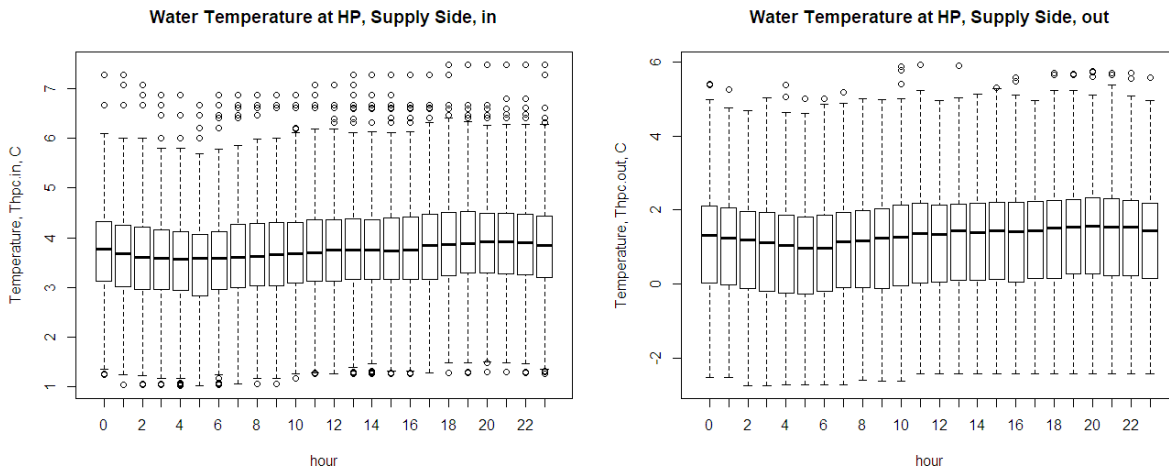


Fig. 8.15 Incoming ($T_{hpc.in}$) and out-going ($T_{hpc.out}$) water temperature at supply side

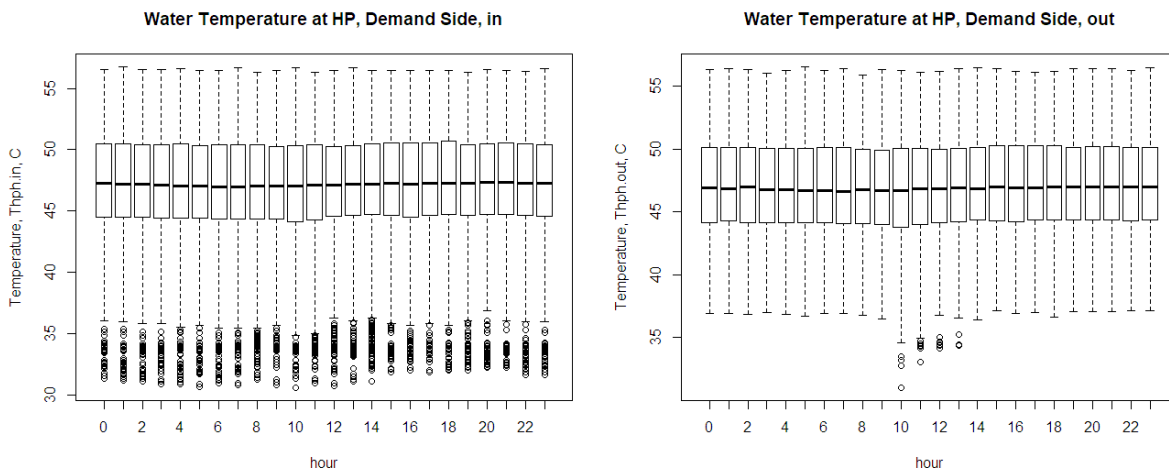


Fig. 8.16 Incoming ($T_{hph.in}$) and out-going ($T_{hph.out}$) water temperature at demand side

11.3.3 Energy Balance

Fig. 8.17 shows the balance of energy at the heat pump of the supply side (evaporator side, Q_{ev}) and electricity input (E_{hp}) at the positive side of the Y-axis and the demand side (condenser side, Q_{cd}) at the negative side of the Y-axis. The COP is estimated at 3.09 on average.

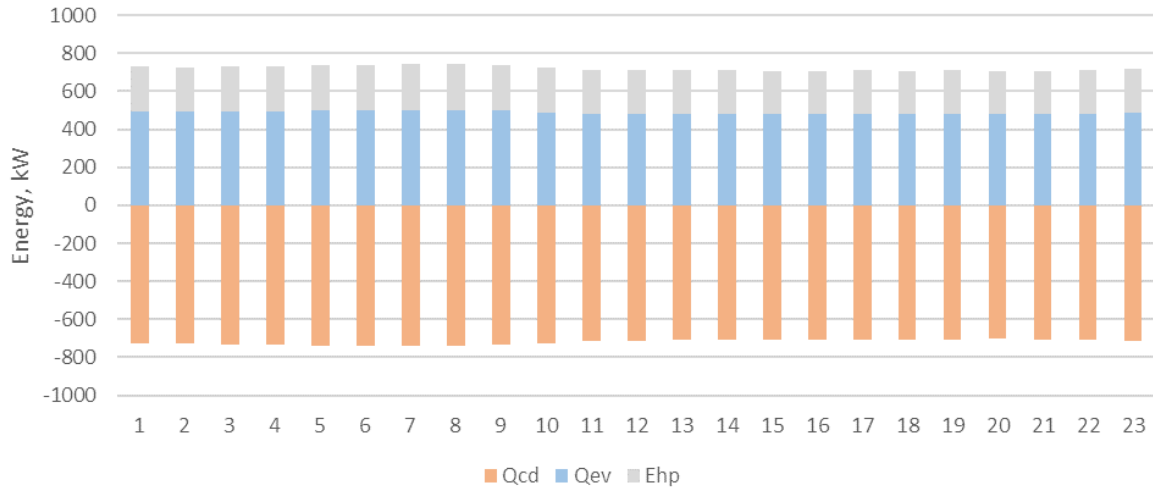


Fig. 8.17 Energy balance at the heat pump

The result shown in the Fig. 8.18 indicates that 29–40% of heat supply was covered by heat recovery ($Q_{heatRecovery}$) and 28–28% of the heat supply was covered by ground source heat from boreholes ($Q_{borehole}$). As a result, the partial load of HP was 57–61% and the COP was 3.06–3.12 (average 3.09). Fig. 8.19 shows the case if the contribution by heat recovery is not included. If the heat from heat recovery systems is not available, the partial load of HP would be increased by 77-86% and the COP would decrease to 1.39-1.62.

