Technology Collaboration Programme
by iea

Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP)

HPT-Annex 46
Domestic Hot Water Heat Pumps

Annex 46

Domestic Hot Water Heat Pumps

Final Report

Operating Agent: Netherlands

Compiled and edited by
Onno Kleefkens M.Sc.
Pheatradico

Project website:
https://heatpumpingtechnologies.org/annex46/

May 2020

Report no. HPT-AN46-1

Published by Heat Pump Centre
c/o RISE – Research Institutes of Sweden
Box 857, SE-501 15 Borås
Sweden
Phone: +46 10 16 53 42

Website https://heatpumpingtechnologies.org

Legal Notice Neither the Heat Pump Centre nor any person acting on its behalf: (a) makes any warranty or representation, express or implied, with respect to the information contained in this report; or (b) assumes liabilities with respect to the use of, or damages, resulting from the use of this information. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement recommendation or favouring. The views and opinions of authors expressed herein do not necessarily state or reflect those of the Heat Pump Centre, or any of its employees. The information herein is presented in the authors' own words.

Production Heat Pump Centre, Borås, Sweden

ISBN 978-91-89167-58-2
Report No. HPT-AN46-1

Preface

This project was carried out within the International Energy Agency Technology Collaboration Program on Heat Pumping Technologies (HPT TCP).

The IEA

The IEA was established in 1974 within the framework of the Organization for Economic Cooperation and Development (OECD) to implement an International Energy Program. A basic aim of the IEA is to foster cooperation among the IEA participating countries to increase energy security through energy conservation, development of alternative energy sources, new energy technology and research and development (R&D). This is achieved, in part, through a Program of energy technology and R&D collaboration, currently within the framework of over 40 Implementing Agreements.

Disclaimer

The HPT TCP is part of a network of autonomous collaborative partnerships focused on a wide range of energy technologies known as Technology Collaboration Programs or TCPs. The TCPs are organized under the auspices of the International Energy Agency (IEA), but the TCPs are functionally and legally autonomous. Views, findings and publications of the HPT TCP do not necessarily represent the views or policies of the IEA Secretariat or its individual member countries.

The Technology Collaboration Program on Heat Pumping Technologies (HPT TCP)

The Technology Collaboration Program on Heat Pumping Technologies (HPT TCP) forms the legal basis for a Program of research, development, demonstration and promotion of heat pumping technologies. Signatories of the TCP, called participating countries, are either governments or organizations designated by their respective governments to conduct. The Program is governed by an Executive Committee (ExCo), which monitors existing projects and identifies new areas where collaborative effort may be beneficial.

Annexes

The core of the TCP are the “Annexes”. Annexes are collaborative tasks conducted on a cost-sharing and/or task-sharing basis by experts from the participating countries. Annexes have specific topics and work plans and operate for a specified period, usually a number of years. The objectives range from information exchange to the development and implementation of heat pumping technologies. An Annex is in general coordinated by an expert from one country, acting as the Operating Agent (manager). This report presents the results of one Annex.

Triennial Heat Pump Conference

The IEA Heat Pump Conference is one of the three major products of the Technology Collaboration Program on Heat Pumping Technologies. The Executive Committee supervises the overall organization and its quality and selects from a tender procedure the host country to organize the Conference and establishes an International Organization Committee (IOC) to support the host country and the ExCo.

The Heat Pump Centre

The Heat Pump Centre (HPC) offers information services to support all those who can play a part in the implementation of heat pumping technologies. Activities of the HPC include the publication of the quarterly Heat Pumping Technologies Magazine and an additional newsletter three times per year, the HPT TCP website, the organization of workshops, an inquiry service and a promotion Program.
The HPC also publishes results from the Annexes under the TCP-HPT.

For further information about the Technology Collaboration Program on Heat Pumping Technologies (HPT TCP) and for inquiries on heat pump issues in general contact the Heat Pump Centre at the following address:
Heat Pump Centre
c/o RISE - Research Institutes of Sweden Box 857, SE-501 15 BORÅS, Sweden
Phone: +46 10 16 55 12

Disclaimer

The information and analysis contained within this summary document is developed to broadly inform on worldwide developments. Whilst the information analysed was supplied by representatives of National Governments, a number of assumptions, simplifications and transformations have been made in order to present information that is easily understood. Therefore, information should only be used as guidance.

The market of domestic hot water heat pumps (HPWH) is developing fast and at the moment of publication some information can already be overtaken by new developments.

In compiling, editing and writing this report I would like to thank Kashif Nawaz and his colleagues (Oakridge National Laboratories, USA), Cordin Arpagaus (NTB Interstaatliche Hochschule für Technik Buchs, Switzerland), Justin Tamasauskas (CanmetÉNERGIE/CanmetENERGY, Canada), the Japanese National Team under Kyioshi Saito (Waseda University, Japan), Neil Hewitt (Ulster University, UK), Jeongsik Seo (Korea Refrigeration and Air Conditioning Assessment Center), Mihai Radulescu and his team (Électricité de France).

Special thanks go to Marion Bakker (Rijksdienst voor Ondernemend Nederland) giving financial support after the finalisation of the Annex in order to update the final reports and website as well as commenting extensively on concepts.

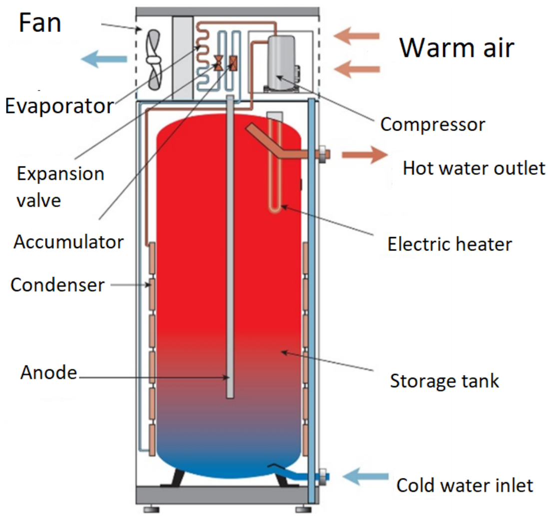
Contents

1 Executive summary

The share of Domestic Hot Water (DHW) production in the total heat consumption of the building has increased. In new low-energy single family as well as multifamily buildings and the temperature of DHW is higher than the temperature for space-heating. Thus DHW production has become a dominant factor in heating systems for new buildings. The same is the case for the ‘deep’ renovation of existing buildings.

The main objective for the Annex has been to provide deeper insight in the challenges to achieve the full potential in applying Heat Pump Water Heaters (HPWH) and to achieve the potential reduction of CO_2-emissions, using various concepts and systems for new as well as existing buildings in the renovation process. This is achieved by giving the right information on the boundary conditions:

- Reviewing available Heat Pump Water Heaters, mainly mono-bloc but also larger collective systems;
- Reviewing the different system concepts for single family as well as multifamily buildings;
- Developing and validating a model to enable an objective comparison of Heat Pump Water Heating technologies and systems;
- Data basing example projects;
- Creating a web based information platform to serve participating countries by publishing information on their market approach and training courses.
- Holding regular workshops.
- An overview of R&D on Heat Pump Water Heaters, along with the R&D still needed.



On Heat Pump Water Heaters (HPWH) we generally are speaking about mono-bloc air source heat pump, defined as a single unit with heat pump (with compressor, expansion valve, evaporator and condenser), with a storage tank integrated, often underneath the heat pump. These mono-bloc systems will remain the preferred solution in many cases for single family houses. However there is a great number of alternatives for Domestic Hot Water with heat pumps in domestic applications, other than the mono-bloc, for single family houses and multifamily buildings, for sanitary hot water systems for hotels, hospitals, sporting facilities, etc.. There is a large number of technologies available with regional differences in demand and usage, thus showing a greater complexity than space heating/cooling systems.

Starting from the overall idea that the focus for the Annex on Heat Pump Water Heaters would concentrate on the mono-bloc air source heat pump water heater as the preferred solution in many cases, the market reality of hot water generated with heat pumping technologies proved to be more complex than assumed at the start of the Annex, more complex then space heating. The main work in the Annex has focused on the technology of the mono-bloc heat pump water heater, under the headings: policy, refrigerants, test procedures, technology modelling and R&D. Next to this the important boundary conditions have been studied, being legionella, system design, collective heating networks and calculation models for large applications, coming into touch with larger heat pumps.

In essence however hot water systems consist of a heat generator (i.e. a heat pump), an insulated storage system/tank and a system distributing the hot water to draw off points or heat exchangers in a smaller system at a required temperature, more than often dictated by legislative requirements.

Throughout the developed world, the heating of water for domestic use is one of the largest consumers of energy in the household sector (10 to 20% energy share). Due to a strict governmental policy on energy performance for new domestic buildings, the inherently better insulation, and higher comfort demands by the end user and the relatively high temperatures needed, due to legislation, for domestic hot water, the energy demand for generating this hot water will dominate the overall energy use of the house, becoming a challenge for policy makers. The actual energy consumed is impacted by consumer usage patterns and ambient environmental conditions. Such complexity creates a number of challenges for policy makers seeking to understand and effectively manage water heating energy consumption. The specific mix of water heater types used varies considerably between countries as a result of culture, historic practice, existing infrastructure and energy source availability. Not surprisingly, the specific policy frameworks developed and deployed by policy makers vary significantly depending on these local conditions.

Market scenario

The Heat Pump Water Heater market is characterized by the presence of a diversified regional and highly fragmented supply side providing with their knowledge of the market customized products. This is posing a stiff competition to the international players. However, the local manufacturers find it increasingly difficult to compete these, while the international players also take over or collaborate more and more with regional or local players.

The best opportunities for HPWH are in:

- Installing in new single family and multifamily buildings to meet building regulation requirements;
- Retrofit of existing gas or oil boiler in single family buildings or terraced houses, with a new boiler and a heat pump water heater or a heat pump for both space and hot water heating;
- Replacement of direct electrical heating of hot water in existing buildings, individual domestic buildings, terraced houses, driven by customer need for energy cost savings;
- Retrofit of collective distribution systems for hot water in domestic multifamily buildings with individual heat pump water heaters, either a booster type or an air source HPWH;
- Homes where space is at a premium, with compact wall-hung systems with < 100L tanks or split HPWH;
- Ability for smart operation with PV integration and/or connection to smart grid;
- Low temperature distribution systems of the 4th Generation District Heating, with booster HPWHs.

The three major markets - North America, Asia and Europe - represented by the countries participating to the Annex have different market conditions and different usage scenarios

Policy

Applying heat pumping technology is one of the possible heat generators to reduce the energy usage and CO_2 emissions significantly. Although there are some noticeable successes in the market developments, heat pump water heaters are still having a relatively small market share with a much larger potential. Traditionally however policy makers are reluctant to make choices, thus except for Japan in the past with the Top Runner program, there seems to be no specific support for market development of heat pump water heaters. In general, mandating the installation of high efficiency water heaters is the main policy tool used to ensure that high efficiency water heaters are installed. Mandated measures can be:

- prohibiting inefficient water heaters from sale by setting clear efficiency standards;
- prohibiting low efficiency water heaters from being installed;
- requiring certain high efficiency technologies, such as solar water heaters, to be installed.

Policies in the different countries in their overall approach have a general nominator focusing on energy conservation, renewables and energy security to reduce the greenhouse gases.

As a basis, there is a number of legislative requirements described in directives, focusing on:

- Creating a challenge for individual technologies, through test procedures, standards and energy performance labelling, like European the ErP and EL regulations, TOP Runner in Japan, China Energy Label (CEL), Energy Star and Energy Guide labels in North America
- Creating a challenge for competing technologies, by setting energy targets for systems in buildings or by simply setting restrictions on certain types of technologies

Finally it is the end-user, either private or collective through housing corporation, but also the building constructor and its engineers having to comply with the Energy Efficiency demands of a building, that decide on the choice of water heating technology to be applied in a new building or a renovation project.

Test procedures

Test procedures are the basis for quality labels, calculation models and therewith an important element in governmental policy instruments. However world-wide there is a disturbing landscape with a great number of test methods for heat pump water heaters in use in different regions of the world, with major differences between them. As a result, manufacturers have to undertake a different set of tests to be able to sell their products on the worldwide market. Harmonisation of test procedures is urgently needed.

The ISO Working Group 12 on Heat pump water heaters of ISO/TC 86/SC 6/WG 12 on HPWHs has developed a harmonisation framework, for drafting a test procedure now available as standard ISO 19967-1:2019.

The European standard EN 16147 and the ISO 19967-1 standards are very similar and are assessing the water heating energy efficiency of the heat pump water heaters based on the rating of a coefficient of performance (COP_{DHW}) over a 24h load profile. Several load profiles, each one consisting of a series of draw-offs characterised by the hot water outlet temperature and the amount of energy tapped, are described and allow to rate a large capacity range of heat pump water heaters. In addition, if the unit is provided with a smart control, i.e. self-learning of the hot water usage, the coefficient of performance can take benefit of this smart function. Other characteristics such as the standby power input and the volume of available water at 40°C within one single draw-off are also performance parameters of the heat pump water heater.

Legionella

Heat pumping technologies for single-family buildings as well as in collective systems for multi-family buildings, sports centres, hospitals, etc. are well fitted and capable to deliver the required temperatures according to general legislation dominant in the participating countries, to fight Legionella. If there is a problem, this cannot be caused by the heat pump itself. For single family buildings this is traditionally done with an additional electric resistance. But, as a consequence of the existing regulations for legionella and the need for heat pumps suitable for retrofit, especially in collective systems, refrigerants and solutions for DHW applications with higher than traditional (>60ºC) heat supply temperature are in demand. Modifications to the refrigerant cycle such as cascading refrigerant cycles can be used to increase the output temperature further up to 80°C with other refrigerants, like CO_2 and in cascade R410A/R134a, but also gas driven heat pumps are in the market.

However based upon literature studies it is concluded that the domestic hot water temperatures can be below 60°C without increased risk of Legionella if the overall volume of domestic hot water in the distribution system is below three litres. This finding sets the rule for designing the domestic hot water systems supplied by low-temperature collective distribution systems in multifamily buildings, as well as for district heating systems.

- Legionella disease is a lung disease originated by inhaling vaporized water from showers and not caused by drinking water from the tap.
- The risks of Legionella infection exists in locations of stored (stagnant) hot water at relatively low temperatures and in collective systems. The bigger and more complicated a water distribution network

is, the greater the risk for the growth of Legionella bacteria. Systems in single-family houses with a water distribution system smaller than three litres are known not to be affected by legionella.

- Harmonization in legislation does not exist but is needed when the demands in legislation differ too much there will be no equal markets as the demands have consequences for the test procedures as well. Although legionella cycles are not included in test procedures because considered as "safety operation" and not "normal use ", the temperature demands affect the test procedures for heat pump water heaters.
- Increasing hot water storage temperatures to 60°C recommended for Legionella control decreases the energy efficiency, increasing CO_2 emissions. It is not suggested to take a slack attitude to the problem, but the broad-brush turn-up-the-thermostat approach, given the energy penalty involved, can be debated. Further study in this area is justified.

Refrigerants

For Heat Pump Water Heaters at this moment no alternative low GWP refrigerant fulfils all the ideal requirements at once.

For HPWHs not much focused research is available in which results show which refrigerant is the ‘best solution’. GWP can be a useful metric to compare different refrigerants. However, it may to overestimate the benefits of low GWP refrigerant to environment, as it does not take into account many other affecting factors, like the use of high efficiency components and system design, such as the optimal storage size, stratification and condenser design. Ensuring proper installation, optimised control and operation, under all common operating and climate conditions are factors not directly related to the technology itself and the choice of refrigerant. In the end, the overall energy use of the installation is an important factor in the calculation of the LCCP or TEWI factor.

The main policies worldwide focus on banning the use of refrigerants with a high GWP. However this does not necessarily result in lowering climate impact, expressed in term of LCCP value. Thus, LCCP evaluation can be necessary in order to account for the entire climate impact of a system when selecting an alternative refrigerant. Alternative refrigerants to the currently used refrigerants (R134a, R410A) are:

- Carbon dioxide (R744) and Propane (R290) are natural refrigerants, which can be used to reach higher output temperatures up to 80°C.
- R152a, R1234yf, R1234ze(E) and Ammonia are interesting alternatives for DHW HP, not yet broadly in use but already tested in R&D projects, while R32 is strongly promoted by a number of manufacturers.

In the choice of refrigerants the condenser configuration exchanging heat with the storage tank and the risks (like flammability) of the refrigerant play an important role. Oak Ridge National Laboratory (ORNL) has done a number of studies in this area and great leap forward with Propane has been achieved with research by Kungliga Tekniska Högskolan (KTH) among others.

Multi Family Buildings

Particularly, water heaters are one of the most complex product categories due to a large variety of product types, technologies, and fuels used for heating water. Simple solutions are available for single family houses, but for collective systems solutions can be more complex. The low efficiency of domestic hot water systems is well known by field practitioners. For many new residential multifamily buildings hot water delivery times and heat losses in distribution systems have been getting steadily worse.

On the subject of "best system design" with regard to energy-efficient hot water supply, a number of conclusions can be drawn:

- Based on the sum of all losses, decentralized solutions (hot water is generated where it is needed) are the best solution.

- In general, 2-pipe systems with home stations perform better in terms of distribution losses than 4-pipe systems, which is mainly due to shorter length of distribution pipes.
- In order to be able to integrate renewable energies in apartment blocks, central solutions can be preferred, with the exception of the combination of photovoltaics and ventilation heat pumps for apartment blocks with a low demand for space heating (such as in the French climatic zones H3 and H2c) and in Energy Zero of Passiv houses.
- Especially with heat pumps an efficient operation by separation of distribution system for hot water heating and space heating can be achieved. For this technology, the advantages of optimized generation (4-pipe system) must be contrasted with the advantages of lower losses (2-pipe system) and evaluated on a case-by-case basis.
- Due to the magnitude of the distribution losses (heat losses through the pipelines) in centralized solutions, it is strongly recommended to optimize all pipeline lengths as early as the planning phase and to insulate distribution lines beyond what is required and to consider the possibility of using inline systems.
- Losses in heat supply represent the second highest loss share for central options and can be reduced by intelligent technology selection and optimization (optimized design, coordination of hot water, heating and storage combinations and control engineering integration, ongoing monitoring).

Power supply (pumps) and storage losses play a minor role. Optimizations in existing (old) systems (pump replacement, additional insulation in storage), however, can certainly lead to significant savings.

System models for DHW production and distribution

Currently, the biggest challenge for every user of building and plant simulation is the large number of different simulation tools. Every simulation software has a main area of application and is optimized for this specific problem. Even software with a wide range of applications or specialized multi-physics software cannot calculate every problem in an accurate and efficient manner. If DHW is not included based on objectively verified values, it will not be possible to assess future systems that are predominantly dimensioned around tap water for their energy performance.

For policy purposes models (often commercially available) have been developed to calculate the energy performance of buildings required for building permits or commercial transactions. Climate, location and building specific components, often traditional for certain regions are the basis of these models, where it is expected that it will be difficult to make clear comparisons between those. Given the market of models already on the market, it does not make sense to develop an 'own' Annex 46 model.

Overall it is important to think in terms of complete system concepts. Even if the heat is produced with a high energy efficiency, high storage and/or distribution losses still remain unnecessary and eventually will cause a low overall system efficiency to the best generating apparatus. It is therefore important to consider the heat generators not only individually but to design a complete DHW concept with a critical view on performance, comfort and legionella prevention. If DHW is not included based on objectively verified values, it will not be possible to assess future systems that are predominantly dimensioned around tap water.

With new distribution systems in the market, especially in collective systems, adequate publicly available calculation models do not exist taking into account the latest innovations in domestic hot water technologies. More specifically a model should be developed that can be used for the different countries basically giving support to the existing formal legal calculation models. A proposal was done under Annex 46 but the required funding for the work was not available.

Technology modelling

Although the monobloc Heat Pump Water Heaters have reached an important level of maturity on the market, it seems that there is still room for improvement of their energy performance. Under this Task modelling on the technology has been executed and has been published upon by:

- EDF has presented a model for a monobloc Heat Pump Water Heater with a 'wrap-around' heat exchanger for the storage tank. The study done by Électricité de France (EDF) has resulted in new design for Heat Pump Water Heaters that achieves appr. 37 % average annual energy saving and appr. 30 % reduction of the electrical bill while ensuring a same level of comfort for the end-users.
- Oak Ridge National Laboratory, developed a heat pump design model with a special model for HPWH. Stratification in the storage tank is an important basis for the optimization of the system. Computational Fluid Dynamics (CFD) model using ANSYS 17.2 and an effective, hardware-based HPWH equipment design tool, a quasi-steady-state HPWH model was developed based on the DOE/ORNL Heat Pump Design Model (HPDM). The model is freely available.
- Waseda University, especially for CO_2 DHW HP's. One very complex model (confidential) and another simplified model were developed.
- Ulster University works with TRNSYS and did a number of studies on storage in relation to smart grids and validation of models on their test houses at the University.

In a survey more than 40 papers from other authors/institutes/universities, than the participants, were studied, with topics ranging from:

- Optimization of refrigerants and condensers;
- Stratification;
- Smart grids and storage;
- Combination with solar, often from the angle of solar thermal.

Understandingly the main modelling initiated for heat pumping technologies has a focus in very special heat pump related topics and challenges, such as refrigerants, heat exchangers etc., but also on the market challenges such as smaller, cheaper and more efficient and fit to market demands such as smart grids.

Worldwide there is a large number of models (some academic exercises!) available also for other condensers. Manufacturers do have often their own models.