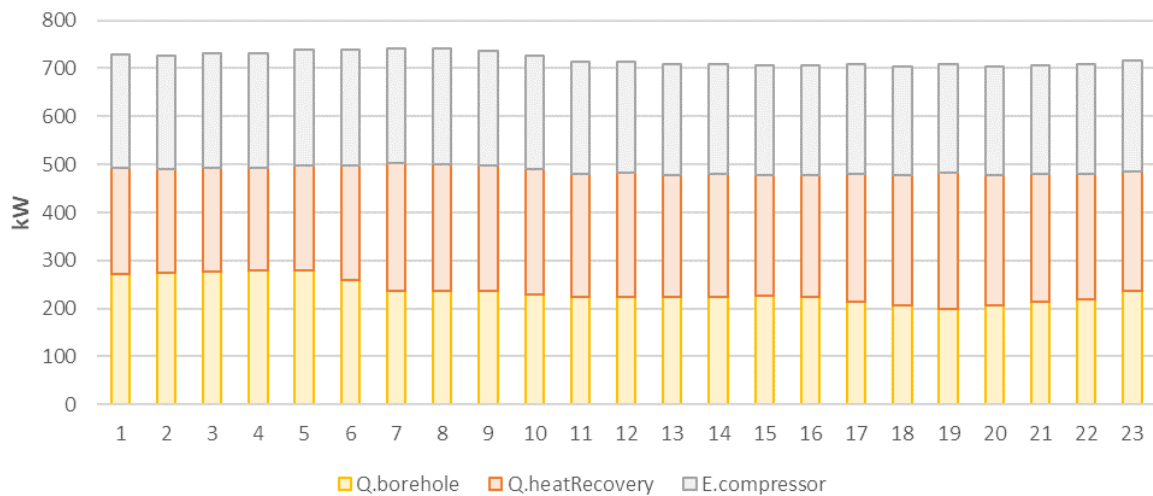


Fig. 8.18 Energy balance

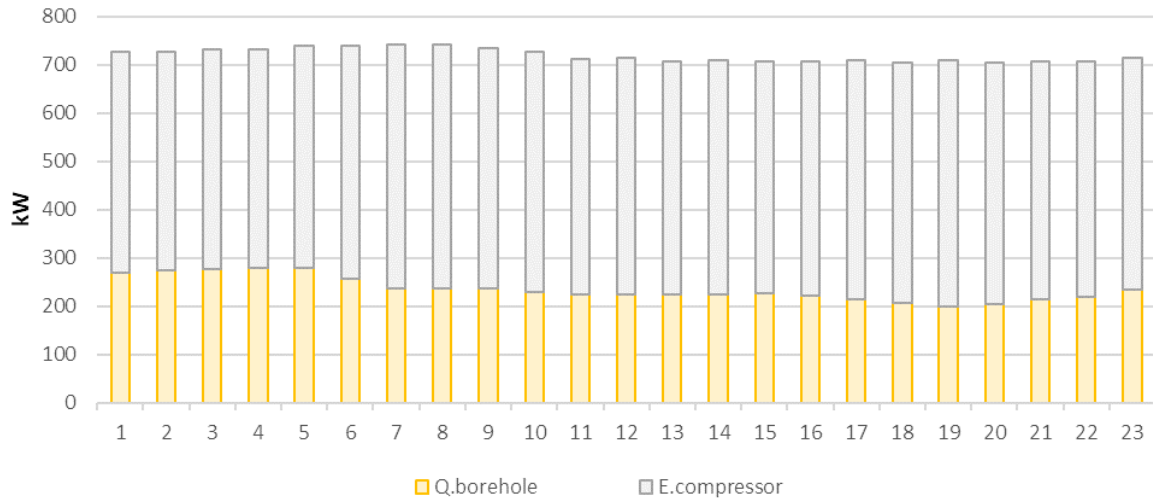


Fig. 8.19 Energy balance without heat recovery components

11.3.4 Exergy Balance

Fig. 8.20 shows the exergy balance at the heat pump. The positive side of the Y-axis is the incoming exergy into the boundary. It includes the exergy input through evaporators from the supply side (X_{ev}) and exergy consumption (X_{cons}). X_{cons} includes the exergy input as electricity (E_{hp}) and exergy consumption ($S_g T_o$), which is the multiplication of generated entropy (S_g) and environmental temperature (T_o). The negative side of the Y-axis is the outgoing exergy from the boundary. It includes the exergy output through the condenser to the demand side (X_{cd}). In every hour, the input and output are balanced. 41.2% of input was covered by the supply side and the rest was covered by electricity consumed by the compressor of the heat pump and through the process.