- Heat Pump Water Heaters are not very energy efficient as in the process of heating and draw offs a lot of losses occur, thus reducing the optimal COP from 4.5 to 2.5.
- In a great number of institutes work is done fairly independent from each other with a different focus on the goals to be achieved. Some, like KTH in Sweden focus on reducing the refrigerant charge with flammable working fluids, others focus on the storage capacity in smart grid applications (Grid Flexibility). Important R&D focus is 'smaller and cheaper' as well as cold climate applications.
- The discussion in the Annex did not come to a clear conclusion whether we should have 'wrap-around', external plate, or internal spiral heat exchangers, although lab-test at ORNL clearly show the advantages of external plate heat exchangers.
- A few degrees temperature difference in the thermostat (hysteresis) gives a better COP. That idea can be used for optimisation of the control mechanisms.
- With an increasing number of heat pumps installed for space heating and cooling the optimisation is in the combination with water heating in double function application. The larger the heating capacity for space heating, the smaller the storage tank (even down to 50 litres)

In comparing DHW concepts and systems a market divide can be made between individual and collective systems and newly developed or built systems and infrastructures compared to existing systems in retrofit.

Research and Development

Although heat pump water heaters are by far the most efficient way to heat water heat pump water heaters in itself are not very energy efficient as in the process of heating and draw offs a lot of losses occur. In the residential market there is the need for downsizing, noise reduction, and cold weather specifications as well as higher efficiency and lower price.

In the participating countries some specific programs for R&D on heat pump water heaters are or have been running and some general R&D programs run in which amongst others heat pump water heater technologies are supported. During the Annex work it became clear that the great number of the main heat pump manufacturers/suppliers are not Original Equipment Manufacturers and get their components for manufacturing heat pumps from the world-wide market, compressor technologies, valves, evaporators and refrigerants. Therewith, R&D from non-OEM manufacturers will be mostly ‘application development’ focusing on the application boundaries of the existing and future markets and customer needs and preferences. This is an interesting market where innovation is of great importance to reach the market. Important topics for development, focusing on local market acceptance are:

- System technologies, especially occurring in collective systems, where smart system lay out and control mechanisms can reduce the temperatures, volume flows and heat losses, thus optimize the energy efficiency as well as economic performance. Booster Heat Pump Technology is one of those technologies that came forward out of the need to reduce distribution losses and are now the technology for the 4th Generation Low Temperature District Heating.
- Installer focused technologies, focusing on making installation of the technology more simple or fit for the local conditions. The traditional installer is not really capable (on a large scale needed for a market transition) to give consumer advice and install the best option. Often oversizing is the case to avoid complaints. Sizing fit for small spaces, Plug & Play concepts are the dominant topics. These technologies are often specific for local manufacturers with a strong home market.
- End-user focused technologies. Consumer adoption is critical to the success of the heat pump water heater technologies. Water heating is a challenging market because units are only replaced when they fail which is typically 10 to 15 years and energy efficiency is not always a priority. End-users are not aware of the advantages on the long term and will traditionally go for the cheapest solution.
- Water quality management technologies and technologies to reduce the usage of water without losing comfort. Having effect on the capacity of the heat pump and storage size this is not directly a topic researched by heat pump manufacturers.
- Smart technologies. Grid operators are interested in the storage capacity of DHW Heat Pumps, although the capacity is smaller than with direct resistance heating and alternative storage technologies are coming on the market and are being researched. Domestic Hot Water Heat Pumps can contribute to solutions for several energy system-related obstacles. Within the Annex 46 working group, we distinguish five main smart heat pump contributions:
  1. Keeping grid load under control while renewable energy production grows to restrict or even avoid grid capacity investments.
  2. Keeping grid load under control during extreme conditions (i.e. ‘coldest week’), again avoiding grid capacity investments.
  3. Increase self-consumption of renewable energy sources (achieving better grid balance and higher economic end user value).
  4. Selling flexibility to the grid, for the benefit of balance responsible parties, grid operators, traders, etc.
  5. Allowing for a higher share of heat pumps in the energy system without risking local overload problems.

2. The Annex work

The objective of the Annex was to analyse the information on DHW-heat pumping technologies and structure it to the market - ranging from end user to consultant, building constructor, and policy maker - in such a way that leads to better understanding the opportunities and implementing them in order to reduce the use of primary energy consumption and CO_2-emisions and lower energy costs.

The Annex's available resources had laid restrictions on the overall ambition of the Annex. Some of the topics which should or could be tackled were where possible handled under national governance. The restriction thus was that there was often no budget available as the goals of the Annex did not fit into a running national program.

Other running Annexes under the TCP of Heat Pumping Technologies and other TCP's are partially working in the same field and covering some of the same topics. This is unavoidable as a large number of the Annexes are focusing on energy technologies for buildings. These Annexes under the TCP-HPT are:

- Annex 42 - Heat Pumps in Smart Grids;
- Annex 45 - Hybrid Heat Pumps;
- Annex 47 - Heat Pumps in District Heating;
- Annex 49 - Design and integration of heat pumps for nZEB;
- Annex 50 - Heat Pumps in Multi-Family Buildings for space heating and DHW;
- Annex 51 - Acoustic Signature of Heat Pumps;
- Annex 54 - Heat pump systems with low GWP refrigerants;
- Annex 55 - Comfort and Climate Box.

Other relations are with the TCP's on Solar Thermal (SHC) and Photovoltaics (PVPS), as well as with the IIR commission E2 Heat Pumps, Energy Recovery.

The main objective for the Annex has been to provide deeper insight in the challenges to achieve the full potential in applying Heat Pump Water Heaters and to achieve the potential reduction of CO_2-emissions, using various concepts and systems for new as well as existing buildings in the renovation process. This is achieved by giving the right information on the boundary conditions:

- Reviewing available domestic hot water heat pumps, mainly mono-bloc but also larger collective systems;
- Reviewing the different system concepts for single family as well as multifamily buildings;
- Developing and validating a model to enable an objective comparison of domestic hot water heat pumping technologies and systems;
- Data basing example projects;
- Creating a web based information platform to serve participating countries by publishing information on their market approach and training courses.
- Holding regular workshops.
- An overview of R&D on DHW HPs, along with the R&D still needed

Task structure

- *Task 1 – Market overview, barriers for application*
- *Task 2 – Systems and concepts in comparison to alternatives*
- *Task 3 – Modelling calculation and economic models*
- *Task 4 – R&D*
- *Task 5 – Example projects and monitoring*
- *Task 6 – Communication and training*

The Annex basically started with desk work, compiling existing knowledge from Country Reports.

TASK 1 Market overview

The goal of this Task was to get insight in market developments and the governmental policies behind these developments. Inspiring has been the work done by the IEA TCP on 4E Mapping and Benchmarking. Most of the participating countries in the Annex delivered country reports, which have been summarized and edited by the Operating Agent in the overall General Report.

This task was extended to get insight in specific topics like:

- Policy on Legionella and Heat Pump Water Heaters
- Refrigerants for Heat Pump Water Heaters
- Test Procedures and Quality Labels for Heat Pump Water Heaters
- Heat Pump Water Heaters for Multifamily Buildings

Reports written under the Annex Task 1 are:

- **HPT-AN46-02-00 - Task 1 - General report - HPT Annex 46**
  Report is based upon the country reports and gives an overview of market developments, policy, technology and gives an analyses of potential scenario's as basis for policy and R&D.
    - HPT-AN46-02-01 - Task 1 - Country Report Canada
    - HPT-AN46-02-02 - Task 1 - Country Report United Kingdom
    - HPT-AN46-02-03 - Task 1 - Country Report France
    - HPT-AN46-02-04 - Task 1 - Country Report Japan
    - HPT-AN46-02-05 - Task 1 - Country Report Netherlands
    - HPT-AN46-02-06 - Task 1 - Country Report Switzerland
    - HPT-AN46-02-07 - Task 1 - Country Report United States
    - HPT-AN46-02-08 - Task 1 - Country Report Korea
- **HPT-AN46-03 - Task 1 - Legionella and Heat Pump Water Heaters**
  Report discusses the various policy and legislative requirements and the technical solutions. Main finding is the lack of harmonisation and the focus in legislation on high temperature thermal sterilisation affecting the efficiency of heat pumps.
- **HPT-AN46-04 - Task 1 - Refrigerants for Heat Pump Water Heaters**
  Report discusses the various policy and legislative requirements and the technical solutions. Main finding is that for Heat Pump Water Heaters there is at this moment no alternative refrigerant that fulfils all the ideal requirements at once and that LCCP/TEWI are in potential important decisive policy instruments.
- **HPT-AN46-05 - Task 1 - Test Procedures and Quality Labels for Heat Pump Water Heaters.**
  Report discusses the various policy and legislative requirements and the urgent need for harmonisation as also reported upon by 'IEA 4E Mapping and Benchmarking'. Although there is movement from ISO working groups towards harmonisation, there is a lack of political interest to effectively follow that development.

TASK 2 Analyses of Systems and concepts in comparison to alternatives

The goal of this task was initially described as the goal for Task 3, being to make an overview and comparison of calculation models for individual and collective systems for buildings. Based upon that a new model had to be developed that had to be aligned with the existing test procedures for DHW HP. In this process of development the test procedures were analysed under Task 1 and under Task 2 an analyses has been made with a strong focus on collective systems of calculation models comparing the different system configurations. Report written is:

- **HPT-AN46-06 - Task 2 - Calculation Models for Domestic Hot Water Systems**
  Report focuses on analysing the calculation models for designing and rating hot water systems in domestic buildings. Important conclusion is that publicly available models for innovative systems and collective systems are lacking or if available non-transparent and superficial on sanitary hot water.

TASK 3 Modelling calculation and economic models

Under this Task a model was presented by EDF that was already under development for a monobloc Heat Pump Water Heater with a 'wrap-around' heat exchanger for the storage tank. This focuses on a relatively small part of the market and was by studying available literature extended to other configurations. Worldwide there is a large number of models (some academic exercises!) available also for other condensers. Manufacturers do have often their own models. This was analysed and reported upon:

TASK 4 R&D

Although DHW HPs seem to be readily available on the market, development as well as research are still needed to increase the performance of the heat pump itself as well as the DHW-side of the DHW HP and the storage system. The main objectives for R&D can be summarized with the concepts of 'smaller and cheaper', with derived from this the terms 'more efficient', 'suitable for cold climates', 'environmentally friendly refrigerants', 'grid flexibility' and 'easy (plug & play) to install'. Based upon four country reports and the analyses of available literature from International Journal of Refrigeration, a number of Conferences and Elseviers Science Direct, an indicative Roadmap has been developed. Reports available under the Annex are:

- **Country reports Task 4 - R&D on Heat Pump Water Heaters**
  Report analyses the work done as reported by participating countries and sets out scenario's, greatly differing per region, in relation to aspects like market needs/developments, refrigerants, legionella, (collective)-systems, etc.
    - HPT-AN46-07-01 - Task 4 - R&D - Country Report Japan
    - HPT-AN46-07-02 - Task 4 - R&D - Country Report Switzerland
    - HPT-AN46-07-03 - Task 4 - R&D - Country Report France
    - HPT-AN46-07-04 - Task 4 - R&D - Country Report Netherlands

TASK 5 Example projects and monitoring

Under this Task the focus has been on finding examples and to create market showcases to be used in communications. These showcases serve, on the one hand, to inform stakeholders of the viability of concepts and, on the other, as learning tools to build up experience.

TASK 6 Communication

Under this Task communication was done by:

- Holding workshops at Conferences and in regional meeting
- Writing articles and publishing in at conferences and in scientific magazines
- Writing and publishing reports
- Reporting to the Executive Committee of the TCP
- Communicating with other Annexes
- Developing and maintaining a website www.hpt-annex46.org

3. Market overview (Task 1)

The goal of this Task was to get insight in market developments and the governmental policies behind these developments. Report is based upon the country reports (including China) and gives an overview of market developments, policy, technology and gives an analyses of potential scenario's as basis for policy and R&D.
This task was extended to get insight in specific topics like:

- Policy on Legionella and Heat Pump Water Heaters;
- Refrigerants for Heat Pump Water Heaters;
- Test Procedures and Quality Labels for Heat Pump Water Heaters;
- Heat Pump Water Heaters for Multifamily Buildings.

3.1 Market developments

The heat pump markets are currently growing at a steady pace. Energy prices and environmental concern have set the focus on energy conservation and use of renewable energy sources. Heat pump markets and policy in many countries have focused mainly on residential heat pumps for space heating.

While the residential market may be satisfied with standardised products and installations for space heating, this is certainly not the case for Domestic Hot Water. Within a growing market in many of the IEA-countries for Domestic Hot Water Heat Pumps, there is still a large potential for energy optimisation and conservation and reduction of CO2-emissions, which are overlooked in policy papers and do not get market attention these type of heat pumps deserve.

Other than for space heating applications there is a great diversity in markets for heat pump water heaters, due to existing traditional markets and the cultural differences in hot water usage. For the general market developments for Asia, the three major markets are Japan, South Korea and China, for America the US and Canadian market were in focus, while for Europe the latest report from EHPA was used.

- In Japan, the Eco Cute hot water heat pump using CO2 as a refrigerant has been a run-away success over the past decade. According to the statistics, the shipments of ECO Cute HPWH's for residential use started around 2001. By the end of February 2015, an impressive 4.7 million units were expected to be installed in Japan alone with annual sales at 400,000-500,000 units per year, reaching a market share of 98% of all new residential heat pump water heaters in the country. By 2020, the Japanese government aims to reach 10 million Eco Cute units. The annual shipment volume declined and has been hovering at the 400,000-unit-level since 2012 due to the impact of the Great East Japan Earthquake. Still there is a large potential as this impressive number represents 12% of the market.

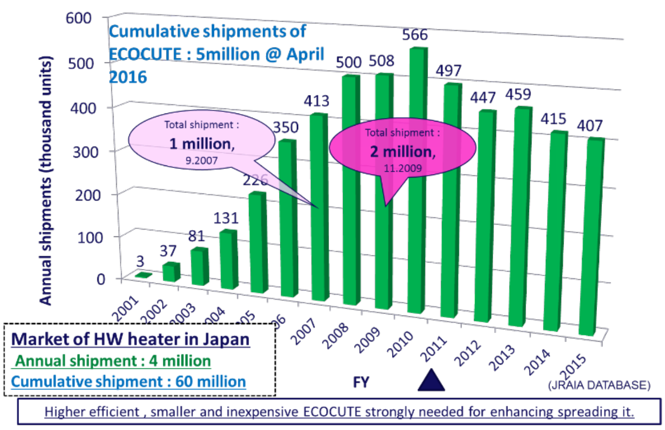


Fig 3.1 – Development of shipments of ECO-Cute heat pumps in Japan

- In Korea KEPCO has launched a new program to promote heat pump water heater with a thermal storage for mid-night electric tariff program in order to replace the existing resistance electric heater, which can be expected to trigger a new market. Collective systems in Multi-Family Buildings are the biggest challenge.

- The largest market in numbers by far is China. Air source heat pump water heaters accounted for about 3% of domestic water heater market (in units) in 2015, showing a huge potential growth room. A great breakthrough in policies for air source heat pump hot water system in 2015 was that the departments of housing and urban-rural development at provincial and city level began to approve including air source heat pump hot water systems into renewable energy sources, and specified its accounting method through a series of regulations.

Fig 3.2 – Installation of DHWH's in China

- In the USA heat pump water heaters have also gained traction in recent years due to their ability to deliver significantly more heat for the same amount of electricity, when compared to conventional electric storage water heaters. By 2017-2018 shipments totalled about 70,000 on average with an estimated market penetration of almost 2%. US has a large potential in replacing Electric and Gas DHW storage tanks (typically still a market of split systems)

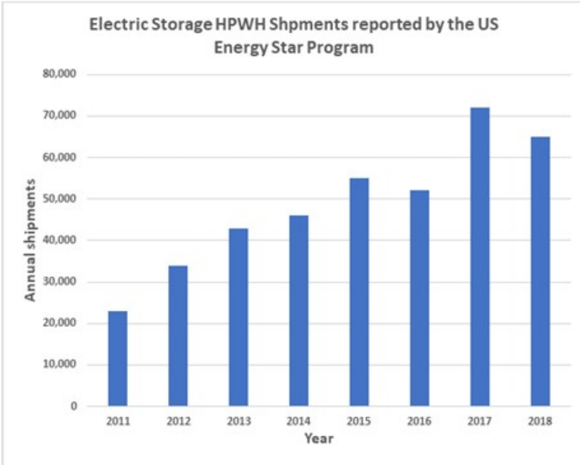


Fig 3.3 – Shipments of HPWH's in USA

- In Europe, after being the fastest growing segment at a growth rate of 21.5%, the pace was slacking down for the single DHW HP in 2017. The recent 2018 report by the European Heat Pump Association shows that after one year of reduced growth, the dynamics of hot water heat pumps have picked up speed again with an overall growth of 13.4%. Double function market is growing, especially in countries with a need for space heating.

However, these growth rates, the worldwide market for heat pump water heaters is still small compared to the other types of water heating equipment sold. Even with the big success recently of the ECO-Cute in the Japanese market, the market share in 2014 was 12.3% of the overall hot water heating market.

Scenario's

The best opportunities for DHW HPs are in:

- Installing in new single family and multifamily buildings to meet building regulations;
- Retrofit of existing gas or oil boiler in single family buildings or terraced houses, with a new boiler and a heat pump water heater or a double function heat pump for space and hot water heating;
- Replacement of direct electrical heating of hot water in existing buildings, individual domestic buildings, terraced houses, driven by customer need for energy cost savings;
- Retrofit of collective distribution systems for hot water (also in district heating systems) with individual heat pump water heaters, either a booster type or an air/air DHW HP, in apartment blocks and multifamily buildings;
- Smaller systems designed for homes where space is at a premium e.g. compact wall-hung systems with <100L tanks; systems with detachable HP module;
- Smart controls to enable integration with PV – and eventually smart grids;

The three major markets in the countries participating in the Annex, Asia, North America and Europe have different market conditions and thus scenario's that are different.

3.2 Policy and potential

The “Introduction Subsidy Scheme” initiated by the Japanese Government in 2002 to subsidize a part of the cost for introduction of heat pump water heaters is a best-practice policy example resulting in recent years that approximately 400,000 to 500,000 units are being shipped every year. This scheme is, however, not currently implemented. The government’s role in raising awareness among market players has been especially instrumental in rapid market adoption. Through energy savings awards, financial support measures for R&D and awareness-raising campaigns, as well as green purchasing laws and consumer subsidy schemes, Japan is now close to its initial target of 5.2 million Eco Cute units by 2010.

Throughout the developed world, the heating of water for domestic use is one of the largest consumers of energy in the household sector. However, water heaters vary in their type and mode of operation, the source of energy used and, potentially more than any other domestic appliance, the actual energy consumed is impacted by consumer usage patterns and ambient environmental conditions. Such complexity creates a number of challenges for policy makers seeking to understand and effectively manage water heating energy consumption. The specific mix of water heater types used varies considerably between countries as a result of culture, historic practice, existing infrastructure and energy source availability. Not surprisingly, the specific policy frameworks developed and deployed by policy makers vary significantly depending on these local conditions.

In getting the right policy it a fine line of supporting the interests of commercial market players selling or installing heat pump technologies, against the sometimes large economic interests of companies selling competing and often traditional technologies. Straightforward policy support for HPWHs is therefore very rare and not consistent across Europe, North America and Asia. The example of Japan cannot simply be copied by other countries.

Yet it can be of governmental interest to support HPWHs as these can contribute to meeting policy targets as HPWHs can:

- Make a significant contribution to meeting energy efficiency and CO_2 targets, through increasing the efficiency of the existing domestic heat sector – particularly displacing gas, electric and oil;
- Be a lower cost option to meet targets than many competing technologies – the upfront cost is relatively low and running cost savings generally high, so the economic proposition is good even without incentives in many markets;
- Make a contribution to renewables targets if they are counted as renewable[1];
- Offer demand side flexibility which is easier to control than space heating (hot water is an easier load to manage than space heating);
- Be a way to manage the grid impact of escalating PV installations.

Yet it is expected that mandating the installation of high efficiency water heaters is the main policy tool to ensure that high efficiency water heaters are installed regardless of any short-term inconvenience issues. In the majority of countries, at least some product types have mandatory and/or voluntary product performance standards in place with these requirements tending to fall into two broad categories:

- Product specific: Typically individual aspects of product energy consumption are limited, e.g. minimum requirements are placed on the efficiency of the water heating process or the rate of heat loss during water storage;
- Technology neutral: Specific levels of water heating service are defined, with an associated maximum energy consumption assigned to that level of service irrespective of technology deployed.

In practice, almost all regulatory regimes deploy a hybrid of the two approaches. For example, until regulatory transition currently underway, the USA specified a generic set of hot water service requirements for almost all

[1] Often HPWHs are not counted as renewable when the heat source is air from an internal space

water heaters, but applied differing minimum performance standards for each water heater type delivering that service. Even where 'pure' technology neutral standards are deployed, the specific service requirements selected often favour one or more particular product type(s).

However, it is interesting to note that some of the best performing products across international markets have resulted from alternate policy interventions. For example:

- In Japan, the Top Runner programme does set mandatory performance requirements but, rather than setting minimum requirements for individual products, future product performance targets are based on a category/application-specific weighted average value of shipments from manufacturers. This has led the Japanese heat pump water heater market to be being dominated by some of the best performing products in the world. Australia also has some very high performing heat pump models apparently drawn into the market by emissions-based white certificate schemes in some States.
- Korea has a high proportion of the best performing instantaneous water heaters despite the Korean minimum performance standard not being particularly challenging. This may be a spin-off from the aggressive advertising promoting condensing boiler systems spilling over into a consumer demand for condensing instantaneous water heaters which are then easily identifiable via the Korean energy label.
- The North American ENERGY STAR programme is encouraging premium performance products across all water heater types.

Given the range of policy deployed, and the specific local conditions, it is not surprising that not one country has the best performing products across all water heater types. For all countries, there is potential to make savings across almost all water heater types. The magnitude of the savings potential varies but in some cases it is very large. For example, savings of over 1 MWh per year per product are available to policy makers in Canada simply by moving the market towards the more efficient gas storage water heaters already available locally. Even for electric storage water heaters where manageable losses are limited, savings of 100 to 200 kWh/year per product are available to policy makers in most countries. Within the context of the total annual energy consumption of water heaters, such savings might appear insignificant. However, savings of this magnitude are often sought for other products (e.g. refrigerators) and could be achieved simply by eliminating the worst performing products from the market with no apparent loss of service to the consumer.

There are much larger potential savings available from moving between types of water heater. On a delivered energy basis, and at the reference conditions used, water heater types providing similar levels of service have annual energy consumptions of (source IEA 4E Mapping and Benchmarking [01]):

- Air sourced heat pumps: 1.1 – 2.0 MWh;
- Direct electrically heated storage: 4.4 - 5 MWh;
- Gas instantaneous: 6.2 - 6.5 MWh;
- Gas storage: 6.0 - 7.7 MWh.

Hence, to take the most the most extreme example, a switch from the worst performing gas storage water heater to the best heat pump model would reduce annual energy consumption by almost 7 MWh per water heater. However, traditionally, policy makers have been reticent in pursuing policies that would drive switching of product type, even where technology neutral policy measures have been deployed. But recently, the technology neutral labelling of the water heaters in the EU clearly has such technology switching as a long term goal. Further, the transition in regulatory requirements currently under way in the USA appears to be moving towards technology neutrality based on primary energy. For water heaters above 208 litres in the USA, it appears the likely impact will be to drive electrically heated water heaters to heat pump technology, and gas storage water heaters to condensing efficiencies. Not only is this likely to yield significant energy savings in the US market, it is also likely to stimulate the introduction of a large number of higher efficiency gas storage and electric heat pump products into the broader market. If this is the case, such products (or similar derivatives) may become more widely available internationally and present policy makers elsewhere with more options for managing their own markets. HPWHs will look strong relative to competing technologies under Eco-design and Ecolabelling in Europe, TOP Runner program in Japan and the ENERGY STAR in USA/Canada, which should support market growth – however this will not create immediate opportunities as there should/must be added value for the market players in the value chain to participate. In the market study [12] the business opportunities for the supply side are listed, which is a further basis for R&D as discussed under Task 4 of the Annex.

Awareness of HPWHs is growing in several markets, but in general, awareness is low amongst end-users (as is the case with space heating heat pumps) while on the other hand technology is broadly available. This means presenting and disseminating a simple, easily understood and compelling message to consumers. Central to this is giving consumers the confidence to embrace the technology, and create pull in the marketplace to assist in transitioning heat pumps from a niche product to one having mass market appeal. Awareness can be raised by:

- Product promotions and programmes;
- Information dissemination;
- Roadshows, information seminars, press and PR activities;
- Involvement of trusted actors and brands;
- On-going field trials, and tests with published results.

There is a role for all industry stakeholders in these activities as well as the other actors in the value chain: building and construction companies, energy companies, housing corporations, energy service companies, installers, knowledge and training institutes, research institutes and universities, branch organizations, financiers, etc.. The structure of an innovation system consists of five elements: Actors, Interactions, Institutions, Technology and Infrastructure.

In line with the above, the policies in the different countries in their overall approach have a general nominator focusing on energy conservation, renewables and energy security to reduce the greenhouse gases and pollution in line with the Paris agreements. As a basis, there is a number of legislative requirements described in directives, focusing on:

- Creating a challenge for individual technologies, through test procedures, standards and energy performance labelling, like European ECO label, TOP Runner in Japan, China Energy Label (CEL), Energy Star and Energy Guide labels in North America
- Creating a challenge for competing technologies, by setting energy targets for systems in buildings or by simply setting restrictions on certain types of technologies

In the end it is the end-user, either private or collective through housing corporation, but also the building constructor and its engineers having to comply with the Energy Efficiency demands of a building, that decide on the choice of water heating technology to be applied in a new building or a renovation project. The renovation project can be a simple replacement of an old heater or system.

3.3 Test Procedures

Test procedures are the basis for quality labels, calculation models and therewith an important element in governmental policy instruments.

Standards are used for various purposes at legislative level and for other purposes:

- Energy performance labelling, like European EnR and EL regulation, TOP Runner in Japan, China Energy Label (CEL), Energy Star and Energy Guide labels in North America;
- In practice, standards are also used for design purposes used in a number of (often commercial) calculation models;
- Governmental information models and in a more general approach for EPBD and national building code, like the Standard Assessment Procedure (SAP) and Reduced Data SAP (RdSAP) models in the UK with which the Energy Performance Coefficient (EPC) for the building is calculated;
- Models developed for marketing by Heat Pump Associations.

Traditionally, energy efficiency standards and labels have set performance requirements for water heaters by type (e.g., storage electric water heater, gas instantaneous water heater, etc.), thus inhibiting the comparison across water heater technology classes. Yet many of the test procedures seem to focus mainly on air source HPWHs, being the main stream, while there is a large number of alternative heat pump technologies supplying domestic/sanitary hot water based e.g. on ground heat. For these there are sometimes no standardized test procedures available or if available not acknowledged at international level.

However world-wide there is a disturbing landscape with a great number of test methods for heat pump water heaters in use in different regions of the world, with major differences between them, like:

- Product configuration (with or without storage tank, air or ground heat source, etc.) and heating capacity of the heat pump
- Temperature conditions in the test room
- Tapping profiles and temperature setting of the heat pump
- Calculation procedures of efficiencies (i.e. considering heat losses in the storage tank)

'There is no single 'best' test method, which could be adopted for global use – all have their advantages and disadvantages'.

As a result, manufacturers have to undertake a different set of tests to be able to sell their products on the worldwide market. This inhibits trade, adds to product costs and slows the development of the global heat pump water heater market. In an ideal form of harmonisation, testing authorities in each economy would be able to take the results from any of the existing HPWH tests, and use a simulation model to predict what the results would be if the same model were physically tested to their own standard. However, this ideal is not likely to be attainable.

Harmonization of the test procedures is urgently needed. A first challenge seems harmonize the nomenclature of systems, then go into a clear definition of performance.

For the existing test procedures for air source heat pumps, given the extent of the differences, it is not considered likely that the standards bodies and energy program regulators in different countries would agree adopting a common standard, without a gradual process of confidence-building and harmonisation. There is some support among global manufacturers who export widely, having commercial interest in reducing the amount of product testing required for each market. For some manufacturers (including global suppliers), differences in methods of test are low on their concerns. Is it of greater commercial interest that the local standards in their export markets shows their products in a good light, and that government support in those markets (e.g. through regulation or direct cash incentives) for favours HPWHs [02].

Table 3.1 – Overview of labels and standards

Characteristics	Country	Organisation	Label/program	Label	Test standards
Voluntary Minimum Energy Performance Standard	United States	DOE			CFR 430
	Canada	Natural Resources Canada			CAN/CSA-C745-03 (R2014)
	Japan	METI	Top Runner Program		JIS C 9220-2011
	South Korea				
	EU (27 countries)	EU Commission	Eco - design		EN 16147
	Switzerland	Fachvereinigung Wärmepumpen Schweiz (FWS)	FWS Zertifikat		EN 16147
	United Kingdom				EN 16147
	China	CNIS			
	Australia	DCCEE			
Mandatory Energy Labelling	United States	FTC	Energy Guide Label		CFR 430
	Canada	Natural Resources Canada	Energy Guide Label		CAN/CSA-C745-03 (R2014)
	Japan	NA	NA	NA	NA
	South Korea				KS B 6410
	EU (27 countries)	EU Commission	EuP program		EN 16147
	Switzerland				EN 16147
	United Kingdom				EN 16147
	China	CNIS	Energy Label		GB/T 23137 - 2008
	Australia	DCCEE	Energy Rating Label		AS/NZS 5125.1:2014
Voluntary Energy Saving Label	United States	EPA & DOE	Energy Star		
	EU (27 countries)	EU Commission			
Mandatory Stand By Warning Label	Australia	DCEE			
	South Korea				

Even the home economies of these manufacturers may wish to retain their own standards as local standards bodies and regulators have a major investment in the existing methods of test. Although some are investigating possible changes, it is in the context of building on what they already have. The range of ambient conditions and draw-off schedules developed for different standards attempt to replicate local conditions and user behaviour.

They have also evolved to reflect the predominant types of product preferred in the local markets, and in some cases do not cover the testing of other configurations.

There is considerable work to be done before internationally-comparable energy efficiency test methods, metrics and efficiency levels are at a stage where they can be used in future efficiency policy measures. The ISO Working Group 12 on Heat pump water heaters of ISO Commission ISO/TC 86/SC 6/WG 12 on Heat pump water heaters has proposed a harmonisation framework, including standardised physical tests and a staged development of simulation methods. It published in August 2018 the ISO Draft HPWH-19967-Part1 and Part2. The draft Standard of Part 1 specifies test conditions and test procedures for determining the performance characteristics of air source heat pump water heaters for hot water supply with electrically driven compressors with or without supplementary electric heater and connected to or including only one hot water storage tank.

It is important to have accurate procedures for standard assessment of the energy performance of DHW-preparation. The question is whether the current and the future Energy Performance Standards that are widely used to evaluate applications actually reflect the current applications. For harmonisation a set of guidelines can be developed:

- Scope of testing procedure;
- Major objectives of the testing procedures (what parameters are to be established);
- Identification of similarities among different procedures;
- Level of complexity/duration of the test procedure;
- Scalability of the procedure to smaller vs. larger storage tanks;
- Applicability of various technologies (electric, gas fired, heat pump, tankless etc.).

For single mode DWH testing, the key to harmonisation is a set of basic tests, which might be similar (but not identical) to the most common test conditions currently in use. A proposal of possible harmonized basic test conditions would be:

- Low-temperature test condition of 7°C DB/6°C WB is already included in the European, Japan and Korea (draft) standards, and would be consistent with one of the conditions in the AS/NZS standard (<10°C);
- Water temperature of 10°C for the above test;
- Warm-temperature test condition of 20°C DB/19°C WB – this is already included in the USA, Canada, and China tests, and would be consistent with one of the conditions in the AS/NZS standard (18 to 20°C);
- Water temperature of 15°C for the above test;
- For models designated as suitable for use in frost conditions, a test at 2°C DB/1°C WB (this designation should be part of the Product Classification system);
- For models designated as suitable for warm and humid climate conditions, a test at about 30°C and high humidity.

No draw-off test would be necessary at the above test conditions – only a heat-up test and either a static operation test (in which the compressor is allowed to run to cover heat loss from the tank) or a cool-down test (in which the compressor is switched off and the tank allowed to cool).

The data from the basic test would be used in a simulation method, which could be developed as part of the ISO test or as a separate document. The product parameters would be entered into a model. To the extent that this method required information about a HPWH's refrigeration system or control strategy, it would be restricted to data that could be observed or established through physical tests (which would form part of the basic test suite for certain product types). More complex modelling options may also be included.

It is understood that the ISO Technical Committee C86/SC6, which will be developing the HPWH test, is yet to decide whether to only cover the testing of HPWHs serving a Domestic Hot Water task ("single mode DHW testing"), or also those capable of serving a space heating task as well – either while in one or other modes, or both modes simultaneously. At present, only EN 16147 and the draft KS standard refer to the possibility of dual-mode HPWHs, and EN16147 only provides for the testing of such units in DHW mode. This provides an opportunity for the ISO to develop both a single mode Space Heating test, and a dual-model (space heating and hot water) test, and have them adopted as default international tests.

The main part of the test procedures for HPWHs focus on air source heat pumps, being the main stream of applied HPWHs, while there is a large number of alternative heat pump technologies supplying domestic/sanitary hot water. For these there are often no standardized test procedures available or if available on national level, not acknowledged at international level. As it is important that innovative solutions find their right place in the market, this lack in the test procedures needs to be addressed. It concerns a range of products such as: multi-function heat pumps, hybrid heat pumps, fresh water heat pump systems, booster heat pumps, combination of solar and heat pumps, extended smart storage systems, larger than 50/80 kW systems, cascade heat pumps, etc.

3.4 Refrigerants

The historic amendment to the Montréal Protocol adopted in Kigali, Rwanda, is a major policy step forward in the global effort to reduce greenhouse gas emissions and the threat of climate change. The amendment sets a gradual phasedown schedule for high-GWP HFCs, which were introduced more than 20 years ago as ozone friendly alternatives to replace CFCs and HCFCs. The search for alternative refrigerants replacing the existing is an ongoing process, dominated by manufacturers of refrigerants as well as the larger heat pump manufacturers (market leaders). Focus is mainly on space heating systems. For Heat Pump Water Heaters however at this moment no alternative refrigerant fulfils all the ideal requirements at once.

Hydrofluorocarbons (HFCs) are an important source of greenhouse gases globally, where climate-friendly, energy-efficient alternatives, such as natural refrigerants and HFO's, are readily available for a growing number of applications. In 2014, the EU took regulatory action to limit the use of these greenhouse gases through a combination of measures. Within not even four years, the changes in the industry are noticeable. The impact will increase as the worldwide regulatory measures switch into high gear in the next decade. It demonstrates that with clear, ambitious and timely regulatory rules, industry is able to take action more quickly than expected.

At this moment, the challenge for many of the alternative refrigerants is flammability, thus their use restricting by a number of safety codes and standards. Research spearheaded by industry is ongoing to support the new codes and safety standards available from the first half of 2017. Industry is getting together to adopt and develop best practices as well as training and certification programs to ensure proper management, servicing, and end-of-life practices for equipment using lower GWP refrigerants.

For Heat Pump Water Heaters not much focused research is available in which results show which refrigerant is the 'best solution'. GWP can be a useful metric to compare different refrigerants. However, it may to overestimate the benefits of low GWP refrigerant to environment, as it does not take into account many other affecting factors, like the use of high efficiency components and system design, such as the optimal storage size, stratification and condenser design. Ensuring proper installation, optimised control and operation, under all common operating and climate conditions are factors not directly related to the technology itself and the choice of refrigerant. In the end, the overall energy use of the installation is an important factor in the calculation of the LCCP (Yunho Hwang, et al [03]) or TEWI factor.

For a HPWH the refrigerant used by a large part of the manufacturers is R134a, a status that will continue for a longer time to come. The tendency of the industry is to move towards natural refrigerants when it is technologically safe and economically feasible. Carbon Dioxide (R744) has a growing market in Asia, while Propane (R290) is very much in development and applied in small domestic applications in Europe. Both are well suited for HPWH. HFO's although already applied in automotive industry is another potential alternative not yet well researched for DHW applications.

As a consequence of the regulations for legionella and the need for heat pumps suitable for retrofit, especially in collective systems, refrigerants and solutions for DHW applications with higher than traditional (>65ºC) heat supply temperature are in demand. Carbon dioxide and propane are natural refrigerants, which have higher critical temperatures and can be used to reach higher output temperatures up to 80°C. Modifications to the refrigerant cycle such as EVI or cascading refrigerant cycles can be used to increase the output temperature further up to 80°C with other refrigerants, momentary mainly R410A/R134a is used.

R152a, R1234yf, R1234ze(E) and Ammonia are interesting alternatives for DHW HP, not yet broadly in use but already tested in R&D projects , while R32 is strongly promoted by manufacturers.

However, no alternative refrigerant fulfils all the ideal requirements at once.

Refrigerants for heat pump water heaters

Since the phase-down of R22 due to high ODP, R134a has been widely accepted as the refrigerant of choice for most HPWHs on the market today. While seeking a replacement for R134a, it is critical to investigate refrigerants that do not require significant modification of the existing system configurations. A drop-in-replacement refrigerant resulting in a measurable improvement in performance will be an ideal candidate.

In order to short-list appropriate refrigerants an extensive list of potential candidates was considered. The following table lists the refrigerants down-selected for further analysis. It can be observed that most of the refrigerants have comparable properties to R134a such as critical temperature and pressure and volumetric capacity.

Table 3.2 – overview of alternative refrigerants (Baomin Dai et.al.[33])

Refrigerant	Physical data				Safety data			Environmental data	
	Molecular mass	T_b (°C)	T_{cri} (°C)	P_{cri} (MPa)	OEL (PPMv)	LEL (%)	ASHRAE 34 safety group	ODP	GWP
R744	44.01	-78.4	31.1	7.38	5000	None	A1	0	1
R41	34.03	-78.3	44.1	5.9	-	-	A2	0	107
R32	52.02	-51.7	78.1	5.78	1000	14.1	A2	0	675
R1270	42.08	-47.7	92.4	4.66	660	2.0	A3	0	~20
R290	44.10	-42.1	96.7	4.25	1000	2.1	A3	0	~20
R161	48.06	-37.6	102.2	5.09	-	3.8	-	0	12
R1234yf	114.04	-29.5	94.7	3.38	500	6.2	A2L	0	<4.4
R134a	102.03	-26.1	101.1	4.06	1000	none	A1	0	1370
RE170	46.07	-24.8	127.2	5.34	1000	3.4	A3	0	1
R152a	66.05	-24.0	113.3	4.52	1000	4.8	A2	0	124
R1234ze	114.04	-19.0	109.4	3.64	1000	7.6	A2L	0	6

Those that are suitable to be used in a given application (considering e.g. operation temperature range, safety requirements), and those that are seen as retrofit replacements to “conventional” refrigerants such as R134a, R410A.

Table 3.3 Alternative refrigerants for R410A (Longhini [12])

Refrigerant	GWP*	Flammability	T critical [°C]	P critical [bar]	Nat. boiling point [°C]
R410A	2088	A1	72.8	48.6	-48.5
R513A	631	A1	101.1	36.8	-29
R450A	601	A1	105.7	40.8	-24
R1234yf	4	A2L	94.7	33.8	-29.5
R1234ze(E)	7	A2L	109.4	36.3	-19
R32	675	A2L	78.1	57.8	- 52
R152a	124	A2	113.3	45.2	-25
R290	3	A3	96.7	42.5	- 42.2
R1270	2	A3	91.1	45.6	-47.6

As there is a number of different types of HPWH, thus a number of different options for refrigerants, where there is an obvious split between single family house standalone heat pumps only supplying hot water and those also supplying space heating, and heat pumps supplying hot water in a collective domestic systems. The latter do have to supply higher temperatures and do have more constant demand over the day.

Though multiple studies have addressed the performance of HCs (pure and mixtures) for HVAC&R applications, no (there are some literatures available, please check) available literature explores the potential of such refrigerants for HPWH applications.

Among the natural refrigerants, Propane and CO_2 seem to be the most appropriate refrigerants for the DHW application. However other alternatives

Energy efficiency

By using an integrated approach to HPWH equipment design and selection, the opportunities to improve energy efficiency or reduce energy use can be maximised. This approach includes:

- Ensuring minimisation of cooling/heating loads;
- Selection of appropriate refrigerant;
- Use of high efficiency components and system design;
- Ensuring proper installation, optimised control and operation, under all common operating conditions;
- Designing features that will support servicing and maintenance

The largest potential for DHW improvement comes from improvements in total system design and components, which can yield efficiency improvements (compared to a baseline design) that can range from 10% to 70% (for "best in class" unit). One of the first can always be minimisation of demand. On the other hand, the impact of the refrigerant on the Energy Efficiency is usually relatively small, yet not to be ignored – typically ranging from +/- 5 to 10%.

On the basis of the small number of investigations found, it can be established that the configuration of the heat exchanger (HX) is important for the efficiency of the heat pump. This requires further research into the optimal design that can be used flexibly in a large part of the market. Theoretically, if a single component refrigerant is used (e.g. propane) and a HX with infinitely large heat transfer area, an infinitely low-temperature difference can be created between DHW and refrigerant, and thus the effect of HX on energy efficiency can be eliminated. Traditionally two main types of HX are applied, being the wrap around and the in tank spiral. Due to the size of the storage tank, the heat transfer area can be limited. The choice of an HX is thus a trade-off between the fixed cost of the HX and energy efficiency gain, where manufacturers end up making trade-off analysis and select the HX that best fits the application and the refrigerant.

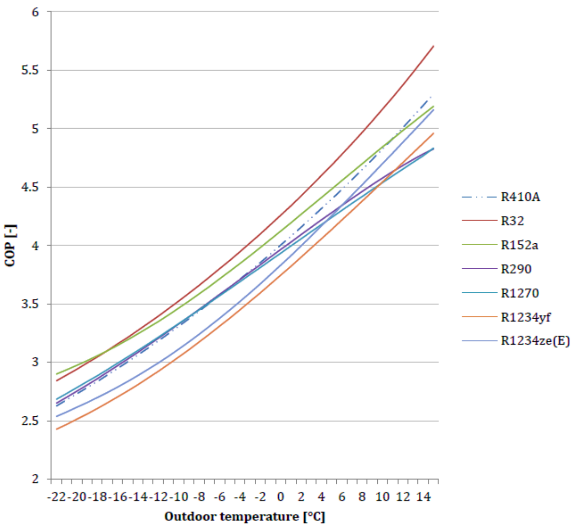


Fig 3.4 Comparison of COP for different refrigerants (Makhnatch et al [05])

Theoretical energy efficiency of pure refrigerants varies (+/- 5%), but the difference in their thermophysical properties influence the heat transfer and thus have an effect on the temperatures that have to be established in the condenser and evaporator to facilitate the heat transfer through a specific heat exchanger (Domanski et al [06]) to see the theoretical COP excluding HX, and including HX. The study shows that the low-GWP refrigerant options are very limited, particularly for fluids with volumetric capacities similar to those of R410A or R404A.

The identified fluids with good COP and low toxicity are at least mildly flammable. Refrigerant blends can be used to increase flexibility in choosing trade-offs between COP, volumetric capacity, flammability, and GWP. Independently of which refrigerants will be used in the future there are strong incentives to reduce the charge of refrigerant in each system. Especially with hydrocarbons the trend is to go to reducing the charge as much as possible by using brazed plate heat exchangers outside of the storage tank. The first published papers by Anderson et al. [07] recorded a reduction of the charge of refrigerant in a 5 kW liquid to liquid heat pump (heating only) to 200 g of propane using mini-channel tubes. It was expected that a further decrease of the charge was possible by redesigning the condenser and by reducing the amount of propane in the compressor, either by using oils in which propane is not soluble or by using compressors with low charge of oil. The same researchers showed at the recent Gustav Lorentzen Conference 2018 [08], that with the right system design it is possible to create a heat pump system that can deliver up to 10 kW heating capacity with as little as 100 g of propane in the system, indicating that it is possible to meet a large cooling needs with a small amount of propane. The designs suggested may open up for the safe use of flammable refrigerants with high energy efficiency such as R152a, R32, R290 and R600a.