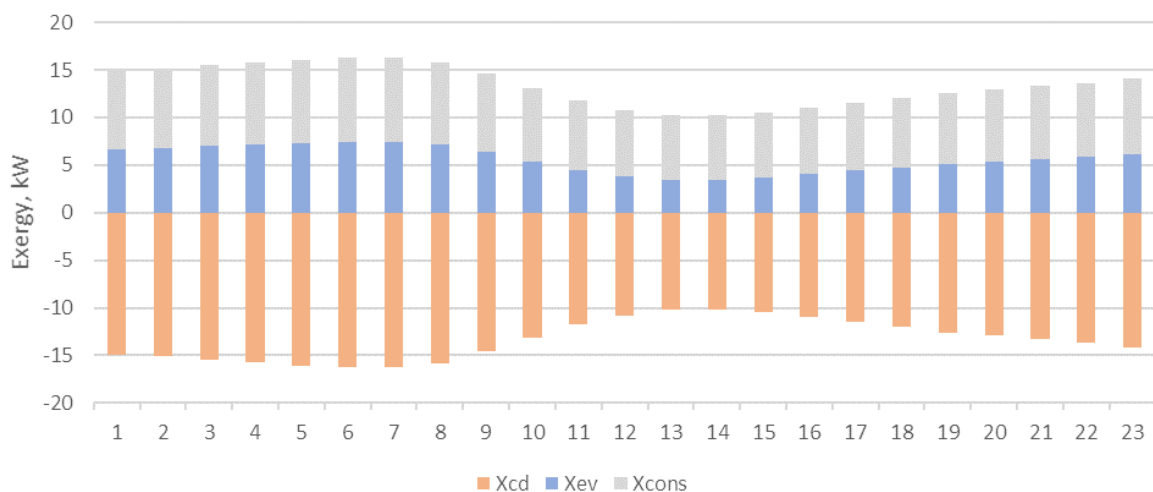


Fig. 8.20 Exergy balance at heat pump

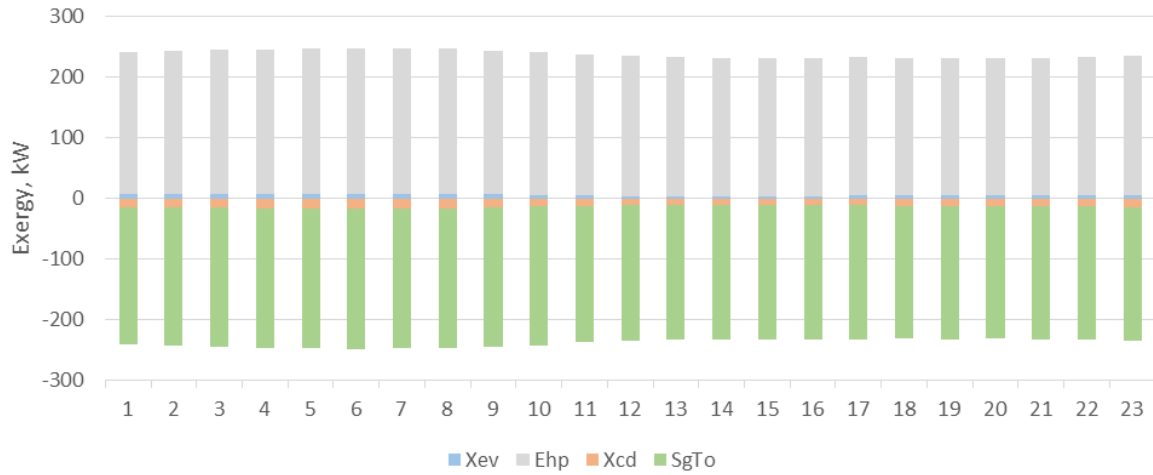


Fig. 8.21 Exergy balance at heat pump

To extend the evaluation boundary, Fig. 8.21 shows the exergy balance between the exergy input as electricity (E_{hp}) and exergy consumption ($S_g T_o$). The result indicates that 5.6% of exergy input is delivered to the demand side (X_{cd}) and the rest is consumed. The exergy theory states the electricity is high quality. When further improvement of exergy efficiency is discussed, the reduced exergy input by electricity will be the key to finding solutions.

11.4 Test Rig System

The investigation was carried out with the setting of three different temperature T_w settings, 24°C, 26°C and 28°C. Fig. 8.22 shows the result of temperature efficiency at the different water flow volume (l/s) and temperature efficiency at different ratio of water flow, V_c/V_w . Orange square plots indicate $V_c = 0.7$ l/s, gray triangle plots indicate $V_c = 0.6$ l/s, and blue circle plots indicate $V_c = 0.5$ l/s. The result shows that the combination of flow rate affects the efficiency.

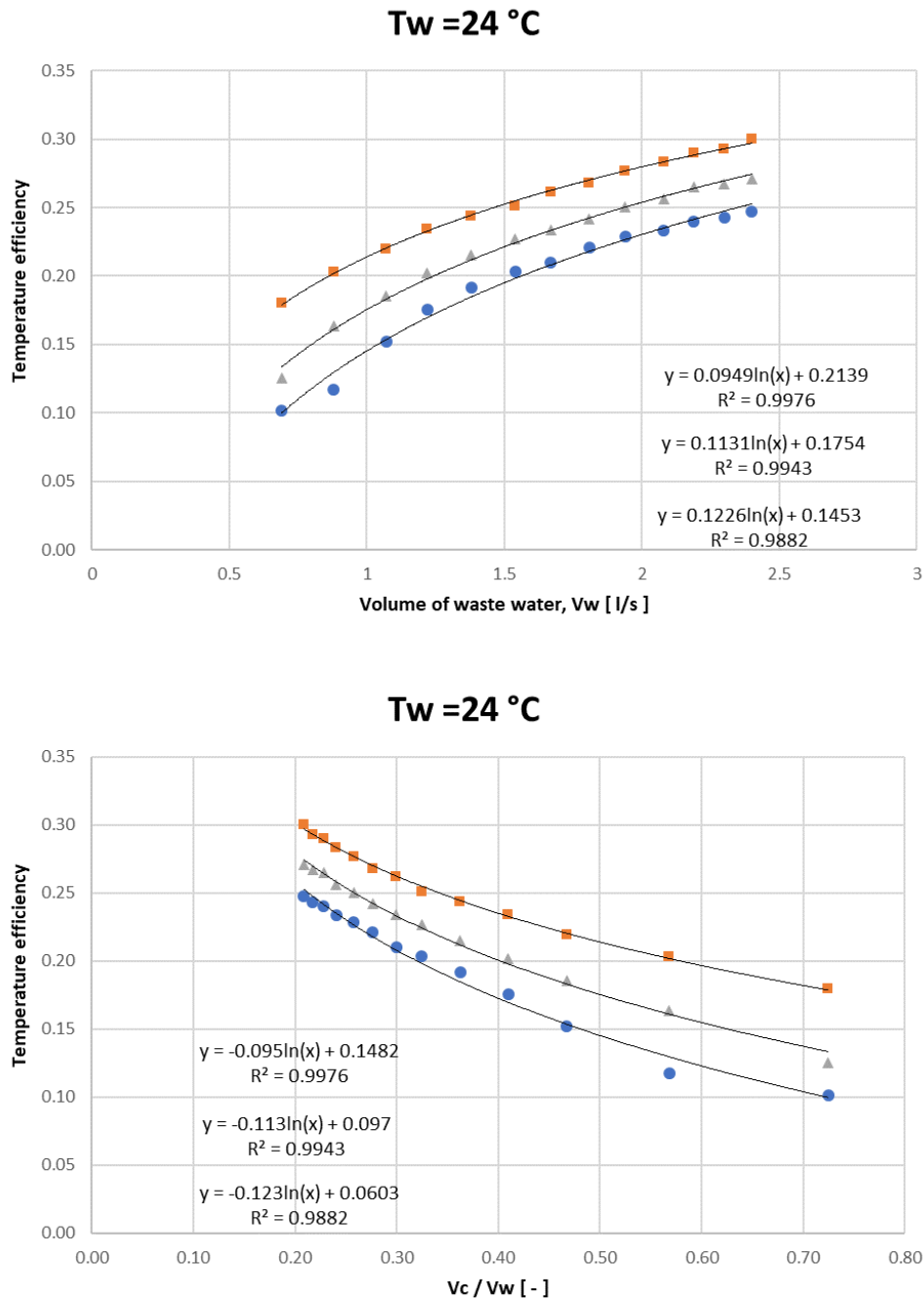


Fig. 8.22 Relationship of cold water flow rate (V_c) and efficiency ($T_w=24^\circ\text{C}$)

The higher flow rate of waste-water increases the temperature efficiency, but it is decreased by the ratio of V_c/V_w . This tendency is clearly seen in the case where T_w is 24°C and 28°C. The results suggest that optimization of heat delivery with the aspect of V_c/V_w ratio is a design variable. Tables 8.1, 8.2, and 8.3 show the evidence of the investigation.

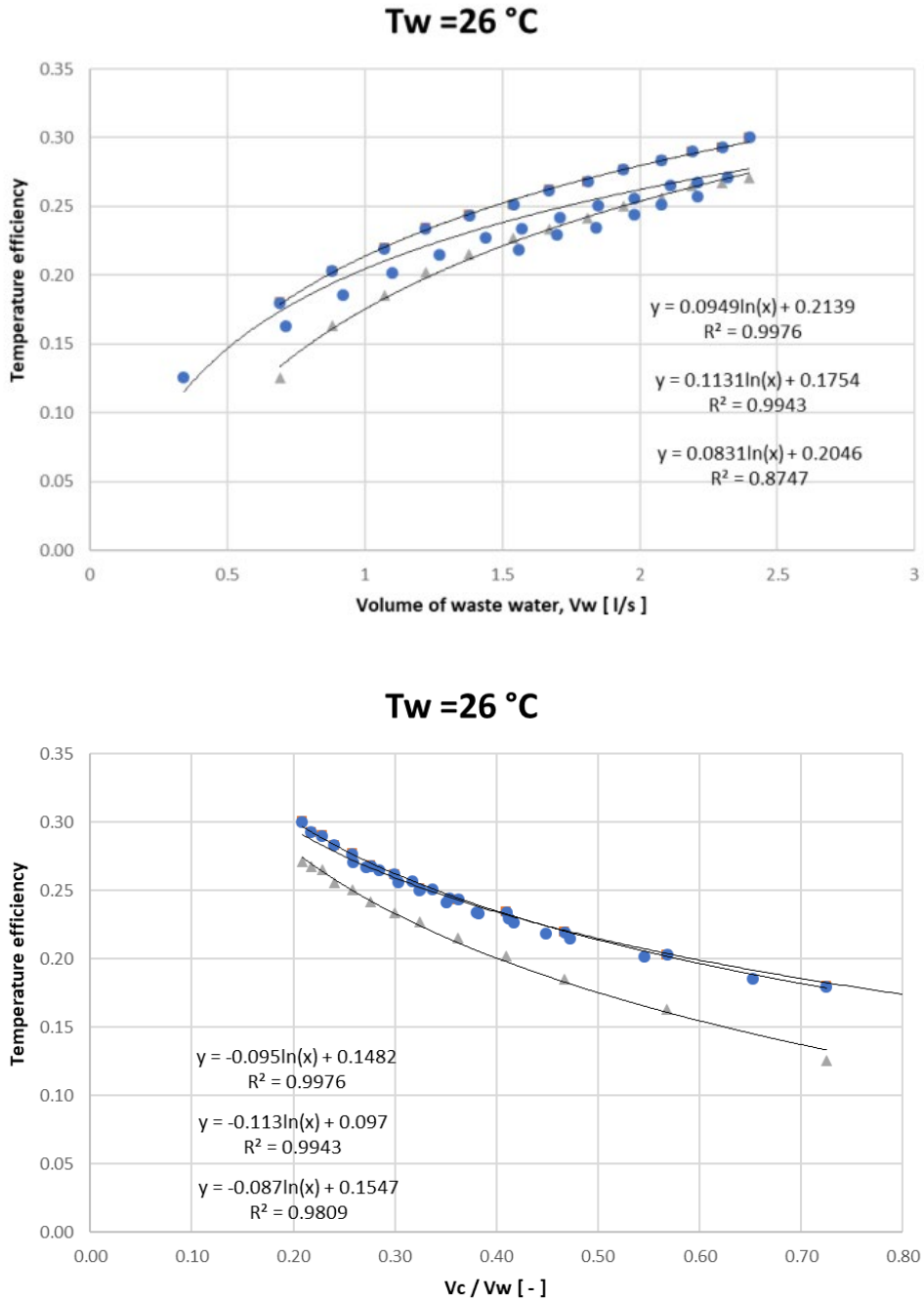


Fig. 8.23 Relationship of cold water flow rate (V_c) and efficiency ($T_w=26^\circ\text{C}$)