Not much of the research is focusing directly on HPWHs. One report on this is from Kashif Nawaz et. al [06] who concluded the performance of CO_2 HPWH can be comparable to that of HPWHs using R-134a, more so with a separated gas cooler configuration. This configuration showed better performance than the wrapped tank configuration for both CO_2 and R134a systems.

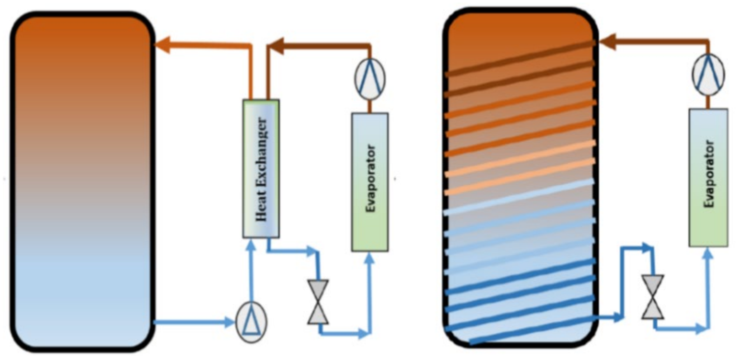


Fig 3.5 – HX configurations tested at Oakridge. Left: separated heat exchanger, Right: HX wrapped around the tank (Nawaz et al [04]).

The Unified Energy Factor for both configurations with CO2 and R134a as working fluids where the water temperature set-point is 125°F (about 52 °C) and both systems have variable speed pumps to control water flow rate for optimized performance.

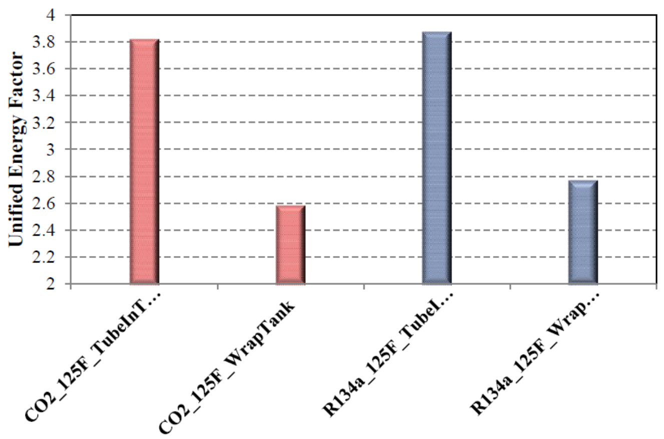


Fig 3.6 – Unified Energy Factor for two HX configurations tank (Nawaz et al [06]).

It is clear that a tube-in-tube gas-cooler (for CO_2 system) or condenser (for R-134a) results in a significantly higher UEF for the same operating conditions. One important reason for the performance improvement is that variable water flow control can better match the tank stratification under changing conditions than does a fixed tank wrap configuration.

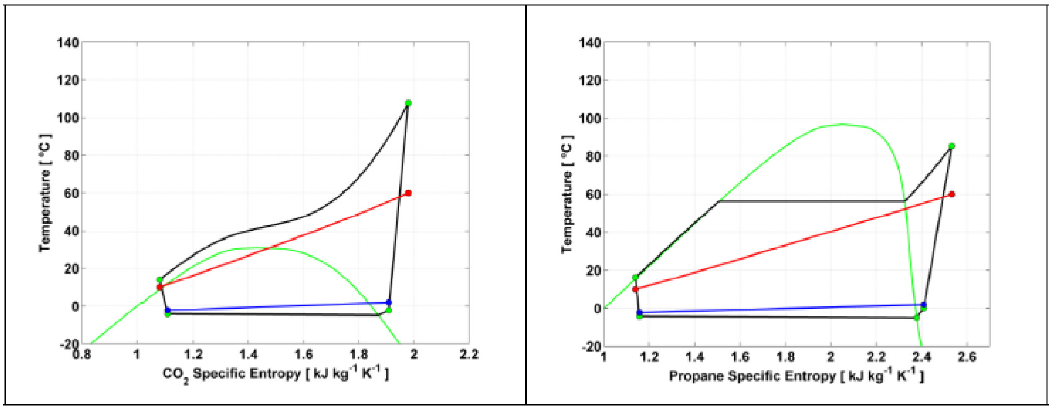
Based on the findings described above, it can be concluded that CO_2 can be an effective substitute for refrigerant (R-134a) for HPWH applications. However, substantial modifications of the system configurations are required to achieve comparable performance such as the additional infrastructure of an appropriate compressor, pump, water-flow control, and gas-cooler. The system is highly sensitive to water circulation rate which directly impacts the stratification and system efficiency and this is an additional requirement along with relatively higher maintenance cost due to potential fouling of the gas cooler. Regardless of these apparent complexities, the system can perform well in lower ambient temperatures and is most suited for split (i.e. modular) HPWH systems using some or all outdoor air.

Chen et.al. [09] have studied gas coolers for CO_2 as refrigerant in HPWH applications. Due to strong nonlinear variation of supercritical CO_2 specific heat capacity with temperature, pinch point would occur in water-cooled CO_2 gas cooler, which has great impacts on the heat transfer characteristics of gas cooler and overall system performance. Pinch point analysis was conducted for CO_2 gas cooler in the present study. The effects of refrigerant pressure, mass flow ratio (mw/mc), inlet water temperature and heat transfer area on pinch point location, approach temperature difference and heat transfer rate were analysed in detail. Based on the analysis of pinch point location in CO_2 gas cooler, the critical flow ratios were proposed to effectively control the approach temperature difference. Furthermore, the actual conductance of gas cooler was calculated and compared with that estimated by LMTD method. The results showed that CO_2 gas cooler may be undersized by as much as a factor of 30 to 60% for different pressures if LMTD method is used. However, the UA value evaluated by LMTD method also may be overestimated under high refrigerant pressures when the approach temperature difference tends to be zero. Results of the present study can be helpful to practical designs of CO_2 gas cooler and heat pump water heaters.

The thesis of Pitarch i Mocholí [10] focuses on sanitary hot water production with heat pumps and concludes that Propane (R290) and CO_2 (R744) seem to be the more appropriate refrigerants for the DHW application. The high water temperature lift in DHW applications (usually from 10ºC to 60ºC) involved has conditioned the type of used solutions. On the one hand, transcritical cycles have been considered as one of the most suitable solutions to overcome the high water temperature lift. Nevertheless, the performance of the transcritical CO_2 heat pump is quite dependent on the water inlet temperature, which in many cases is above 10ºC. Furthermore, performance highly depends on the rejection pressure, which needs to be controlled to work at the optimum point in any condition. On the other hand, for the subcritical systems, subcooling is critical for the heat pump performance when working at high temperature lifts, but there is not any published work that optimizes subcooling in the DHW application for these systems. Therefore, the subcritical cycle should require a systematic study on the subcooling that optimizes COP depending on the external conditions, in the same way as it has been done for the rejection pressure in the transcritical cycle.

In the study of Mocholí two different approaches to overcome the high degree of subcooling were designed and built to test them in the laboratory:

- Subcooling is made at the condenser: The active refrigerant charge of the system is controlled by a throttling valve. Subcooling is controlled independently at any external condition.
- Subcooling is made in a separate heat exchanger, the subcooler. Subcooling is not controlled, it depends on the external condition and the heat transfer at the subcooler.



- *Fig 3.7 CO2 (left) and propane (right) heat pump thermodynamic cycle on the T-s diagram at nominal design conditions (Tamb = 2°C, Tw,in,gc or Tw,in,co = 10 °C). (Tamaro et al [11])]*

The heat pumps were tested at different water temperatures at the evaporator inlet (10ºC to 35ºC) and condenser inlet (10ºC to 55ºC), while the water production temperature was usually fixed to 60ºC. The obtained results have shown that COP depends strongly on subcooling. In the nominal condition (20ºC/15ºC for the inlet/outlet water temperature at the evaporator and 10ºC/60ºC for the inlet/outlet water temperature in the heat sink), the optimum subcooling was about 43 K with a heating COP of 5.61, which is about 31% higher than the same cycle working without subcooling. Furthermore, the system with subcooling has been proved experimentally as being capable of producing water up to 90ºC and has shown a higher COP than some CO2 commercial products.

In the study by M. Tammaro et.al. [11] two heat pump systems for the production of sanitary hot water were modelled and simulated. The two systems were based one on the refrigerant CO2 and the other one on propane. It resulted that, in order for the heat pumps to have the same heating capacity, the compressor size of the propane unit was 2.5 times larger than the CO_2 one while the brazed plate heat exchanger needed to heat water was 3 times larger than the CO_2 one.

Ambient temperature has the most influence on the increase of the heating capacity with a higher slope for the propane unit, which had higher heating capacity than the CO_2 at ambient temperatures above 8°C and lower for colder temperatures. Water inlet temperature increase, instead, had a detrimental effect on the heating capacity, more pronounced on the CO_2 unit. In both cases, a stratified storage was found to be functional to obtaining better energy performance while retaining a correct water delivery temperature in order to preserve user comfort.

TEWI and LCCP

The GWP is a useful metric to compare different refrigerants. However, over 80% (if not more) of the global warming impact of HP systems comes from indirect emissions generated operating the HP (i.e. electrical power consumption), with a lower proportion coming from the use/release (direct emissions) of GHG refrigerants through leakage (2%/year) and recovery [12]. To translate this into numbers the factor describing the Total Equivalent Warming Impact (TEWI) is used.

It is obvious that a system with a high COP and dependent on the application and climate zone the SCOP (Seasonal COP) has a good TEWI score, when low GWP refrigerants are used. However, power consumption of the heat pump in relation to efficiency and emissions of power generation become very important factors where in general the benefits of low GWP refrigerant to environment may be overestimated, as it does not take into account many other affecting factors.

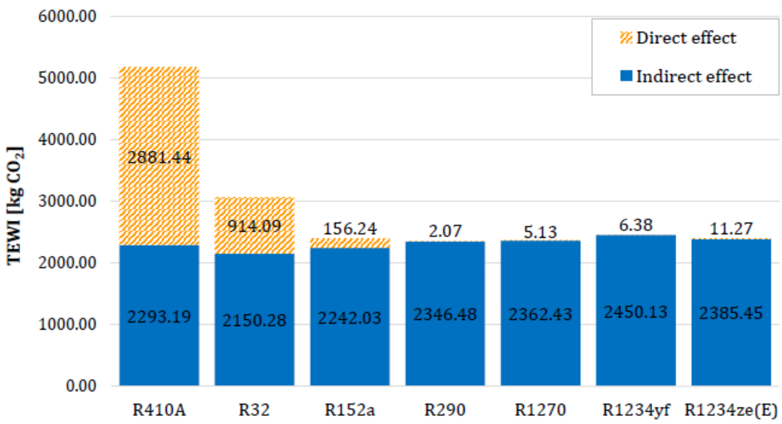


Fig 3.8 TEWI - Direct and indirect effect (radiator heating in Sweden) (Longhini [12])

In order to evaluate the influence of the characteristics of the system on the TEWI, Longhini et. al. [12] performed a sensitivity analysis on three of the parameters:

- Leakage rate, this is assumed being 2%, but can in the best situation be lower than 1%. The higher the GWP, the more pronounced are the consequences of a leakage increase[2].
- Lifetime, is assumed to be 15 years, having a major impact in the indirect emissions
- Recovery factor, only influences the direct effect of refrigerant choice

Moreover, the electricity mix is of great importance as with an increased share of renewables the indirect emissions will decrease. The results in Figure 3.8 are valid for Sweden with a CO_2 emission factor for the Sweden energy mix of 0.023 kg CO_2/kWhe. This is justified by the fact that Sweden has a very clean energy mix for energy production, and thus does not have a large indirect effect. The lowest reduction is obtained by R32, with a reduction of 40.8%.

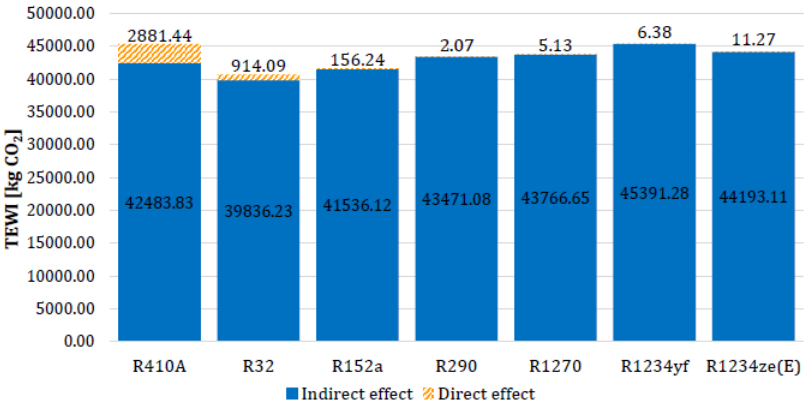


Fig 3.9 TEWI - Direct and indirect effect based upon the European energy mix (radiator heating) (Longhini [12])

When evaluating TEWI with the emission factor for the European average, i.e. β=0.4261 kg CO_2/kWhe, the outcome is completely different as seen in Figure 3.9. While not affecting the direct effect of the refrigerants, the increase of the emission factor shows a large increase in their indirect effect and thus in the overall TEWI. The major increases are experienced by refrigerants with lower SCOP.

It is important from this study by Longhini to understand that the results obtained are highly dependent on the area for which they have been calculated and that these are only valid for a number of space heating conditions. Furthermore, the results may be comparable to results to be expected for HPWH applications, but are not directly valid.

The Japanese Refrigeration and Air Conditioning Industry Association has made a study on the Life Cycle Climate Performance (LCCP) for a number of refrigerants assuming:

- CO_2 emission coefficient: 0.425[CO_2-kg/kWh];
- Lifetime: 12 years;
- Operation hours: 9 h/day;
- Refrigerant leakage ratio: 2%/year;
- Refrigerant recovery ratio at disposal: 30%.

[2] In the case of R410A, in fact, the TEWI can increase up to 41.8% for a leakage increase of 3 percentage points. When considering the HCs and the HFOs, instead, an imperceptible variation is observed, being maximum 0.066%, 0.16%, 0.19% and 0.35% respectively for R290, R1270, R1234yf and R1234ze(E). This could represent a further advantage in the usage of such refrigerants, as the number of leakage checks could be reduced and thus the maintenance cost.

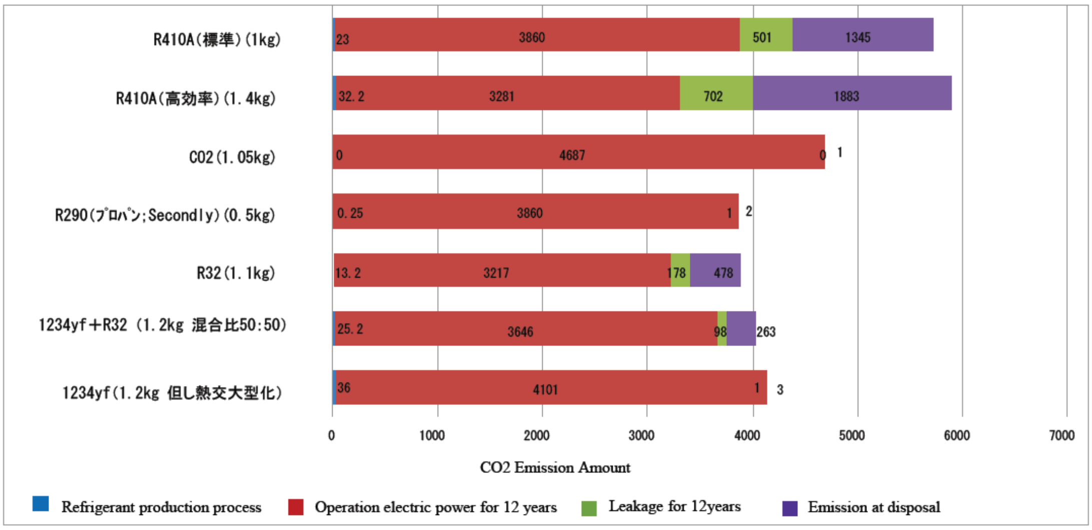


Fig 3.10 Comprehensive warming impact estimation and energy efficiency by refrigerants - Residential Air-Conditioner 4.0kw [13]

However, in practice, the LCCP is more complex than TEWI and the contribution of additionally accounted emissions is debatable. While the results given by each of the environmental metrics were different from one metric to another, TEWI as an environmental metric is simpler to use than LCCP.

The F-gas Regulation provides incentives for the use of refrigerants with reduced GWP. In such cases, direct emissions from Heat Pump systems are expected to be reduced . However this does not necessarily result in lowering climate impact, expressed in term of LCCP value [14]. Thus, LCCP evaluation can be necessary in order to account for the entire climate impact of a system when selecting an alternative refrigerant. The challenge regarding the wide implementation of the LCCP method is its uncertainty, which originates on different levels (e.g. missing or unrepresentative input data, modelling uncertainty). These uncertainties should be addressed when calculating the LCCP of an Heat Pump system. Moreover, the uncertainties can be incorporated in a comparative LCCP analysis [15].

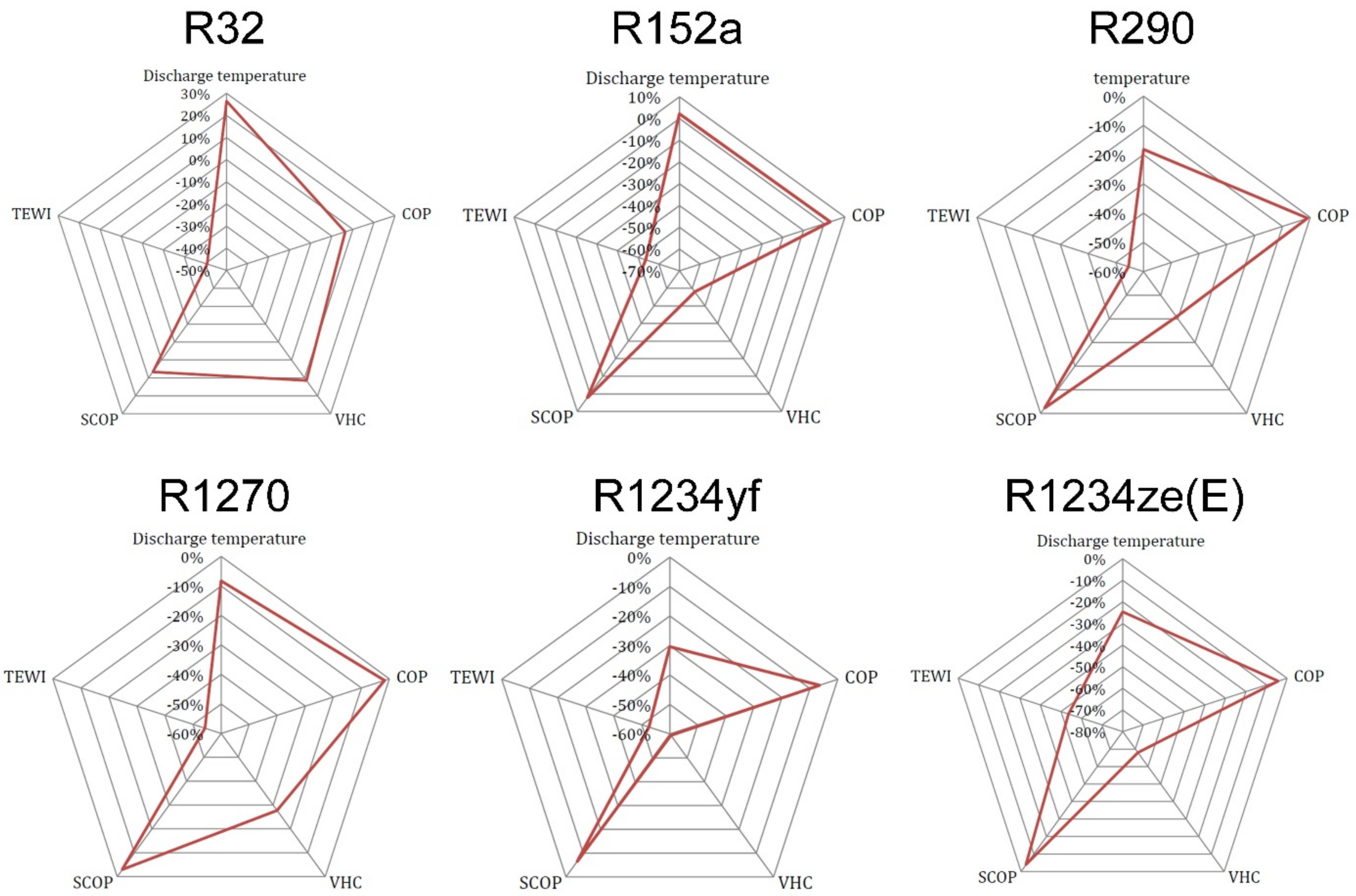


Fig 3.11 Relative difference of refrigerants performance (Discharge temperature, COP, VHC, SCOP, TEWI) compared to R410A at operating conditions corresponding to -22°C to 16°C outdoor temperature (adapted from Longhini et al. [12].

SKVP requests exemptions for heat pumps

In 2018 the Swedish Kyl & Värmepumpföreningen (SKVP) requested that the Swedish state apply for exemptions from the European Union pursuant to Article 15.4 of the F-Gas Regulation for products listed in the Ecodesign Directive Lot 1 (boilers and heat pumps), as well as Lot2 (water heaters and accumulator tanks). This is to give the heat pump industry access to refrigerants outside the F-Gas Regulation quota system in order to ensure a qualitative and energy efficient transition to new low-GWP refrigerants.