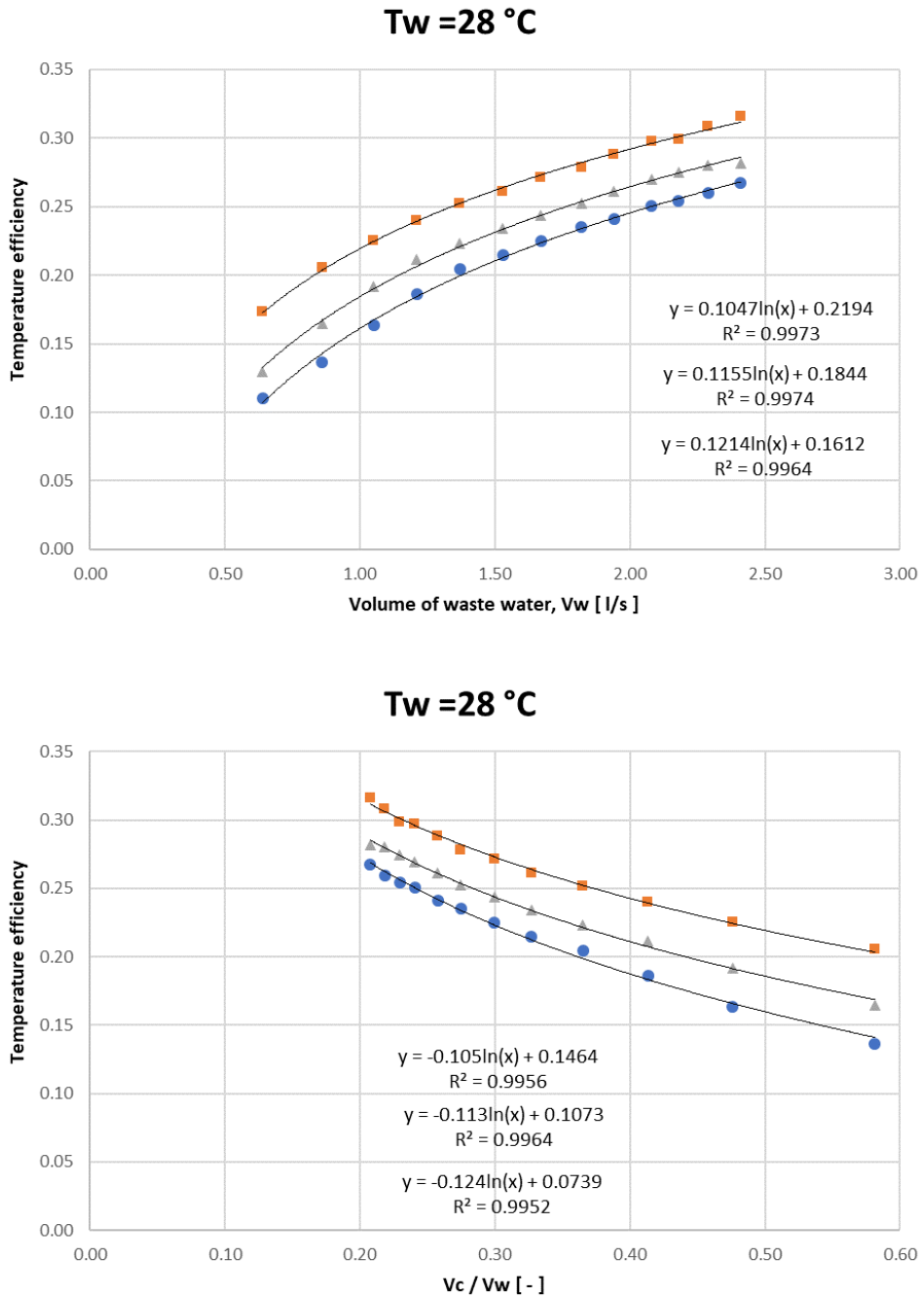


Fig. 8.24 Relationship of cold water flow rate (V_c) and efficiency ($T_w=28^\circ\text{C}$)

Table 8.1 Result, $T_w=24$ °C

Setting				Results						
V_c	T_c		V_w	T_w		$T_{c.out}$	$T_{w.in}$	$T_{c.in}$	$T_{w.out}$	
P1 [%]	MF2 [l/s]	GT1 [C]	P4 [%]	MF1 [l/s]	GT4 [C]	MT1 [C]	MT2 [C]	MT3 [C]	MT4 [C]	Teff
0.44	0.50	4.7	0.4	2.4	24.1	11.59	25.25	5.73	23.18	0.30
0.44	0.50	5.2	0.38	2.3	24.2	11.57	25.24	5.91	23.13	0.29
0.44	0.50	4.8	0.36	2.19	24	11.49	25.2	5.89	23.03	0.29
0.44	0.50	5.1	0.34	2.08	23.9	11.3	25.04	5.87	22.85	0.28
0.44	0.50	5	0.32	1.94	24	11.25	25.07	5.96	22.92	0.28
0.44	0.50	5.2	0.3	1.81	24	11.06	25.07	5.93	22.81	0.27
0.44	0.50	4.9	0.28	1.67	24.2	10.95	25.2	5.9	22.93	0.26
0.44	0.50	5	0.26	1.54	24.1	10.66	25.12	5.81	22.84	0.25
0.44	0.50	5.1	0.24	1.38	24.2	10.68	25.06	6.05	22.77	0.24
0.44	0.50	4.8	0.22	1.22	24	10.26	25.02	5.75	22.5	0.23
0.44	0.50	5.1	0.2	1.07	24	10.09	25	5.9	22.56	0.22
0.44	0.50	5.1	0.18	0.88	24	9.86	24.97	6.01	22.29	0.20
0.44	0.50	5	0.16	0.69	24.2	9.39	24.93	5.98	21.79	0.18
0.60	0.60	4.90	0.40	2.32	24.00	11.02	24.74	5.92	22.60	0.27
0.60	0.60	5.20	0.38	2.21	24.30	11.09	25.32	5.90	23.11	0.27
0.60	0.60	4.70	0.36	2.11	24.00	10.88	25.17	5.73	22.90	0.26
0.60	0.60	5.00	0.34	1.98	23.90	10.74	24.95	5.85	22.70	0.26
0.60	0.60	5.20	0.32	1.85	24.20	10.83	25.14	6.05	22.84	0.25
0.60	0.60	4.80	0.30	1.71	24.00	10.45	25.13	5.77	22.71	0.24
0.60	0.60	4.90	0.28	1.57	24.10	10.25	25.11	5.72	22.66	0.23
0.60	0.60	5.20	0.26	1.44	24.10	10.26	25.11	5.90	22.53	0.23
0.60	0.60	4.90	0.24	1.27	24.00	10.02	25.01	5.91	22.39	0.22
0.60	0.60	5.00	0.22	1.10	24.10	9.65	24.95	5.78	22.28	0.20
0.60	0.60	5.00	0.20	0.92	24.00	9.40	24.94	5.86	22.17	0.19
0.60	0.60	4.80	0.18	0.71	23.90	8.84	24.87	5.71	21.53	0.16
0.60	0.60	4.90	0.16	0.34	24.10	8.12	24.92	5.71	17.75	0.13
0.73	0.70	5.00	0.40	2.22	23.70	10.38	24.84	5.63	22.46	0.25
0.73	0.70	4.90	0.38	2.13	23.80	10.47	24.92	5.83	22.47	0.24
0.73	0.70	4.80	0.36	2.00	23.80	10.31	24.88	5.71	22.50	0.24
0.73	0.70	5.10	0.34	1.88	24.00	10.32	25.02	5.84	22.56	0.23
0.73	0.70	5.10	0.32	1.75	24.10	10.39	25.15	6.01	22.70	0.23
0.73	0.70	4.80	0.30	1.62	24.00	9.98	25.00	5.72	22.46	0.22
0.73	0.70	5.00	0.28	1.47	24.10	9.88	25.05	5.85	22.44	0.21
0.73	0.70	5.10	0.26	1.31	24.20	9.86	25.06	5.98	22.38	0.20
0.73	0.70	4.80	0.24	1.13	24.00	9.42	25.01	5.73	22.26	0.19
0.73	0.70	5.10	0.22	0.96	24.10	9.20	24.96	5.85	22.12	0.18
0.73	0.70	5.10	0.20	0.75	24.00	8.87	24.97	5.98	21.80	0.15
0.73	0.70	4.90	0.18	0.37	23.80	7.94	24.87	5.69	17.76	0.12
0.73	0.70	4.80	0.16	0.18	24.30	7.64	24.99	5.68	18.37	0.10

Table 8.2 Result, $T_w=26^\circ\text{C}$

Setting				Results						
V_c	T_c		V_w	T_w		$T_{c.out}$	$T_{w.in}$	$T_{c.in}$	$T_{w.out}$	
P1 [%]	MF2 [l/s]	GT1 [C]	P4 [%]	MF1 [l/s]	GT4 [C]	MT1 [C]	MT2 [C]	MT3 [C]	MT4 [C]	Teff
0.44	0.50	4.7	0.4	2.4	24.1	11.59	25.25	5.73	23.18	0.30
0.44	0.50	5.2	0.38	2.3	24.2	11.57	25.24	5.91	23.13	0.29
0.44	0.50	4.8	0.36	2.19	24	11.49	25.2	5.89	23.03	0.29
0.44	0.50	5.1	0.34	2.08	23.9	11.3	25.04	5.87	22.85	0.28
0.44	0.50	5	0.32	1.94	24	11.25	25.07	5.96	22.92	0.28
0.44	0.50	5.2	0.3	1.81	24	11.06	25.07	5.93	22.81	0.27
0.44	0.50	4.9	0.28	1.67	24.2	10.95	25.2	5.9	22.93	0.26
0.44	0.50	5	0.26	1.54	24.1	10.66	25.12	5.81	22.84	0.25
0.44	0.50	5.1	0.24	1.38	24.2	10.68	25.06	6.05	22.77	0.24
0.44	0.50	4.8	0.22	1.22	24	10.26	25.02	5.75	22.5	0.23
0.44	0.50	5.1	0.2	1.07	24	10.09	25	5.9	22.56	0.22
0.44	0.50	5.1	0.18	0.88	24	9.86	24.97	6.01	22.29	0.20
0.44	0.50	5	0.16	0.69	24.2	9.39	24.93	5.98	21.79	0.18
0.60	0.60	4.90	0.40	2.32	24.00	11.02	24.74	5.92	22.60	0.27
0.60	0.60	5.20	0.38	2.21	24.30	11.09	25.32	5.90	23.11	0.27
0.60	0.60	4.70	0.36	2.11	24.00	10.88	25.17	5.73	22.90	0.26
0.60	0.60	5.00	0.34	1.98	23.90	10.74	24.95	5.85	22.70	0.26
0.60	0.60	5.20	0.32	1.85	24.20	10.83	25.14	6.05	22.84	0.25
0.60	0.60	4.80	0.30	1.71	24.00	10.45	25.13	5.77	22.71	0.24
0.60	0.60	4.90	0.28	1.57	24.10	10.25	25.11	5.72	22.66	0.23
0.60	0.60	5.20	0.26	1.44	24.10	10.26	25.11	5.90	22.53	0.23
0.60	0.60	4.90	0.24	1.27	24.00	10.02	25.01	5.91	22.39	0.22
0.60	0.60	5.00	0.22	1.10	24.10	9.65	24.95	5.78	22.28	0.20
0.60	0.60	5.00	0.20	0.92	24.00	9.40	24.94	5.86	22.17	0.19
0.60	0.60	4.80	0.18	0.71	23.90	8.84	24.87	5.71	21.53	0.16
0.60	0.60	4.90	0.16	0.34	24.10	8.12	24.92	5.71	17.75	0.13
0.73	0.70	5.10	0.40	2.21	26.10	11.37	26.97	5.97	24.48	0.26
0.73	0.70	5.20	0.38	2.08	26.30	11.40	27.30	6.07	24.68	0.25
0.73	0.70	5.10	0.36	1.98	26.30	11.27	27.37	6.07	24.69	0.24
0.73	0.70	4.90	0.34	1.84	26.10	10.85	27.19	5.85	24.54	0.23
0.73	0.70	4.80	0.32	1.70	26.20	10.63	27.20	5.70	24.41	0.23
0.73	0.70	5.00	0.30	1.56	26.00	10.48	27.16	5.82	24.33	0.22