SKVP in their letter mentions the following challenges and obstacles for the heat pump council [16]:

- Most low GWP refrigerants are flammable to a higher or lower degree. Something that in most EU countries creates problems, as neither building rules nor industry standards have yet to be updated and adapted.
- Market prices for F-gases have risen sharply during the year, in some cases up to 1000%. Nevertheless, it has been found that most players in our industry, from manufacturer, through wholesalers to installers, are increasingly unable to obtain the required amount of refrigerant to ensure the delivery of equipment and the operation of facilities.
- The use of low GWP refrigerants requires a completely new design solution. A solution that not only needs to take into account technical, and security challenges, but also the requirements for high energy efficiency and reliability.
- The necessary components such as compressors and heat exchangers have so far been developed by the manufacturers mainly towards the industrial industry and air conditioning. The relatively small segment of heat pumps has until recently been largely unprecedented. The consequence of this is a lack of access to key components, both in number and capacity.
- The expected shortage of refrigerants can reduce the sale of heat pumps and instead lead consumers to alternative technologies, such as fossil fuel based boilers. This is contrary to the European and global targets for reducing greenhouse gas emissions.

Discussions on the effects of the F-Gas Regulation on the heat pump industry are also conducted by the European Heat Pump Association (EHPA). EHPA, the association representing the majority of the European heat pump industry, is currently in dialogue with the European Commission on the consequences of the F-gas regulation for European heat pump manufacturers.

3.5 Legionella

Legionnaires' disease, also known as legionellosis, is a form of serious pneumonic infection caused by inhaling the bacterium *Legionella pneumophila* or other *Legionella* species. After the first recognition of Legionnaires' disease occurring in people attending a hotel conference in the USA in 1976, surveillance for the disease began in several countries and is now recognized as an infection which can be acquired worldwide wherever conditions allow legionellae to proliferate. Community-acquired outbreaks of Legionnaires' disease are most commonly associated with aerosols generated by evaporative cooling towers. Wet cooling towers and evaporative condensers are used for comfort cooling in commercial buildings, hotels, etc., and for cooling industrial processes. Legionella are also associated with causing infections from other systems such as spa pools and hot tubs including those on display. However, any system or equipment, which contains, stores or recirculates non-sterile water[3] and has the potential to be aerosolized is a potential source of legionellosis.

Legionnaires' disease principally affects older adults. Those with risk factors including increasing age, smoking, and underlying diseases such as diabetes are at increased risk from the disease. The case fatality rate for community-acquired cases is currently around 10% and despite the availability of appropriate antibiotic treatment, a certain number of deaths are recorded each year in otherwise healthy persons with no known underlying risk factors.

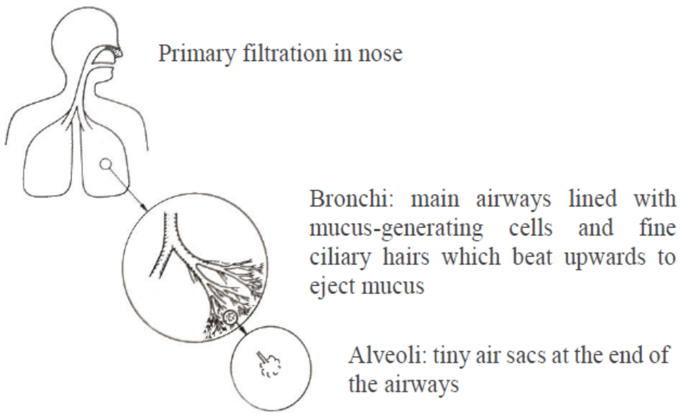


Fig 3.12 – Legionella disease is a lung disease and not caused by drinking water

For a number of reasons people travelling to holiday destinations are particularly at risk of Legionnaires disease, and such cases account for up to half of the cases reported in some European countries. Through extensive media coverage, the public has become increasingly aware of Legionnaires' disease and the specific risks associated with travel, cruise ships and hotel stays.

However, the acquisition of legionellosis is not limited to travel-associated buildings, but may be acquired from any water system in buildings, which is not maintained and controlled to minimize the risk of infection. After Legionella grows and multiplies in a building water system, water-containing Legionella then has to spread in droplets small enough for people to breathe in.

Any water system that has the right environmental conditions can potentially be a source for legionella bacteria growth. There is a reasonably foreseeable legionella risk in a water system if:

- Hot and cold water storage tanks have water temperatures between 20°C and 45°C., often occurring in solar thermal storage tanks;
- In any part of the hot water system where water temperatures are between 20°C and 45°C, which can occur in distribution pipes and heat exchangers with little or no water flow;
- There are deposits that can support bacterial growth, such as rust, sludge, scale and organic matter in pipes, showers and taps.

The bigger and more complicated a water distribution network is, the greater the risk for the growth of Legionella bacteria, when no proper precautionary measures have been taken. This is particularly a risk in distribution systems where the distributed water is directly used, such as in multi-family buildings, hotels, hospitals, health

[3] Disinfected water is not sterile; disinfection reduces the number of microorganisms but does not eliminate them

care centres, homes for the elderly, office blocks, commercial buildings, shopping malls and passenger ships. Heat distribution networks and district heating encounter the same challenges as open systems. By taking advantage of the knowledge of how water- and heating installations ought to be designed, the growth of Legionella bacteria can be prevented. It is basically a question of keeping installations clean, the cold water cold and the hot water hot.

The risks for single family houses are much smaller, where it can be debated if there is any risk at all. In small systems without warm distribution (distribution pipes are cooling down after each tapping) Legionella is very rarely found in large quantities. Such systems can be considered safe with > 52°C at storage outlet and > 50°C at the tap [19]. The piping system, between generator and the draw-off point with the highest risk, rarely contains more than 3 litres of stagnant water and the water in the system is refreshed regularly. Solutions for multi-family buildings creating a small individual system (<3 litres) separated from the collective distribution by a heat exchanger is presented in paragraph 3.6.

Systems with lower risk situation are found where:

- The in-house distribution system is smaller than 3 litres, i.e. single family houses and individual apartments separated from the distribution system;
- Daily water usage refreshes the entire system;
- Cold water is directly fed from a mains supply (no stored water tanks[4]) to be heated in instantaneous heaters or low volume water heaters (supplying outlets at 50°C);
- The only hot/cold water draw-off points are toilets and wash hand basins (no showers).

Consequences for Heat Pump System design

One of the main technical solutions required by legislation in most countries to avoid the growth of Legionella is thermal disinfection by raising the temperatures of stored and distributed water to temperatures above 65 to 70°C.

The desired usage temperature at the draw off point with the highest risk (i.e. the shower head) is however only 30 - 40°C. This means that the temperature difference between hot water outlet and the cold water inlet almost doubles with his type of thermal disinfection, which has a negative effect on the energy demand for the system especially in larger collective systems, increasing the distribution losses.

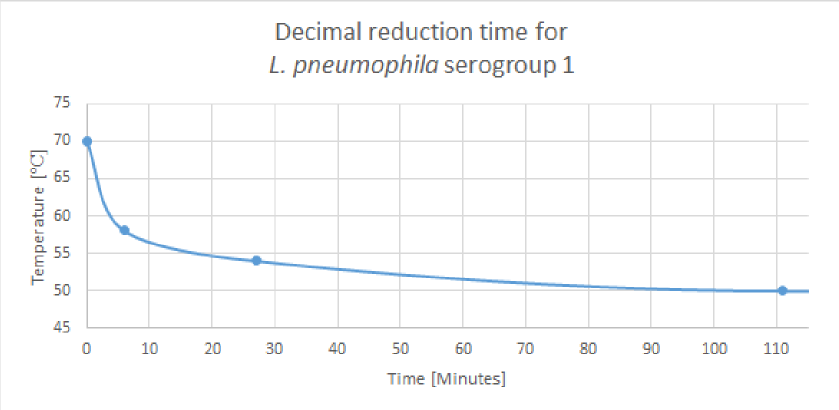


Fig. 3.13 General representation of the decimal reduction time for a strain of Legionella pneumophila [02]

[4] Little attention is given to open heater tanks in lofts (a UK habit also seen in Japan and other countries) these open-top tanks (hopefully with cover) sit in warm lofts in summer. One might expect that if a cylinder is fed from one of these, it might require a different sterilisation regime to a mains fed cylinder, and surely, there should be at least as much concern from the loft tank that there should be from the hot cylinder kept at only 50°C for example.

No other method than thermal treatment (super heat and flush) provides complete elimination and permanent protection from re-colonization of Legionella. Thermal disinfection is the most commonly method in terms of controlling Legionella in hot and cold water systems. Fig. 3.13 shows the decimal reduction time for a strain of Legionellla pneumophilia. The decimal reduction time is the time required, at a given condition (e.g. temperature) or set of conditions, to achieve a log reduction, that is, to kill 90% (or 1 log) of relevant microorganisms. The curve shows that the time necessary to kill Legionella is reduced by increasing temperature. Elevation of water temperature to 70 to 80°C kills off Legionella within seconds.

Legionella can thus be safely and easily controlled with good design, engineering and management protocols. The most effective treatment against Legionella is to keep cold water cold under 20 to 25 °C and hot water, above 55 °C, as there is no growth. A benefit of thermal treatment is that it there are no additives required into the water. This makes it the preferred method in countries that have strict limits on water quality. An alternative for water disinfection are UV radiation or the addition of chlorine.

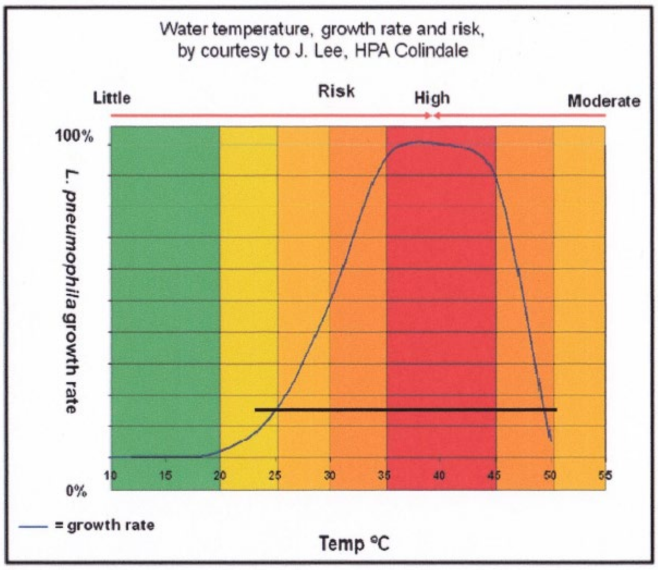


Fig. 3.14 Temperature levels of thermal desinfection

In many legislation raising the temperature of water heaters once a day or even once a week to 55°C (131 °F) is required at the coldest part of the water heater for 30 minutes to control legionella. It has been shown however that heating once a day or once a week to a higher temperature (of 60 or even 70 °C) is increasing the risk for Legionella rather than decreasing it. Such weekly disinfection schemes should be abandoned [19].

The threshold for the water temperature when reaching the tap point is for the majority of countries 50°C. That is because it is above the limit for Legionella growth as at > 46°C Legionella bacteria are inactivated. Some countries, such as Norway, have decided on a higher system temperature to further ensure the absence of Legionella. Interestingly the origin country of the “3 litres rule”, Germany, is not applying it. Germany recommends an operation temperature of a DHW system to be at least 50°C (DVGW, 2004). There are only two exceptions to a temperature requirement of at least 50°C. These are in Denmark at peak flow times, when a temperature of 45°C is accepted, and in France that has applied the 3 L rule for small systems. Under other circumstances and in the other countries the minimum temperature in the domestic hot water system varies between 50°C and 65°C. It is difficult to say if and how these legislations could be altered or even how these can be harmonized. To change regulations, it is imperative to present a safe solution, guaranteeing the water quality with regards to Legionella that is also accepted by the general public.

Thus, the traditional solution to inhibit Legionella growth is to keep the DHW above a certain temperature. There is a number of other technologies that could theoretically be applied. These can be divided into three subcategories: mechanical technologies, sterilization and alternative system design. Although some of the technologies is already commercially, available many cannot directly be implemented.

There is a number of heat pump designs capable of achieving high temperature outputs, including:

- Products with optimised design for specific refrigerants;
- Cascade systems with two separate refrigeration cycles;
- Enhanced Vapour Injection (EVI);
- Use of natural refrigerants and sorption products.

Whilst these products have been specifically designed for high temperature operation, the designs of "conventional" domestic heat pumps are increasingly being improved to reach 60 - 65 °C at reasonable efficiency [18]. For comparison, high temperature heat pumps with heat supply temperatures of 100 - 160°C will increasingly become commercialize in the coming years, especially for industrial drying, sterilization and evaporation processes in the food, paper, metal and chemical industries.

Another solution originating from the solar thermal market is the 'fresh water system', where the storage tank is used to store heat at a certain temperature, heated by solar thermal or a heat pump. The water that is used for showers or other domestic use flows through a heat exchanger in the storage tank and thus heated to the required temperature. This is more or less an instantaneous water heater where the risk of legionella is relatively small, thus the in-tank temperatures could be lower than required according to legislation on legionella.

High temperature heat pumps for domestic hot water heating are suitable for retrofit to existing properties as they can be used with existing, high temperature distribution systems (e.g. existing radiators) and are also capable of meeting hot water demand. However, as the performance of heat pumps reduces with increasing output temperature, most suppliers will first try to specify systems that can run at lower temperatures for increased efficiency (even where that requires some heat emitters to be upgraded). Especially in collective systems, alternatives are being developed and getting into the market.

For the heat pump water heater there obviously is a clear difference in solutions for individual systems in single family buildings and collective hot water systems in multi-family buildings or district heating systems.

Conclusions

Heat pumping technologies for single-family buildings as well as in collective systems for multi-family buildings, sports centres, hospitals, etc. are well fitted and capable to deliver the required temperatures to fight Legionella.

If there is a problem, this cannot be caused by the heat pump itself. But, as a consequence of the existing regulations for legionella and the need for heat pumps suitable for retrofit, especially in collective systems, refrigerants and solutions for DHW applications with higher than traditional (>65ºC) heat supply temperature are in demand. Modifications to the refrigerant cycle such as EVI or cascading refrigerant cycles can be used to increase the output temperature further up to 80°C with other refrigerants, momentary mainly R410A/R134a is used.

- Legionella disease is a lung disease originated by inhaling vaporized water from showers and not caused by drinking water from the tap.
- The risks of Legionella infection exists in locations of stored (stagnant) hot water at relatively low temperatures and in collective systems. The bigger and more complicated a water distribution network is, the greater the risk for the growth of Legionella bacteria. Systems in single-family houses with a water distribution system smaller than 3 litres are known not to be affected by legionella.
- Harmonization in legislation does not exist but is needed when the demands in legislation differ too much there will be no equal markets as the demands have consequences for the test procedures as well. The temperature demands for legionella also affect the test procedures for DHW HP's.
- Calculations suggest that increasing hot water storage temperatures to 60°C recommended for Legionella control increases CO_2 emissions. It is not suggested to take a slack attitude to the problem, but the broad-brush turn-up-the-thermostat approach, given the energy penalty involved, can be debated. Further study in this area is justified.

3.6 Multi Family Buildings

Particularly, water heaters are one of the most complex product categories due to a large variety of product types, technologies, and fuels used for heating water. Seemingly simple solutions are available for single family houses, but for collective systems solutions can be more complex. The low efficiency of domestic hot water systems is well known by field practitioners. For many new residential multifamily buildings hot water delivery times and water waste have been getting steadily worse with newer buildings. The sources of inefficiency can be found in every one of the diverse phases entailed by domestic hot water systems: from the design of the piping structure and the sizing of equipment to the selection of the applied control strategies [20].

In general, based on the sum of all losses, individual solutions, where hot water is generated where it is needed, are the best solution. Yet collective systems are installed in a larger percentage, even in new buildings. An optimal design and maintenance of the distribution system is then needed. A great number of examples of different systems in the Annex participating countries have been found and analysed.

The overall efficiency of a system is determined by the generation efficiency and the distribution efficiency. In order to obtain a high generation efficiency, an extensive/complex generation installation with separation of energy flows at different temperature levels is usually required. If the total efficiency is the most important criterion, a multi-pipe distribution system is the first choice because the heat flows in both the supply and the return remain separate, and are therefore not energetically mixed. With such a system, however, the number of pumps and the amount of pump energy used increase. And the total heat-emitting capacity of all distribution pipes is also higher, if the same degree of insulation is assumed as with simpler distribution systems.

Broadly speaking, you can conclude from this that systems with more energy-efficient generation (ie the multi-pipe systems) have higher distribution losses. Especially now that the heat demand of modern, well-insulated buildings is decreasing, the emphasis will be more on distribution losses than on buildings with a high energy demand. There is an exception to this "rule" as a system in which every apartment has its own, individual combination heat pump scores well in terms of energy efficiency on the generation side, while at the same time also having a low distribution loss. It can be expected that in high-rise projects more and more attention will be focused on the distribution system. Heat pumps and related systems are being further developed and they are generating ever better generation yields.

For multifamily buildings, mainly owned in the inner cities by housing corporations, the options of individual solutions are more complex. Collective systems maintained, optimized outside of the apartments in the building seems to be an interesting solution. Optimisation will have to be found outside of the front door of the apartment. Domestic hot water can be supplied centrally by a heat pump with a small heat exchanger in the apartment. A solution for potential legionella will have to be found. Another solution is to split space heating and domestic hot water and install a booster heat pump in the apartment. Major obstacle in that will be the lack of space for such a booster heat pump with storage tank in the apartment. District heating, fed with sustainable energy options at low temperatures, is another option.

One of the main barriers for the implementation of energy-saving measures, especially in rented apartments, is the divergence in interests of the tenant and the owner/investor. Whereas the owners of houses (e.g. housing associations) invest in energy-saving measures, the tenants benefit from the reduction of energy costs. Opportunities to increase the rent often are (legally) limited, or the return on investment is extended over a long period of time.

Most of the tenants enjoy rent protection. Low income tenants can apply for a social rent house with a low rent that is bound to a legal maximum. The rent does include the heating and hot water systems, but does not include the energy bill. So corporations who plan to invest in energy efficient equipment will not reap the benefits. To work around this problem, corporations can raise the rent under a guarantee that the energy costs will decrease by at least the same amount. This cannot be done in social rent houses, as the rent is bound to a maximum.

The possibilities for financing for existing housing appears to be more restricted than for new buildings. Options like credit from suppliers, leasing of systems or design/build/maintain constructions are hardly used. In large renovation projects, corporations can reach price reductions from suppliers. The large scale also facilitates engineering and the development of solutions for specific situations.

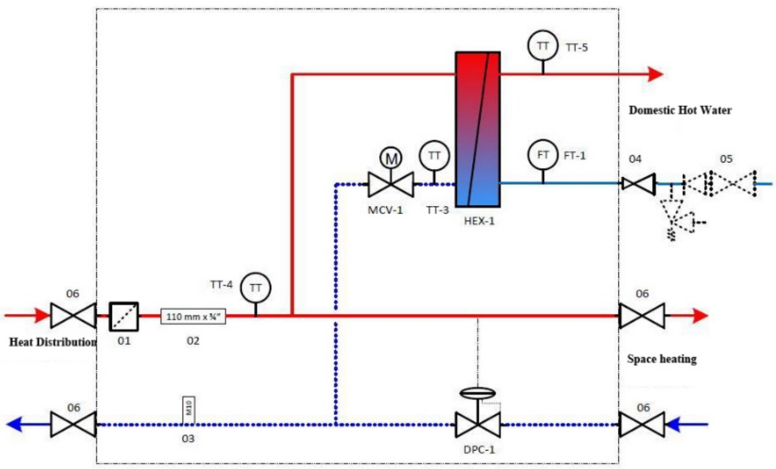
Technical options

As already reported on in paragraph 3.5, the bigger and more complicated a water distribution network is, the greater the risk for the growth of Legionella bacteria, when no proper precautionary measures have been taken. This is particularly a risk in distribution systems where the distributed water is directly used for showers and other applications where distributed hot water is sprayed and can reach the lungs as a vapor. That occurs mainly in hotels, hospitals, health care centres, homes for the elderly, office blocks, commercial buildings, shopping malls and passenger ships. Most of the collective systems in multifamily buildings are circulation systems. The water, which is circulated as energy bearer in the system, is not used as domestic hot water for shower, bath or consumption by the individual end user. The heat exchanger between the collective system and the individual end user system is for the domestic water use fed with cold water to be heated and used as domestic hot water. Also In many cases in multifamily buildings decentralized systems are installed, being the best energetic option. However in some markets there is a growing tendency towards collective systems for new buildings.

Any attempt at energetic optimization of water heating requires an overall view of the areas of deployment - distribution - use. In addition, there are - under given boundary conditions - also within each system, possibilities for improvement. However, it should be noted that there is no blanket statement about the "best system", as this depends on the local conditions (i.e. connection to the district heating network, possibility of using geothermal or groundwater) but also on the actual operation or user behaviour. Overall, it is necessary to consider the efficiency of the hot water preparation together with that of the building heating, as this is solved in many cases together or at least affect the systems.

Therewith a number of different markets exist, being:

- New multifamily buildings, with a great freedom of design of the system;
- Existing multifamily buildings owned by housing corporations or city councils, with either a collective system or e decentral system;
- Existing multifamily buildings owned by the occupants, with either a collective system or a decentral system.



For smaller collective systems, i.e. blocks of multifamily buildings increasing the temperature of the distributed water to a level of 65 to 70ºC is the standard solution, requiring a high temperature central heat pump (EVI, Cascade, Two …).

The most simple distribution system is a two pipe system in blocks of multifamily buildings distributing water at a level of 65 to 70ºC. This standard solution, requiring a high temperature central heat pump [18].