Table 8.3 Result, $T_w=28^\circ\text{C}$

Setting				Results						
V_c	T_c		V_w	T_w		$T_{c.out}$	$T_{w.in}$	$T_{c.in}$	$T_{w.out}$	
P1 [%]	MF2 [l/s]	GT1 [C]	P4 [%]	MF1 [l/s]	GT4 [C]	MT1 [C]	MT2 [C]	MT3 [C]	MT4 [C]	Teff
0.44	0.5	4.9	0.40	2.41	28.1	13.19	29.3	5.75	26.85	0.32
0.44	0.5	4.9	0.38	2.29	28.1	13.1	29.34	5.86	26.84	0.31
0.44	0.5	5.1	0.36	2.18	27.9	12.71	28.87	5.82	26.45	0.30
0.44	0.5	4.8	0.34	2.08	27.9	12.73	29.01	5.84	26.55	0.30
0.44	0.5	5	0.32	1.94	28	12.44	28.97	5.75	26.48	0.29
0.44	0.5	5.2	0.30	1.82	28.1	12.46	29.11	6.04	26.6	0.28
0.44	0.5	4.8	0.28	1.67	28	12.11	29.02	5.81	26.35	0.27
0.44	0.5	5.2	0.26	1.53	28.1	11.97	28.98	5.95	26.31	0.26
0.44	0.5	5.1	0.24	1.37	28	11.8	28.99	6.01	26.39	0.25
0.44	0.5	4.9	0.22	1.21	27.9	11.28	28.89	5.73	26.08	0.24
0.44	0.5	4.9	0.20	1.05	28.2	10.99	28.95	5.77	26.07	0.23
0.44	0.5	4.8	0.18	0.86	28	10.48	28.91	5.72	25.64	0.21
0.44	0.5	4.8	0.16	0.64	27.9	9.73	28.89	5.72	24.36	0.17
0.60	0.60	4.80	0.40	2.24	28.00	12.34	29.09	5.77	26.40	0.28
0.60	0.60	4.90	0.38	2.19	28.10	12.42	29.17	5.90	26.47	0.28
0.60	0.60	5.20	0.36	2.10	28.10	12.33	29.10	5.98	26.54	0.27
0.60	0.60	5.00	0.34	1.98	28.10	12.15	29.06	5.91	26.42	0.27
0.60	0.60	5.00	0.32	1.86	28.00	11.86	29.01	5.80	26.38	0.26
0.60	0.60	5.00	0.30	1.74	28.10	11.74	29.04	5.91	26.25	0.25
0.60	0.60	4.90	0.28	1.60	28.10	11.47	28.97	5.83	26.14	0.24
0.60	0.60	4.80	0.26	1.45	28.00	11.14	28.91	5.70	26.13	0.23
0.60	0.60	4.90	0.24	1.28	28.20	10.91	28.97	5.72	25.99	0.22
0.60	0.60	4.80	0.22	1.12	28.00	10.60	28.88	5.70	25.91	0.21
0.60	0.60	4.90	0.20	0.94	28.00	10.20	28.88	5.77	25.49	0.19
0.60	0.60	4.90	0.18	0.73	28.10	9.53	28.87	5.72	24.42	0.16
0.60	0.60	4.80	0.16	0.35	28.00	8.72	28.96	5.70	23.00	0.13
0.73	0.70	5.00	0.40	2.24	28.20	12.22	29.26	6.00	26.44	0.27
0.73	0.70	4.80	0.38	2.14	28.10	11.78	29.09	5.71	26.25	0.26
0.73	0.70	5.10	0.36	2.05	27.90	11.83	28.92	6.00	26.11	0.25
0.73	0.70	4.90	0.34	1.92	27.90	11.58	28.91	5.79	26.06	0.25
0.73	0.70	5.00	0.32	1.80	27.90	11.35	28.91	5.77	26.10	0.24
0.73	0.70	5.00	0.30	1.67	28.10	11.27	29.03	5.81	26.10	0.24
0.73	0.70	4.90	0.28	1.53	27.90	10.96	28.84	5.77	25.81	0.22
0.73	0.70	4.80	0.26	1.38	27.80	10.64	28.74	5.69	25.82	0.21
0.73	0.70	4.90	0.24	1.20	27.90	10.42	28.85	5.69	25.71	0.20
0.73	0.70	4.80	0.22	1.03	28.00	10.01	28.89	5.69	25.51	0.19
0.73	0.70	4.80	0.20	0.83	28.00	9.50	28.84	5.72	24.89	0.16
0.73	0.70	4.80	0.18	0.61	28.00	8.85	28.78	5.70	23.44	0.14
0.73	0.70	4.80	0.16	0.25	28.80	8.19	28.62	5.66	23.01	0.11

Through the tests at different waste-water temperatures, the following are clarified. Higher waste-water flow allows higher heat exchange efficiency. Lower cold water flow rate allows higher heat exchange efficiency. Lower waste-water flow rates reduce efficiency more than the higher waste-water flow rate. The actual performance at the middle level of waste-water flow rate is better than regression results.

There is some difficulty to measure the values of flow rate in case the water does not fill up the full cross-sectional area of the pipe. The test rig system study also shows the importance of data quality to assess the performance of heat exchanger technology. The series of parametric studies using the test rig system assesses the performance of the target technology. The temperature level of waste-water is not in the same range, but the behavior of heat exchanger technology is clarified.

12 Conclusions

12.1 Literature Review

The literature review conducted within this project provides state-of-the-art information on key characteristics and aspects of different types of waste-water heat-recovery systems in the context of large-scale energy management and monitoring, and energy retrofitting.

12.2 Stakeholder collaboration and Networking

This project significantly benefitted from the exchange of expertise and information with Inex International Exergi AB, Tokyo City University, Aalto University, IEA EBC Annex 64 (LowEx Communities), and IEA HPT Annex 52 – (Long-term measurements of GSHP system performance in commercial, institutional and multi-family buildings), as well as the HÅVA-project (Chapter 6). Contacts have also been established with the newly initiated SEQWENS Project (see also Chapter 14) which deals with related issues in a broader system and life-cycle perspective. The Principal Investigator for this project is member of the reference group for the SEQWENS Project.

12.3 Data Collection

Access to high-quality measurement data is a prerequisite for conducting an accurate evaluation of component and system performance. Difficulties in performance assessment were caused by lack of key measurement data, faulty measurement equipment (generating erroneous measurement data), and – notably - communication issues with facility management for the Beckomberga complex. The limited amount of data which was made available to the research team was not formatted for user-friendly post-processing analysis.

12.4 Development of a Model for Exergy Efficiency Analysis

In collaboration with Tokyo City University (Prof Masanori Shukuya), energy and exergy analysis models for 1) a waste-water heat exchanger, 2) a borehole heat exchanger and 3) a heat pump were developed. Since the data sets used include uncertain values because of unreliable measurement data, the models developed calculate the energy balance, assuming approximate values for the missing data. The exergy model provides new insight into the overall performance of the heat exchangers, especially with regard to related energy quality aspects.

12.5 Waste-Water Heat Exchanger Performance

The performance evaluation was conducted using a limited amount of measured data and assuming approximate values for the missing data. The temperature level of the waste-water was around 15 - 20 °C on average. The study showed that the heat collection from the waste-water can be a key factor which contributes to the source of heat supply.

The energy study showed that the flow rate of waste-water which passes through the heat exchanger is a key factor. Even when large amounts of waste-water are generated, the high flow rate doesn't allow enough for heat to be transferred from the warm waste-water side to the cold water side. Flow-rate optimization emerged as a parameter of key interest for future research work.

The exergy analysis showed that 12% (on average, range: 3 - 24%) of exergy contained in the waste-water was delivered to the cold water. 76% (on average, range: 60 - 88%) of exergy was consumed during the process. It was concluded that there are two ways to increase the exergy efficiency: Adjusting flow rates through the system, and reducing pump electricity use. Thus, optimizing the scale of waste-water heat recovery application is needed. The possible strategies are, for example, to reduce the capacity of the pump by optimizing the flow rate of the cold water or optimizing the scale of heat collection. In the case of the Beckomberga site, the cold-water circulation loop is too long.

12.6 Borehole Heat Exchanger Performance

The study on the borehole heat exchanger showed that the temperature of the ground was very stable through the day, around 2.2–2.3°C on average. The energy gained by exchanging heat from the borehole was 247 kW/h on average with a maximum of 293 kW/h at 4 am.

The exergy performance analysis showed that 48% of exergy from the borehole ($X_{b.in}$) was delivered to the cold water side ($X_{c.out}$). 27% of $X_{b.in}$ was consumed through the process (X_{cons}). To extend the evaluation boundary, the exergy input to the pump (E_p) and exergy consumption at the pump ($X_{cons.ep}$) occupy the large part of the balance. The analysis suggests that the E_p and $X_{cons.ep}$ would be reduced if the capacity of the pump could be minimized. Future work should explore the optimal number of boreholes and the capacity of the circulation pump.

12.7 Heat Pump Performance

Through the analysis of the heat pump performance, the average balance of the temperatures around the heat pump were analysed. For the water at the supply side, incoming ($T_{hpc.in}$) was 3.7°C and out-going ($T_{hpc.out}$) was 1.0°C. For the water at the demand side, incoming ($T_{hph.in}$) was 46.9°C and out-going ($T_{hph.out}$) was 47.0°C. The trend of temperature changing was stable throughout the day.

The energy performance analysis showed that 29–40% of the heat supply was delivered by recovery from waste-water and 28–38% of the supply was covered by ground source heat from the boreholes. As a result, the partial load of the heat pump was 57-61% and the COP was 3.06–3.12 (3.09 on average). An additional scenario was explored in which the contribution by heat

recovery was not included. For this case, the partial load of heat pump was increased by 77–86% and the COP was reduced by 1.39–1.62.

The exergy balance study showed that 41.2% of input was covered by the supply side and the rest was covered by electricity consumed by the compressor of the heat pump and consumed through the process. To extend the evaluation boundary, the result indicates that 5.6% of exergy input was delivered to the demand side (X_{cd}) and the rest was consumed. The exergy theory states that the electricity is high quality. Exergy efficiency could clearly be further increased by decreased electricity use in the system.

In closing, the various technical and logistical difficulties faced by the research team throughout this project, provide an example of how difficult (and frustrating) it can be to depend on third-party measurement data in conducting system performance studies, even in facilities equipped with advanced instrumentation and building management systems. Numerous studies have shown that this issue is, unfortunately, rather prevalent in the built environment, especially in the case of complex plants and facilities. Building system performance data is often incomplete, faulty or formatted in ways that make it difficult to use. Efforts are currently in progress in collaboration between six Swedish universities and key stakeholders from the private and the public sectors to establish a national innovation platform for user-adapted, building performance management (Martinac et al. 2017).

13 Future Work

Building on strong, continued industrial interest, the research partnership is currently exploring how the continued performance of waste-water heat-recovery systems, (such as those in the Beckomberga complex, but also in other facilities) can be evaluated in a follow-up study, to provide a better understanding of the long-terms performance and potential benefits of low-exergy residual heat.

14 Information Dissemination

The results from this study will be disseminated through the following channels:

- In collaboration with the “GrönBostad” project, a short film about this study is currently being produced and will become available at (<https://gronbostadstockholm.se/kontakt/>).
- A conference paper abstract, entitled “*Kayo, G., Shukuya, M. and Martinac, I.: Energy and exergy behaviour analysis on the heat recovery from a waste-water system*” has

been accepted towards preparation of a full paper to be presented at the conference: 10th Int. Conference on Indoor Air Quality, Ventilation and Energy Conservation in Buildings, IAQVEC, Bari/Italy, 5-7 September 2019.

- An extended paper, partly based on the above conference paper will be submitted to a scientific journal.
- The project team continues to collaborate with IEA HPT Annex 52 (operated by Svenskt Geoenergicentrum) and participates in related information dissemination.
- The project team continues to contribute to the reference group work for the HÅVA project.
- The Principal Investigator for this project is a Reference Committee member for the newly initiated Formas-funded project “Ensuring sustainability and equality of water and energy systems during actor-driven disruptive innovation (SEQWENS, 2018-2020)” where issues related to the management of water and energy resources will continue to be discussed. The project is managed by the KTH Water Center.
- Experiences from this project will be shared with and disseminated through the extensive CIEB-consortium (Samverkansplattform för brukaranpassad, hållbar byggnadsdrift), see also (Martinac et al. 2017).
- A paper is intended to be submitted to at least one professional journal (such as Energy och Miljö, Förvaltaren, etc.).

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