Fig. 3.15 - Standard two-pipe distribution system

Popular became the 4 pipe distribution system with a high temperature for hot water and a low temperature for space heating. The distribution pipes for domestic hot water have to be kept on temperature during the whole year, but not on full capacity as the overall demands fluctuates during the day. By good management the losses can be decreased. For this a better understanding of water deployment is desired in order to improve the whole system, both in the initial design phase and in the final control phase (Iglesias et.al. [20]). Next to these 2/4-pipe systems there are other systems in order to optimize the distribution of hot water.

In the 3,5 pipe distribution (HT and LT), the system runs via three pipes, one of which has a double function: the HT distribution for tap water (70°C) and LT distribution for floor heating (45°C) have a common return pipe. A joint return can lead to energy destruction because you mix water with different temperatures. However energy can be saved during the heating season with a low demand for domestic hot water by injecting a small amount of HT water into the LT distribution grid, the LT heat pump needs to deliver less capacity. By adding an additional cooling pipe to the 3,5 pipe distribution network it becomes possible to have simultaneous heating and cooling in a building. The basic principle behind a 4,5-pipe design is the same as that of a 3.5-pipe system.

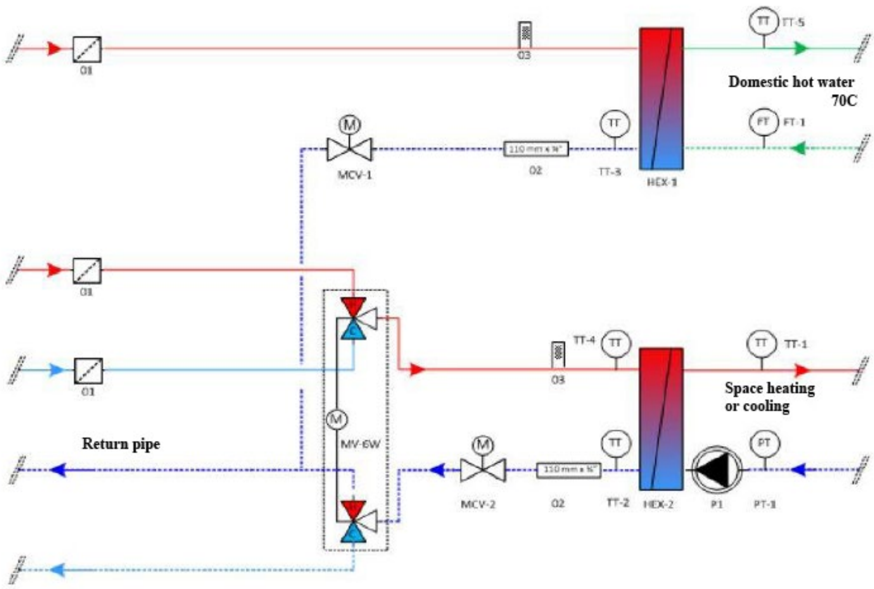
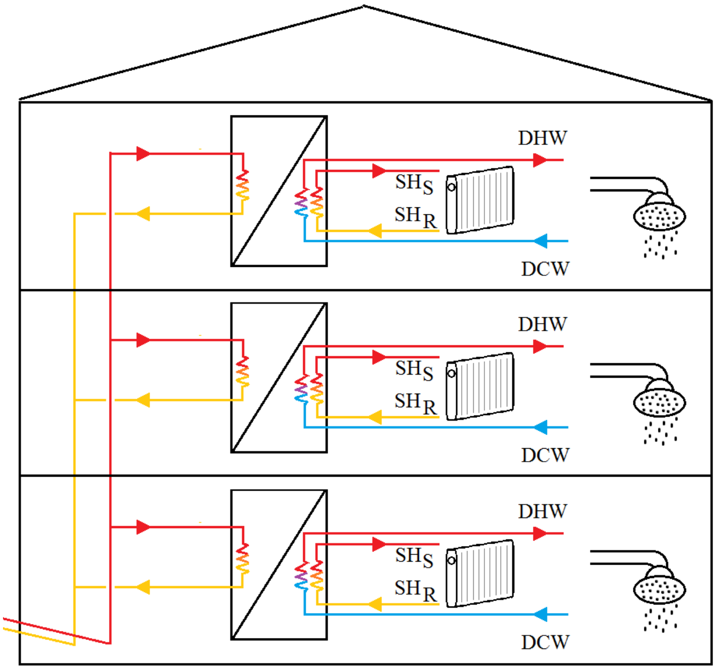


Fig 3.16 – Five and half pipe distribution system includes cooling mode

Since insufficiently high temperatures and long-term stagnancy are the main risk factors for Legionella proliferation in collective hot water systems, alternative designs are proposed Xiaochen Yang et.al. [21] that can eliminate those factors. The basic concepts behind such designs are temperature boosting and volume limitation.

Volume limitation concept

Linita Karlsson et.al. [22], in accordance with the German Standard W551 is that, if controlled properly, a system with a total volume (from hot water production to end use) of less than 3 L can eliminate the risk of Legionella. With a central heat pump in the basement a decentralized substation can be used where the feed is 55°C. Decentralized substations inhibit growth of Legionella by limiting the residence time in what might otherwise be favourable conditions.



Decentralized substations have the potential to limit Legionella growth even with the lower supply temperatures from low temperature district heating. Yang et. al. [21] performed a study on a six story residential building in Denmark and concluded that an LTDH system with a supply temperature of 55°C could be operated with decentralized substations while still ensuring the water quality with regards to Legionella. Other advantages are that there is no need for water circulation which can significantly reduce the heat losses and that there is no addition of chemicals that may affect the water quality. The drawback is that it requires considerable investments (number of substations) and can be difficult to implement in existing buildings, as the installation would require extensive renovations.

Fig 3.17 Process diagram of decentralized substations [22].

Boosting the temperature

To avoid 4 pipe system, which can hardly be applied in a renovation project, the low temperature can be decentrally boosted by an auxiliary heating device to meet the required temperatures for domestic hot water. There are many types of heating devices and three will be presented here: electric heat tracing, micro heat pumps and electric heating elements.

- **Electric heat tracing**: One of the above mentioned heating techniques is to install electric cables on the DHW pipes (see figure 17 for a process diagram of the setup). The DHW can thus be heated to the required temperature even if the primary supply water temperature is too low. This also eliminates the need for circulation of hot water since the heating process is nearly instantaneous (Vetsch [23]). Replacing the hot water circulation system with electric heat tracing can lead to large energy savings and economic benefits. To make electric heat tracing more efficient it is advised to introduce smart control where the heat load at varying times is considered.

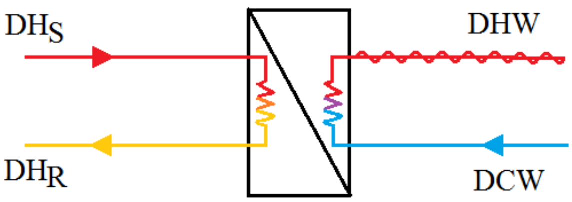


Fig 3.18 Process diagram of electric heat tracing [21]

- **Booster Heat Pumps**: Another way to heat up the domestic hot water is to install a microbooster heat pump. The central LT heat pump feeds the floor heating in the houses, but at the same time the low temperature heat serves as a source for the booster heat pumps, which make hot water decentrally per apartment and store them in a tank. An advantage of this 'semi-central' system, the less complex distribution system, being a two-pipe system.

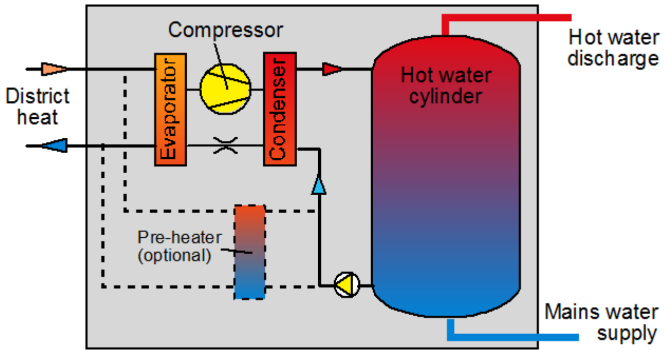


Fig. 3.19 Basic layout of a booster heat pump [24]

- **Instantaneous electric heater**: The concept of an electric heater is to have an electric heater in addition to the heat exchanger. This provides instantaneous heating of either the supply stream, i.e. before the heat exchanger or directly of the DHW, i.e. after the heat exchanger.

Especially in Finland there is a tendency to move away from collective systems and district heating[5]. While other developments for collective systems tend towards small low temperature (4th Generation) district heating systems with technologies boosting the temperatures where needed, i.e. older buildings and domestic hot water.

Individual Domestic Hot Water Heat Pump

There is a number of examples where individual DHW HP's are installed in the individual apartments separately of the two-pipe distribution system for low temperature space heating. This seems to be a good solution for renovation of existing distribution systems to lower temperatures, but also for new buildings. AFPAC gives a number of examples in its brochure '[La Pompe à Chaleur. Des solutions pour l'eau chaude sanitaire en habitat collectif]'.

Individual combi heat pump

As an alternative to those complex distribution system, the alternative is the individual double function heat pump. The distribution through the building is very simple: from every apartment only 2 pipes run to the ground source heat exchanger. An advantage for residents is that they can choose individually for heating or cooling; the 'multi-boiler' system just discussed is heated or cooled per four homes. The disadvantage of the individual solution is that with a heat pump, storage tank and some piping, a lot of technology is installed in a (often relatively limited) (technical) space, which is not always possible in (small) apartments. A fine examples is to be found at De Tas in Biddinghuizen.

Conclusions

On the subject of "best system design" with regard to energy-efficient hot water supply, a number of conclusions can be drawn:

- Based on the sum of all losses, decentralized solutions (hot water is generated where it is needed) are the best solution.
- In general, 2-pipe systems with home stations perform better in terms of distribution losses than 4-pipe systems, which is mainly due to shorter length of distribution pipes.

---

[5] https://yle.fi/uutiset/3-11191581?fbclid=IwAR1xievPi5-SMKmzVzzXB8gZYpVLTx4IaqfAPh07JFZ3tNkFbrIkvZtrm0M

- In order to be able to integrate renewable energies in apartment blocks, central solutions should be preferred, with the exception of the combination of photovoltaics and ventilation heat pumps for passive houses. Exceptions are widely branched individual customers, e.g. in row houses, where decentralized solutions will continue to be advised.
- Especially with heat pumps an efficient operation by separation of hot water heating and space heating can be achieved. For this technology, the advantages of optimized generation (4-conductor system) must be contrasted with the advantages of lower losses (2-conductor system) and evaluated on a case-by-case basis. If 2-conductor systems are to be used, solutions with low system temperatures and electrical reheating are to be preferred.
- Due to the magnitude of the distribution losses (heat losses through the pipelines) in centralized solutions, it is strongly recommended to optimize all pipeline lengths as early as the planning phase and to insulate distribution lines beyond what is required and to consider the possibility of using inline systems.
- Losses in heat supply represent the second highest loss share for central options and can be reduced by intelligent technology selection and optimization (optimized design, coordination of hot water, heating and storage combinations and control engineering integration, ongoing monitoring).

Power supply (pumps) and storage losses play a minor role. Optimizations in existing (old) systems (pump replacement, additional insulation in storage), however, can certainly lead to significant savings.

4. Calculation models for systems (Task 2)

As new buildings become more energy efficient, CO_2 emissions from hot water preparation start to exceed those from space heating. This effect is exaggerated by the fact that because the total space heating demand is lower, the usefulness of 'losses' from the hot water system decreases. As we move towards more energy efficient houses, a similar level of detail should be applied to hot water system design as to the building envelope and ventilation systems. The way in which most current building energy models and energy standards consider hot water system losses is too simplistic for new build and deep renovation dwellings.

General available models calculate hot water consumption on the basis of the living area and a standard occupancy depending on the surface of the housing. In comparison with real life, these methods lead very often to an oversizing of the DHW production and storage. In retrofit, the simplest way is to replace the old DHW equipment with a new one having the same capacities. Thus, the DHW remains oversized and the real performance is usually lower than the theoretical one.

Calculation models can be defined in (at least) four categories:

- Specific physical calculations on detailed parts of the heat pump and the storage tank itself, designing the configuration of the heat pump, like the model developed by EDF (reference?);
- Calculation for the energy performance of a building in relation to legislative procedures, like the Standard Assessment Procedure (SAP) and Reduced Data SAP (RdSAP) models in the UK with which the EPC for the building is calculated or the Dutch EPC calculation (NEN 7120).
- Calculation for designing the optimal system, used by consultants, building constructors, architects, installers, etc. These models are often 'owned' by and developed by consulting companies and commercially available.
- Advanced complex simulation models, like TRNSYS.

These models have a number of characteristics:

- With the model it is often not possible to compare different system concepts;
- Innovative technologies and concepts are often not included in the model;
- The focal point of the model is space heating/cooling, DHW is often a secondary part of the energy system, based upon flat rate/default values, often leading to over-dimensioning of the system;
- Models for developing a system are often based upon Economical models;
- Models often don't use the chain efficiency as basis for the calculation, except those which have a relation to legislative procedures.

A number of models like RETScreen and Expert developed by NRCan use Seasonal Performance and base their calculation of weighted average performance during a specific period (mostly annual) based on certified testing data of the heat pump itself.

Climate, location and building specific components, often traditional for certain regions are the basis of these models. Thus it is difficult to make clear comparison between the available models as systems differ much. Moreover many models are thus not usable for policy makers at local level to make the right long-term choices for the support of developments in building projects for new buildings or renovation.

Available models

There are governmental communication programs available like the US 'Selecting a new water heater', which is a broad program developed by the US Department of Energy to support the customer to make the right choices. On the other hand the website by the UK Energy Saving Trust and their pages on Saving Water and the Water Energy Calculator by don't even mention DHW Heat Pumps as option.

Some of these models, although commercial, are part of the legislative process in these countries, used for getting building permits. It proves that energy is an important aspect in this and that with the decreasing demand for space heating/cooling the focus ‘must’ be on optimizing the models for domestic hot water.

On the other hand, although a number of existing and new models go into depth, we do not recommend micro-component modelling of hot water use as part of this, especially for single family buildings and individual systems since it is a behavioural variable rather than one that is suited to incorporating in plumbing system design models.

Conclusions

Currently, the biggest challenge for every user of building and plant simulation is the large number of different simulation tools. Every simulation software has a main area of application and is optimized for this specific problem. Even software with a wide range of applications such as MATLAB and Simulink or specialized multi-physics software such as ANSYS or COMSOL cannot calculate every problem in an accurate and efficient manner.

If DHW is not included based on objectively verified values, it will not be possible to assess future systems that are predominantly dimensioned around tap water for their energy performance.

Climate, location and building specific components, often traditional for certain regions are the basis of these models, where it is expected that it will be difficult to make clear comparisons between those. Given the market of models already on the market, it does not make sense to develop an 'own' Annex 46 model. The existing model and available models seems of importance to enter into fruitful discussions and develop guidelines on how to act.

Objective comparison of systems from a policy point of view has to be based upon the chain efficiency where the overall efficiencies for the complete chain from primary (fossil) energy to the end user are compared and the weakest links in the chain are analyzed. The following aspects for hot water production then have to be taken into account:

- Energy transition from primary energy into heat, i.e. gas/oil/wood/coal etc into heat or ‘indirect’ by electricity into heat with the electricity generation efficiency (including fossil and renewable generated power)
- Energy losses during starting and stopping of the heat production at the level of the end user
- Energy losses in energy storage, i.e. the hot water storage tank
- Transport and distribution losses in collective as well as individual systems
- Energy use of auxiliary/utility equipment (fans and pumps)
- Auxiliary heating (solar system and collective systems)

These aspects of the chain efficiency are of importance at the macro level of policy decisions. Two levels lower is the micro level of decision for the end user. It is important to mention that when the time comes to replace the existing installation, the end user often bases his decision on the initial cost of the DHW generator, the energy efficiency being often overlooked. Between those levels is the installer, consultant, designer of the hot water heating system, whereas housing corporations and house rental companies can belong to this group.

A number of guidelines for designing and engineering an optimal DHW heating system can be drawn, starting with the awareness that there is a number of different target groups:

- Macro-level of policy decisions focusing on technology solutions to support in R&D for the longer term and where the overall chain efficiency and the changing landscapes of energy supply security are of importance in the future energy systems until 2050.
- Meso-level, with the installer, consultant, designer of hot water heating systems, whereas housing corporations and house rental companies also belong to this group. At this level the acceptability in legal

procedures to acquire permits for new building and/or large scale renovation is more important than the chain efficiency. Local government can play an important role in this process. As we move towards more energy efficient houses, calculating methodologies for hot water system design with a level of detail to similar to the ones for building envelope and ventilation systems (incorporating the latest innovative technological developments[6]) is needed.

- Micro-level of private house owners, i.e., the end user. The leading concern here is the replacement of the existing installation, where the main driver for the end user is the cost of the DHW generator, energy efficiency being often overlooked. Governmental information programs as well as educational programs for installers would support a 'better choice' for the end user. Legislation is another instrument for the government which is marketed through informative labelling of DHW generators and even ban on sales of specific less efficient generators (as an example, high efficiency gas boilers are banned in specific applications in Denmark).

Overall it is important to think in terms of complete system concepts. Even if the heat is produced with a high energy efficiency, high storage and/or distribution losses still remain unnecessary and eventually will cause a low overall system efficiency to the best generating apparatus. It is therefore important to consider the heat generators not only individually but to design a complete DHW concept with a critical view on performance, comfort and legionella prevention.

With new distribution systems in the market, especially in collective systems, adequate publicly available calculation models do not exist taking into account the latest innovations in domestic hot water technologies. More specifically a model should be developed that can be used for the different countries basically giving support to the existing formal legal calculation models. This is a task that should be taken up by the work under Annex 50. A proposal was done under Annex 46 but the required funding for the work was not available.

[6] The way in which most current building energy models and energy standards consider hot water system losses is too simplistic for new build and deep renovation dwellings.

5. Technology modelling (Task 3)

Under this Task a model has been presented by EDF for a monobloc Heat Pump Water Heater with a 'wrap-around' heat exchanger for the storage tank. The final results of this study were presented by Dr. Kevin Ruben Deutz at the 10^{th} International Conference on System Simulation in Buildings, Liege, December 10-12, 2018[7]

Although the monobloc Heat Pump Water Heaters have reached an important level of maturity on the market, it seems that there is still room for improvement of their energy performance. For Heat Pump Water Heaters to increase their market penetration, other criteria such as end-user comfort level and economical payback should not be disregarded in an optimization process. The study done by Deutz is resulted in new design for Heat Pump Water Heaters that achieves a 37 % average annual energy saving and a 30 % reduction of the electrical bill while ensuring a same level of comfort for the end-users.

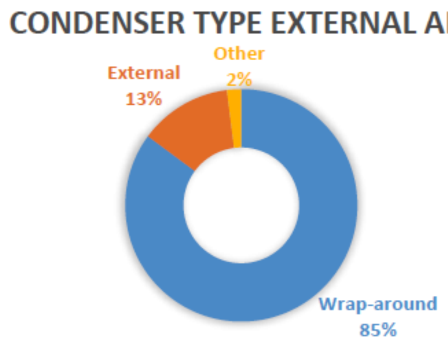


Fig. 5.1 – Market share of condenser types [25]

The study focused mainly on the concept of a wrap-around condenser and other condensers are available in the market. Typically three kinds of condenser layouts can be found for the connection between the heat pump unit and the storage tank which consist of mantle, immersed and external heat exchangers. Although the majority of available DHW HP's have a wraparound condenser there is a noticeable trend towards external brazed plate heat exchangers. Although seemingly more expensive and complex these systems can have a much smaller refrigerant charge with excellent thermodynamic performance.

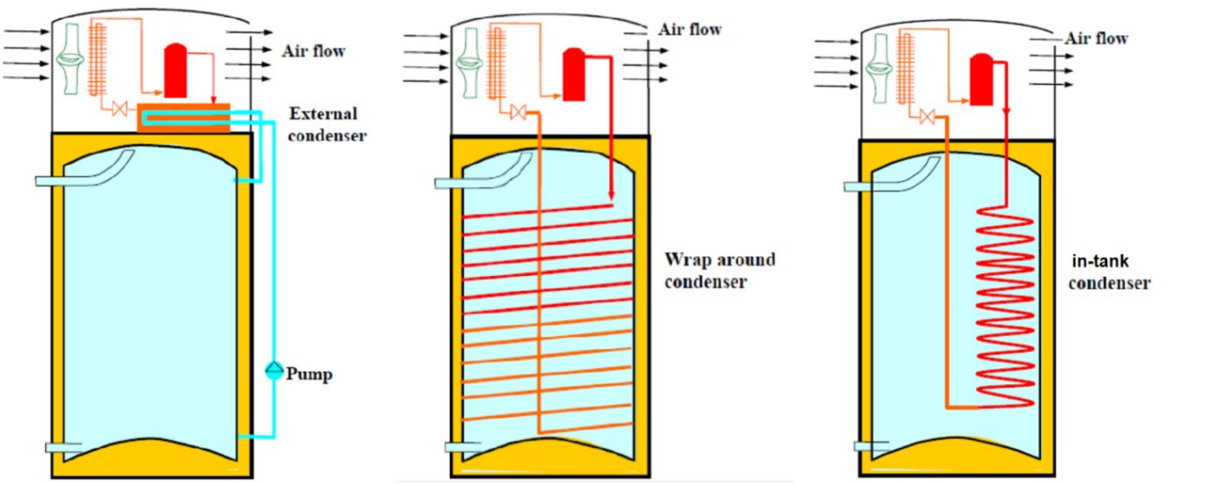


Fig 5.2 – Heat pump condenser types combined with storage tanks

Other modelling studies by the Annex participants, with sometimes a different focus, were undertaken by Ulster University, Oakridge National Laboratories and Waseda University.

Worldwide there is a number of models (some academic exercises!) available. The majority of research done on modelling has a focus on finding the optimization for alternative refrigerants. Manufacturers do have often their own models. Work is often done in combination with the work on refrigerants. In a survey more than 55 papers were selected, with topics ranging from:

---

[7] Multi-criteria Air Source Heat Pump Water Heater optimization combining optimized thermodynamic performance and control

- Optimization of refrigerants and condensers;
- Stratification;
- Smart grids and storage;
- Combination with solar, often from the angle of solar thermal.

Understandingly the main modelling initiated for heat pumping technologies has a focus in very special heat pump related topics and challenges, such as refrigerants, heat exchangers etc., but also on the market challenges such as smaller, cheaper and more efficient and fit to market demands such as smart grids.

One of the main interests for solar thermal is an adequate stratification of the hot water in the storage tank. This is also the case for Heat Pump Water Heaters as the storage tank is an important part of the technology and temperature distributions are essential in control strategy designing and assessment of the usable hot water volumes. To assure high quality thermal storage and high efficiency, optimizing thermal stratification is an important modelling challenge directly related to the choice of condenser. The whole motivation of stratification lies in the fact that mixing effect can be minimized during operational cycle of the tank so that high temperature water could be taken at the load end, thus maintaining high thermal efficiency at demand side, while low-temperature water can be drawn at lower bottom, thus maintaining the high efficiency at energy collection side. With Heat Pump Water Heaters the impact of the charging/discharging process by the heat pump on thermal stratification is a decisive factor for the overall energy efficiency of the system. But not only the charging/discharging process of the heat pump but also the draw-off process of hot water should be such that stratification is guaranteed during this process.

An overview has been made, based on study of available literature, of institutes active in modelling:

- Oakridge National Laboratory, developed a heat pump design model with a special model for water heaters (free available) The DOE/ORNL Heat Pump Design Model is a research tool for use in steady-state and quasi-steady-state design analyses of extensive thermal system configurations and HVAC applications. The WEB version has an HTML-based input interface which generates the required input file, executes the application, and summarizes the results on your Web browser.
- Waseda University, especially for CO2 DHW HP's. Very complex model (confidential), the other model is simplified.
- Ulster University works with TRNSYS (ext plate hex). Testing and being validated with draw off patterns in practical circ.
- Gree Electric Appliances, using computational fluid dynamics (CFD)
- Xi'an Jiaotong University, using Pinch point analysis on a CO2 gas cooler
- CEA, Laboratoire des Systèmes Thermiques (LETh), using computational fluid dynamics (CFD)
- Institut für Solartechnik SPF, using computational fluid dynamics (CFD)
- Carleton, mostly in relation to solar thermal using TRANSYS
- CANMET models
- Universitat Politècnica de Catalunya ;
- Tongji University;
- Ryerson University,

By the Annex participants modelling studies on Heat Pump Water Heaters were done by EDF, Ulster University, Oakridge National Laboratories and Waseda University.

EDF Modelling

The model used in this study is a dynamic grey box modelica based model, developed with Dymola®, that was further presented in a previous paper (Deutz, Charles, Cauret, Rullière, & Haberschill, 2018 [26]). This model gathers a heat pump model developed thanks to the TIL® thermal component library and a storage tank model including a zonal model. The reference model concerns a R134a ASHPWH with a mantle tank condenser (MHX) and a variable speed compressor

Manufacturers face multiple constraints such as: guaranteed user comfort, maximum energy performance, manufacturing costs, refrigerant choice and quantity, succeed normative tests. The importance set on each of the constraints has a particular impact on the product design ending up in a variety of possible HPWH designs. A way of solving the constraints can be done by weighing the importance of each in a multi criteria model based design approach and an iterative sequential tool chain such as presented in figure 5.3 considering that there is enough input data.

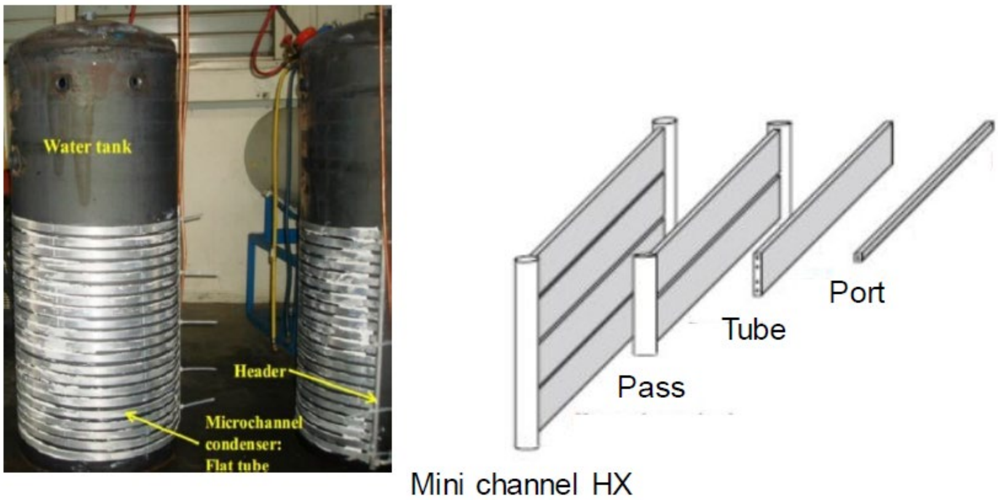


Fig.5.3 Mini channel condenser layout

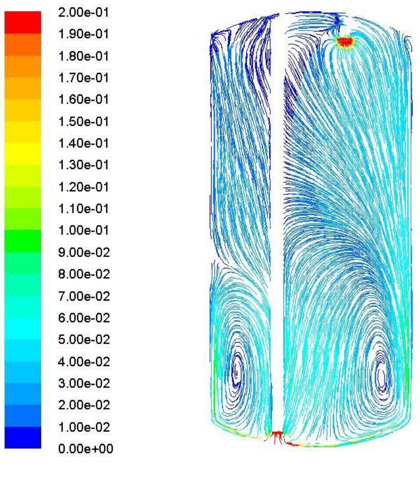
The study done by Deutz is resulted in new design for Heat Pump Water Heaters that achieves a 37 % average annual energy saving and a 30 % reduction of the electrical bill while ensuring a same level of comfort for the end-users. The results of this study were presented in the thesis by dr Deutz and at the 10th International Conference on System Simulation in Buildings, Liege, December 10-12-2018 [26].

In this paper, a previously developed detailed thermodynamic model was used to assess the energy performance improvement potential first based on ASHPWH design, then control and finally analyzing a combination of both. First, a multi criteria optimization potential was assessed and it was shown that on a given optimization example, heating COP could be improved by 15 % while minimizing refrigerant charge by 18 % by adopting mini channel condensers and adapting the evaporator design. Propane based ASHPWH optimization was repeated with a 150 g charge constraint and it was shown that although having a smaller thermodynamic performance, the constraint could be fulfilled by further adapting the mini channel condenser design. Then on the control side, a model based ASHPWH controller was presented that allows to vary tank thermal energy according to DHW needs on two operating periods (morning and evening) using a variable speed compressor. It was shown that on a standard fixed draw off profile, the heat pump COP improvement potential was of 22 % and the comfort was not deteriorated. In an ultimate part of the paper, the model based controller was coupled to the reference ASHPWH and an optimized design example. This combination was tested on a variety of 28 real draw off profile ranging from 0.5 to 3.5 MWh. The results indicate that the proposed optimization can reach an average 37 % end user annual COP increase with a more stable COP according to DHW needs and reducing electricity bill by 30 %. This performance was reached with a same level of comfort for small and mid-range DHW needs and an increased comfort for higher DHW needs. These two aspects make the proposed optimized ASHPWH more adaptable to a wide range of draw off profiles using a same ASHPWH design in terms of tank size and heat pump capacity.

Oak Ridge National Laboratory did a number of studies and developed a model where Stratification is an important basis for the optimization of the system. Computational Fluid Dynamics (CFD) model using ANSYS 17.2 was used and an effective, hardware-based HPWH equipment design tool, a quasi-steady-state HPWH model was developed based on the DOE/ORNL Heat Pump Design Model (HPDM).

Heat pump water heater systems (HPWH) introduce new challenges for design and modelling tools, because they require vapor compression system balanced with a water storage tank. In addition, a wrapped-tank condenser coil has strong coupling with a stratified water tank, which leads HPWH simulation to a transient process. Two new component models were added via this study. One is a one-dimensional stratified water tank model, an improvement to the open-source EnergyPlus water tank model, by introducing a calibration factor to account for bulk mixing effect due to water draws, circulations, etc. The other is a wrapped-tank condenser coil model, using a segment-to-segment modelling approach. The HPWH system model was validated against available experimental data. After that, it was used for parametric simulations to determine the effects of design factors.

The focus of the Oakridge study has been on a wrapped coil condenser. Thermal stratification, caused by varying heat transfer rate from the condenser to the water depending on the phase of the refrigerant and the wrap configuration, is often observed inside the tank, especially for HPWHs using CO2 as the refrigerant. The current study investigates the impact of the charging/discharging process on thermal stratification. A series of simulations were conducted based on the draw patterns recommended by the DOE method of test for rating water heater performance. Oakridge also analyzed the water circulation patterns during charging/discharging process. The thermal stratification was adversely affected because of the circulation even when the Heat Pump (HP) was operational. It was observed that a relatively higher charge/discharge flow rate disrupts the thermal stratification quickly and thus lowers the supply water temperature. Furthermore, the duration of charging/discharging also plays an important role. It was noticed that the back flow has insignificant effect on the supply water temperature if charging/discharging time is relatively small. However, the effect was obvious for larger water draw flow rates that last for longer time.



It is important to validate and include the bulk mixing occurring during water draw from the tank. In order to validate the assumption, a series of CFD simulations were carried out to observe the impact of mixing due to “backflow effect”. Figure 5.4 represents water velocity streamlines (in m/s) for an adiabatic water tank as the hot water is withdrawn from the top and replenished by cold water entering the tank through the dip tube near the bottom. The bulk mixing happening solely because of “backflow effect” is obvious. It is important to note that all previous modeling approaches including “EnergyPlus” ignore this relatively important phenomena which dominates the natural convention currents but occurs only during water draw events.

Fig. 5.4 Streamline for water flow in the tank during draw (scale shows velocity-m/s) [04]

A preliminary analysis was conducted to analyze the performance of a heat pump water heater that uses CO2 as the refrigerant. A model to predict the performance was developed and calibrated based on the experimental data for an existing HPWH using a CO2 refrigerant. The calibrated model was then used to run a parametric analysis in which factors such as water supply temperature, water circulation rate, tank stratification, and condenser configuration were considered. The performance of a commercial CO2 system was compared with that of a similar system using R-134a as the refrigerant. It was found that CO2 HPWH performance was comparable to that of an R-134a HPWH, more so for a separated gas cooler configuration. For comparable performance, the compressor size and the tube-in-tube heat exchanger (condenser/gas cooler) size were compared for CO2- and R-134abased systems. The impact of the water circulation rate on the water temperature stratification in the tank, an essential requirement for higher performance for CO2 HPWH systems was also investigated.

Ulster

Ulster University did a number of studies on storage and validation of models on their test houses at the University. A list of studies is given under paragraph 8.

One study [27] presents the validation of TRNSYS models for a high temperature air-water heat pump and a thermal energy storage based on field trial data. This validation aims at clarifying strengths and weaknesses of the models and verifying the model accuracy which can support further studies conducting advanced models related to HTAWHP-TES. Results show good agreements with field trial results for condenser water outlet temperatures and Coefficient of Performance of the validated model, with CV(RMSE) of 4.14% and 11.6% respectively. Discrepancies caused in start-up operation of the heat pump are the main disadvantage that the model cannot address and have been discussed. The storage model was validated in three modes: charge, discharge and standby. Very strong coincidences of tank node temperatures are observed between simulation and collected data in both charging and discharging mode. In standby mode, less than 2.5˚C difference is observed in top tank nodes, whereas bottom nodes are within 1˚C uncertainty. Stratification

(a) Test house (b) Shed (c) Test-rig

Fig 5.5 – Test houses at Ulster University

Storage in relation to Smart grids with a focus on demand side management is presented in a number of papers It is undeniable that energy storage combined with heat pump has brought valuable benefits for demand side management which may have a significant role in future non-dispatchable renewable energy electrical supply systems. Off-peak electricity can be used to run heat pumps to store energy in storage, and this energy is then drawn to buildings for heating demands, which may help to reduce peak electricity demand for grid and utility bills for consumers.

Although energy for heating and cooling represents the largest proportion of demand, little progress towards meeting environmental targets has been achieved in these sectors. The recent rapid progress in integrating renewable energy into the electricity sector however, can help in decarbonising heat by electrification. This paper investigates the impacts and benefits of heat electrification in a wind dominated market by considering two options; with heat pumps, and with direct electric heating, both operated with energy storage. The Irish all-island electricity market is used as a case study. Modelling results reveal the significant potential of heat pump electrification, delivering at least two and three times less carbon emissions respectively, when compared with conventional options such as gas or oil for 20% of domestic sector of the All Ireland market. Heat electrification using direct, resistive heating systems is found to be the most carbon intensive method. Energy storage systems combined with heat pumps could deliver potentially significant benefits in terms of emissions reductions, efficient market operation and mitigating the impacts of variable renewable energy on baseload generation. The main barrier to heat electrification in the all island market is the absence of appropriate policy measures to support relevant technologies.

Combination with Solar Energy

A large number of modelling studies have been done for the combination of heat pumps and solar thermal from the perspective of optimizing the use and economies of solar energy.

In Netherlands modelling was done from the perspective of heat pumping technologies with the solar thermal input as support. This was presented at the 12th IEA Heat Pump Conference by van Berkel et.al. [28] and has become a supporting part of legal procedures in Netherlands to prepare Declaration of Conformity of commercial heat pump systems.

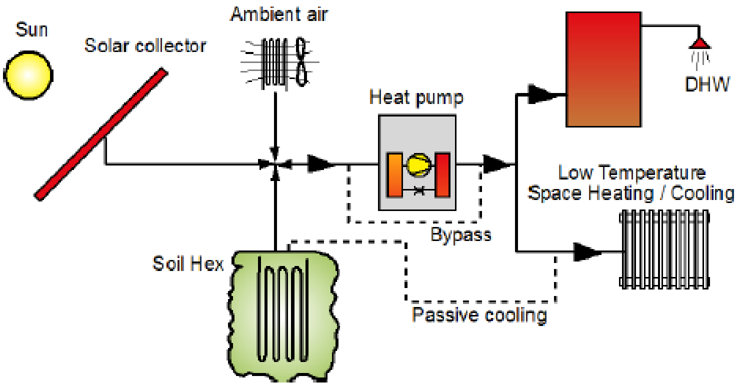


Fig 5.6 generic lay out of the model of a solar assisted heat pump system.

Due to their extremely high COP's, solar thermal systems may advantageously be combined with heat pump systems. Though these systems are now entering the market, the lack of open energy performance assessment tools has been acknowledged by the Dutch authorities (RVO), and has led to initiation of this project. The investigated systems typically comprise a relatively small (< 5 kWth) heat pump, combined with a 200 liter DHW-tank and around 5-25 m2 of solar collector, in combination with a ground- or ambient air heat source. Modeling of the entire system is done conform the regulating Dutch Standards for Energy Performance of Buildings:

- An open and versatile Standard Assessment Model is built for determination of the energy performance of combined solar thermal heat pump systems. The program is built in Excel and evaluates the system status for a year, hour-by-hour. The processing time needed to run the model is less than a second.
- Regarding modeling of the system components: meteorological conditions and solar collector; heat pump; DHW-tank; heating and hot water energy and temperature demands, the model is built according to the principles of the European Energy Performance Standards.
- The model can be used for initial system analysis and optimization. An example shows that for an average house (around 50 GJ total heating load) the optimal size of the solar collector could be in the range of 10-20 m2 , depending on the precise assumptions regarding energy- and component costs.
- Following validation, the model may serve as a tool for evaluation of the energy performance e.g. within the Dutch NEN7120 standard.

The model is open and available for anyone interested in combined Solar Thermal Heat Pump Systems. Compared to other models, especially for systems in mild climates, the optimized systems for NzEB's consist of small storage tanks (max 200 liters) and small surface areas of solar thermal collectors (2,5 m^2), leaving ample room for Solar Photo Voltaics.

Conclusions

Small is beautiful. Why install a 300 litre storage tank with heat losses up to 240Wh as a 150 litre (or smaller) storage size with optimal stratification and control has losses down to 25Wh's and is sufficient for a 'normal' family, dependent on the capacity of the heat pump. The main focus of institutes is on the heat pumping technology, not so much on the behaviour of the storage tank and stratification. Yet small HPWHs with a high SPF are available in the market!

This focuses on a relatively small part of the market and was by studying available literature extended to other configurations. Worldwide there is a large number of models (some academic exercises!) available also for other condensers. Manufacturers do have often their own models.

- Heat pump water heaters are not very energy efficient as in the process of heating and draw offs a lot of losses occur, thus reducing the optimal COP/SPF from 4.5 to 2.5.
- In a great number of institutes work is done fairly independent from each other with a different focus

on the goals to be achieved. Some, like KTH in Sweden focus on reducing the refrigerant charge with flammable working fluids, others focus on the storage capacity in smart grid applications (Grid Flexibility). Important R&D focus is 'smaller and cheaper' as well as cold climate applications.

- The discussion in the Annex did not come to a clear conclusion whether we should have 'wrap-around', external plate, or internal spiral heat exchangers, although lab-test at Oakridge clearly show the advantages of external plate heat exchangers.
- A few degrees temperature difference in the thermostat (hysteresis) gives a better COP. That idea can be used for optimisation of the control mechanisms.
- With an increasing number of heat pumps installed for space heating and cooling the optimisation is in the combination with water heating in double function application. The larger the heating capacity for space heating, the smaller the storage tank (even down to 50 litres)
- The combination with Solar Photovoltaics is the next step.

In comparing DHW concepts and systems a market divide can be made between individual and collective systems and newly developed or built systems and infrastructures compared to existing systems in retrofit.

6. Research and Development (Task 4)

In the residential market there is the need for downsizing, noise reduction, and cold weather specifications as well as higher efficiency and lower price. These general needs that were described in the Country reports can be translated in a number of specific goals.

Manufacturers face multiple constraints such as: guaranteed user comfort, maximum energy performance, manufacturing costs, refrigerant choice and quantity, succeed normative tests. The importance set on each of the constraints has a particular impact on the product design ending up in a variety of possible HPWH designs. There is a number of categories and types of manufacturers/suppliers producing heat pump water heaters:

- Companies producing heating boilers, the biggest in Europe being Bosch, Viessmann, Vaillant, BDR-Thermea. As these companies are well established with a strong brand and large installer networks, they are well positioned to upsell existing boilers with DHW HPs, or sell boiler + DHW HP as a boiler replacement package. They could capture a large share of the boiler upgrade/replacement market. These companies also have a large market share of larger collective heating systems;
- Companies with a background of manufacturing water heaters, originating from the specific market of electric or gas storage water heaters. Like the companies with heating storage systems they traditionally already have a strong market base. In their strive for diversification these companies often also produce solar thermal systems;
- Heat Pump Manufacturers, traditionally focused on space heating, but a number of these manufacturers also manufacture heat pump water heaters only.

The main heat pump manufacturers/suppliers are not Original Equipment Manufacturers and get their components for manufacturing heat pumps from the world-wide market, compressor technologies, valves, evaporators and refrigerants. Therewith, R&D from non-OEM manufacturers will be mostly 'application development' focusing on the application boundaries of the existing and future markets and customer needs and preferences. This is an interesting market where innovation is of great importance to reach the market. Business focused on being an OEM supplier, and with partnerships in place with several major European players, they have a strong route to market. The future potential for this type of specialist OEM company is strong as an increasing number of European players aim to get quickly to market with a DHW HP, leap-frogging the product development stage.

Although heat pump water heaters seem to be readily available on the market, development as well as research are still needed to increase the performance of the heat pump itself as well as the storage system.

In the participating countries some specific programs for R&D on heat pump water heaters are or have been running and some general R&D programs run in which amongst others heat pump water heater technologies are supported.

- USA – based upon the DOE report W. Goetzler, M. Guernsey, and M. Droesch, Research & Development Roadmap for Emerging Water Heating Technologies, DOE 2014;
- Japan – focus on ECO Cute which started in 1995 and got after completion a successful follow up with individual manufacturers. Next to fundamental research on components the focus seems now to be on application;
- France – The PACTE ECS program by ADEME has been run in which 33 companies participated;
- Switzerland - SFOE research program as presented has a number of R&D priorities, such as: High-efficiency heat pumps and refrigeration systems, Intelligent heat pumps and additive energy systems, Heat pumps with a broad, flexible temperature regime;
- Netherlands - the TKI-Urban Energy program is the leading program for the support of heat pumping technologies in buildings.

A comparison with the research topics of the publicly funded projects shows the high research relevance of the topic "Increasing the efficiency of the refrigeration cycle". Of a certain urgency is also a "more efficient system integration in the living area." The main challenges for Heat Pump Water Heaters are Smaller, Cheaper, More efficient. As a derivative of this you arrive at a number technology approaches:

- Component technologies;
- System technologies;
- Installer focused technologies;
- End-user focused technologies;
- Water quality management technologies;
- Smart technologies (ZEB, smart grid, smart energy).

Component technologies

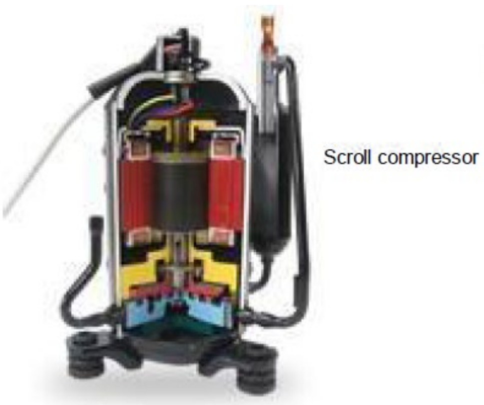
Component technologies is mainly the work done by Technical Institutes and by Original Equipment Manufacturers, focusing on:

- Increasing the efficiency of the refrigeration cycle in relation to the choice of refrigerant;
- Reduction of production costs;
- Improvement of manufacturing processes.

This type of research is often confidential and if made public, the results can be found on scientific websites or at governmental websites, when part of a governmental financing scheme. An important source is IIR.

A classic example is the initiative by the Central Research Institute of Electric Power Industry in Japan that started the research into natural working fluids. Supported by the Japanese Government many new technologies emerged from this, such as a new type of water heater using CO2 as a refrigerant. After the field test in various localities, a natural refrigerant CO2 heat pump water heater for residential use was commercialized in May 2001, named “EcoCute” tradename of Kansai Electric Power Co. Inc.. Thereafter, other manufacturers also put their EcoCute units, developed by themselves, on the market. Although it is not well-known internationally, each these Original Equipment Manufacturers developed its own EcoCute utilizing different core technologies and has put such EcoCute units on the market. These manufacturers are: Sanden, Denso, Hitachi, Panasonic, Toshiba Carrier, Mitsubishi Electric, and Daikin.

In Japan, Denso developed the first heat pump water heater using a CO2 refrigerant, and began selling the product in 2001. Figure 6.1 shows the scroll compressor developed by Denso. Figure 6.2 shows the operating principles of the scroll compressor. Denso's compressor has superior noise control, and its interior forms the low-pressure side of the system, thereby allowing for a reduced wall thickness of the container, as well as compact size and weight.



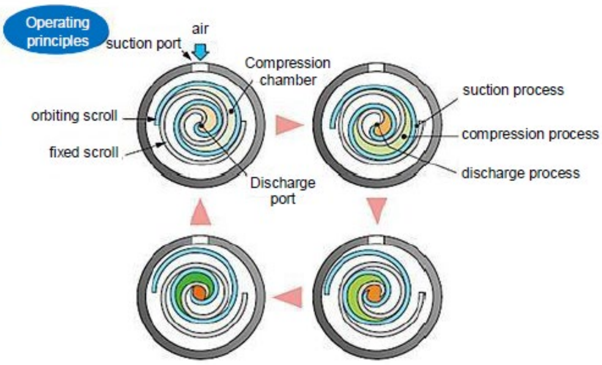


Figure 6.1 Denso’s scroll compressor

Figure 6.2 Operating principles of the scroll compressor

(http://www.hitachi-ies.co.jp/products/cmp/scroll_oilfree/index.html)

The **Japan Country report** gives more examples, where the focus for the development of heat pumps with CO_2 as working fluid has been on:

- Compressor, where structures can be largely classified into scroll, rotary, and swing types. When CO_2 is used as a refrigerant, the high pressure side is compressed to a supercritical state and may exceed 10 MPa. To overcome this, various technological innovations have been made for water heater systems that use CO_2 as a refrigerant. These are now broadly on the market, still being improved further by the manufacturers.
- Gas cooler (or condenser), the gas cooler was replaced with a heat exchanger which had not been used in conventional systems. This condenser is placed outside of the storage tank. Wrap around condensers also occur.

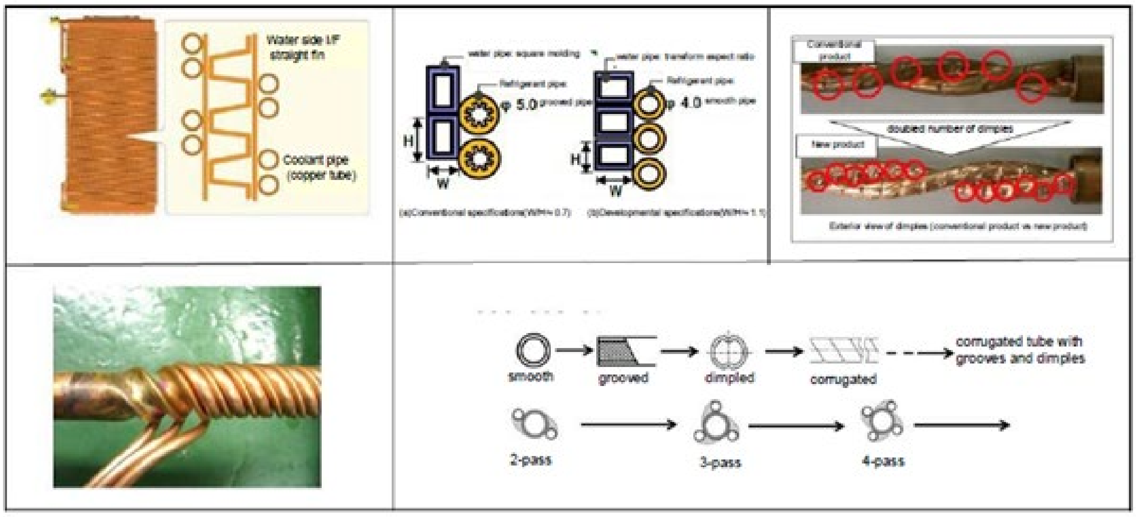


Figure 6.2 Types of gas coolers

- Evaporator, the challenges are numerous, ranging from noise reduction to optimisation of defrosting in cold climates.
- Ejector, the huge difference between the high and low pressures in the CO2 heat pump hot water heater leads to a very large loss in the expansion valve. The ejector can reduce this loss and re-use it as energy to pressurize the refrigerant.

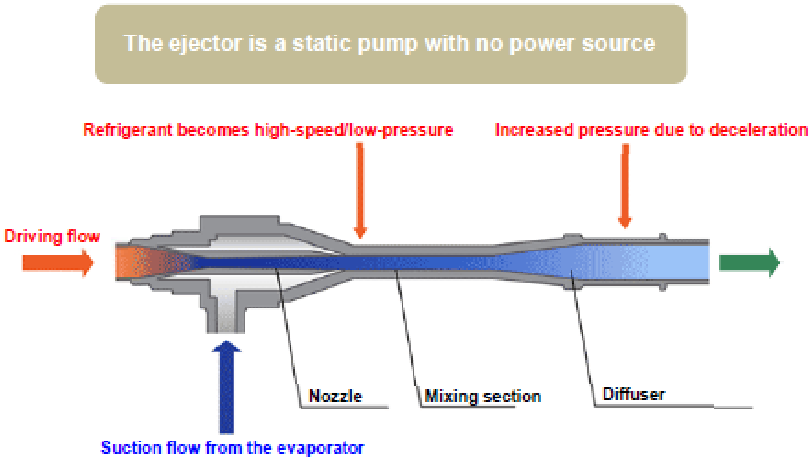


Figure 6.3 Operating principles of the ejector

- Hot Water Storage Tank, where there is a special focus on better insulation methods.
- Control Technology, focusing on smart control and combination/integration with other technologies.

The **US research** program is not so much focused on one technology and has a broader perspective. Component technology development is the basis for a number of R&D projects focusing on developing complete market fit products. Overview of US projects funded by DOE:

1. A Combined Water Heater, Dehumidifier, and Cooler (WHDC), University of Florida, Gainesville, Florida Partners: -- Oak Ridge National Laboratory - Oak Ridge, TN -- Stony Brook University
2. Advanced Hybrid Water Heater using Electrochemical Compressor, Xergy - Seaford, DE, with GE Appliances -- Louisville, KY
3. Commercial Absorption Heat Pump Water Heater, Oak Ridge National Laboratory, with A.O. Smith Inc. - Milwaukee, WI.
4. Commercial CO2 Electric Heat Pump Water Heater, Oak Ridge National Laboratory, with
5. Heat Pump Water Heater using Solid-State Energy Converters, Sheetak - Austin, TX
6. HVAC, Water Heating, and Appliances R&D, Oak Ridge National Laboratory
7. Max Tech Electric Heat Pump Water Heater with Lower GWP Halogenated Refrigerant, OakRidge National Laboratory, with A.O. Smith, University of Illinois, Texas A&M - Kingsville, University of Tennessee.
8. Residential Absorption Heat Pump Water Heater, Oak Ridge National Laboratory with General Electric - Louisville, KY; SRA International - Knoxville, TN; University of Florida - Gainesville, FL; Purdue University - West Lafayette, IN; Ionic Research Technologies, LLC - South Bend, IN; -Yankee Scientific - Medfield, MA
9. Residential CO2 Heat Pump Water Heater, Oak Ridge National Laboratory - Oak Ridge, TN Partner: General Electric Appliances - Louisville, KY
10. Residential Gas-Fired Adsorption Heat Pump Water Heater, Oak Ridge National Laboratory – Oak Ridge, TN

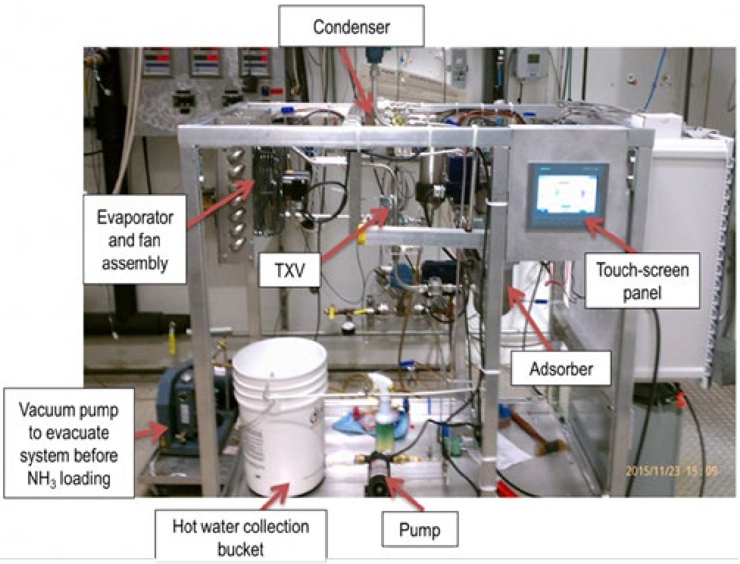
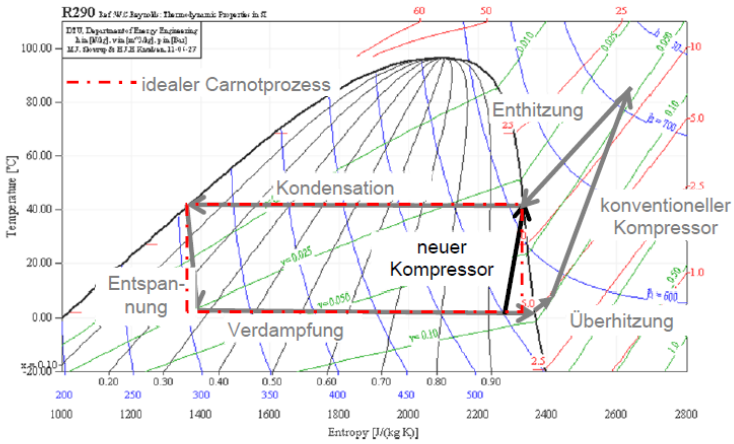


Fig 6.2 Gas-fired adsorption heat pump water heater prototype.

Oak Ridge National Laboratory is working together with a number of commercial partners and institutes. It is expected that a number of technologies developed are getting to the market on short term, where some pilots are already running for some years since 2017.

In **Switzerland** two component developments were reported upon, being:

- R134a miniature turbocompressor by Schiffman [30]
- Friedl et.al. [29] proposed a new concept for the compression of the working fluid starting from a two-phase state at the compressor inlet to a saturated gas state at the compressor outlet with a temperature equal to the condensation temperature (Fig.6.3).



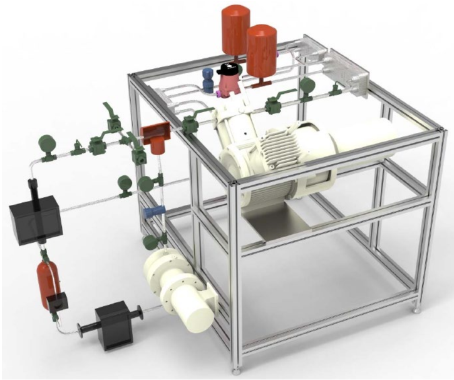


Fig. 6.3 Left: T-s diagram of R290 (propane) as an example, illustrating the process with the two-phase compressor (evaporation temperature 0°C, condensation temperature 40°C), a conventional compressor and an ideal Carnot process, Right: CAD model of the compressor test stand (Friedl *et al.*, 2012).

In Netherlands under the '[Topsector Energie'](#)-program the project on the Thermo Acoustic Heat Pump is a spin-off from the project run by ECN on industrial heat pumps. Project goal is to develop a prototype compact TAWP for decentralized heating and cooling of buildings with a COP of 3.5 to 4.0 (air / water) and a thermal capacity of 1kW. This contributes to compact, inexpensive and efficient developments in the field of heat pump technology in the built environment.

Blue Heart heat pumps are closed systems that are filled with Helium under pressure.
Application of thermo acoustic heat pump
With a thermal capacity of 1 – 100kW's the heat pumps of Blue Heart are developed for residents and offices. Special applications are as:

- Hybrid application with gas boilers;
- Domestic hot water generating. The thermo acoustic technology is especially suitable as an application for domestic hot water. Because there is no maximum temperature for thermoacoustics, it is extremely suitable for upgrading from low temperature (for example heating networks) to tap water temperature;
- Replacement of gas-boilers;
- Small office buildings;
- NzEB's;
- Air Conditioning in buildings.

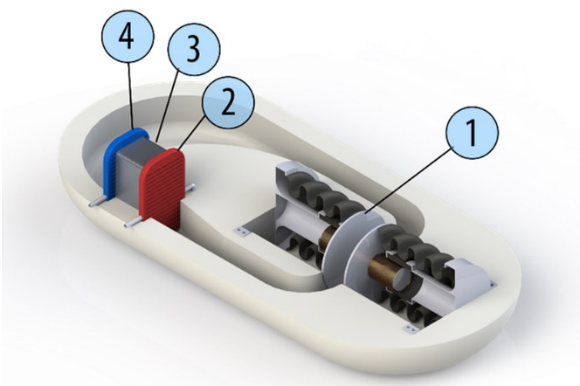


Fig 6.4 – Model of Thermo Acoustic Heat Pump

Blue Hart Energy B.V will produce the thermos acoustic as OEM supplying the component to heat pump manufacturers.

System technologies, especially occurring in collective systems, where smart system lay out and control mechanisms can reduce the temperatures, volume flows and heat losses, thus optimize the energy efficiency as well as economic performance. Not much, except for one study by AIT is publicly known and there no public calculation models available.

Especially with a focus on existing markets system technologies are developed by locally operating heat pump manufacturers. In Netherlands, as well as Denmark, typically the Booster Heat Pump Technology, started with ideas on how to reduce the transport losses in heat distribution systems. This in multifamily buildings and 4th Generation District Heating Systems. The development was taken up in a project in the Nijmegen area where manufacturers were invited to find a solution for domestic hot water in a low temperature district heating system. The a very low capacity water/water-heat pump, which is able to use heat sources of 25 to 40°C at the evaporator side for the DHW-production, which is stored in a storage tank with a capacity of 100 – 150 litres.

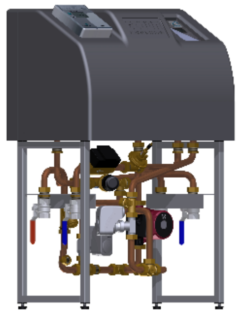


Fig 6.5 – Booster heat Pump Module by [ECOON]

Refrigerants

Manufacturers are very well aware of the refrigeration challenges and are 'working on it' as a consequence of worldwide regulation after the Kigali agreement. In Japan and China the main focus is on the application of CO2 as refrigerant in the monobloc heat pump water heater. In Europe other working fluids, especially propane, are in focus where the biggest challenge is flammability and reducing the refrigerant charge. Developments in this are dominated by the big worldwide operating companies in the market for refrigerants and the Original Equipment Manufacturers.

Installer focused technologies, focusing on making installation of the technology more simple or fit for the local conditions. The traditional installer is not really capable (on a large scale needed for a market transition) to give consumer advice and install the best option. Often oversizing is the case to avoid complaints.

Sizing fit for small spaces, Plug & Play concepts are the dominant topics in countries like Japan, Switzerland and Netherland numerous examples exist. These technologies are often specific for local manufacturers with a strong home market. Collaboration with other disciplines in the building sector is the basis for these developments

Nefit/Bosch, the large manufacturer of gas-boilers launched two total concepts with a heat pump for zero-meter homes: the Nefit Energy Bar, primarily intended for new construction projects and the Nefit Energy Top for renovation. The Energy Top was developed by 'Dutch Heat Pump Solutions', a small start-up have based upon Panasonic technology developed as a plug and play concept for existing and new domestic buildings. The complete installation is built pre-fab at the factory, avoiding potential installation failures with 'new technologies'.

Fig 6.6 – [Nefit Energy Top]

Other suppliers/manufacturers in Netherlands with this interesting market focused development are Alklima/Mitsubishi Electric, Ambrava/Samsung, Nathan/Alfa-Innotec, Inventum, ITHO-Daalderop/Klimaatgarant and [Factory Zero].

In Switzerland an excellent example is the CTI-project “KoDeWa” a compact decentralized domestic hot water supply system for front-wall installations of bathrooms was developed, built and tested (Büchel *et al.*, 2016). The KoDeWa system from the company Swissframe AG consists of a waste heat recovery system for ventilation of the complete housing unit. In the project the front-wall installation was extended with a boiler with a high-tech isolation, a small heat pump and an intelligent control unit. The heat pump is sourced by solar electricity and the remaining energy in the exhaust air is recovered by the heat pump, upgraded and delivered to the hot water boiler[8].

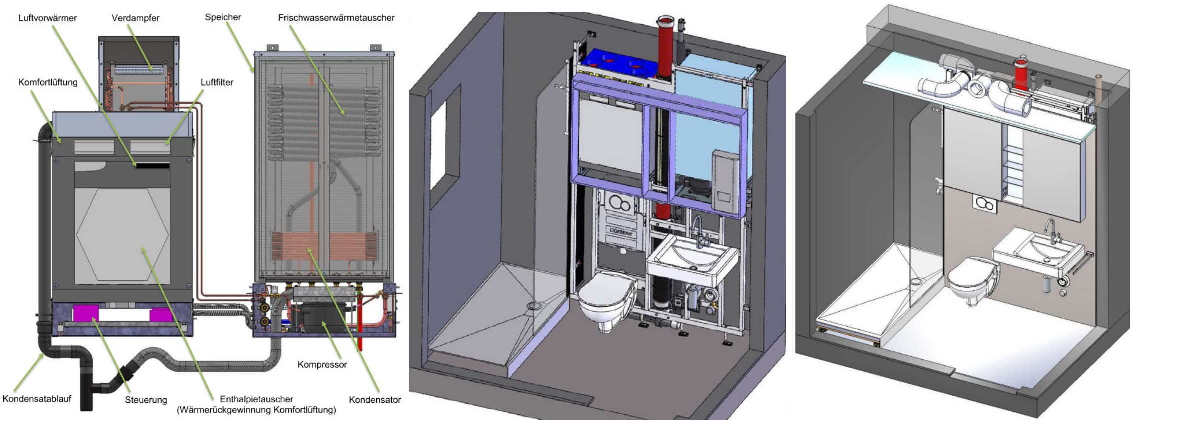


Fig.6.7: Left: New components of the wall unit THERMOS, Right: Renovated bathroom with integrated wall unit THERMOS (Swissframe AG).

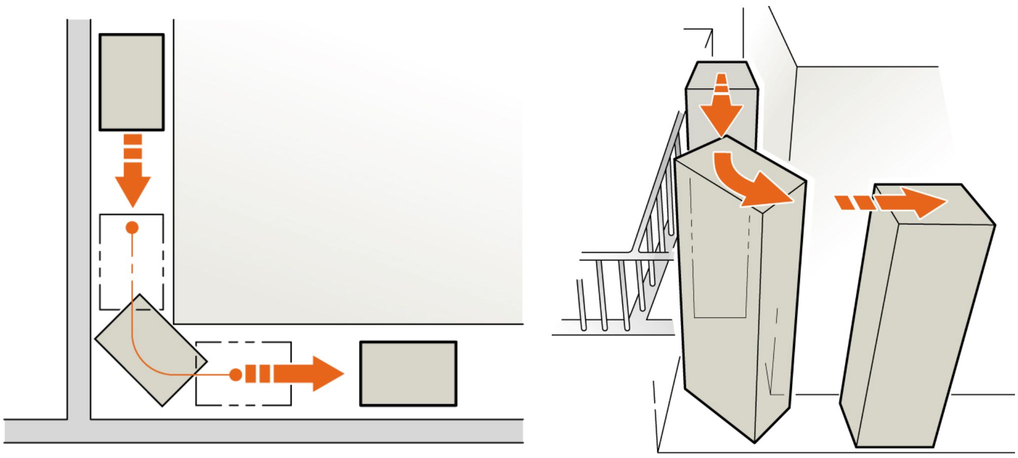


Fig 6.8 Because Japanese houses are often small, the compactification of appliances is also progressing. Companies have developed slim and compact hot water storage tanks to enable installation even in very narrow spaces

End-user focused technologies, is often focusing on smart control, making the installation efficient to handle, and on smart water saving technologies.

Consumer adoption is critical to the success of the heat pump water technologies. Water heating is a challenging market because units are only replaced when they fail which is typically 10 to 15 years and energy efficiency is not always a priority. End-users are not aware of the advantages on the long term and will traditionally go for the cheapest solution. In modern times most new technologies for domestic use have smart interfaces to control the systems, often it increases the ‘fun-factor’ of having such in-house technology. It also increases the understanding of the peculiarities of the technology.

While efforts to reduce water consumption have gained momentum in recent years, there are a number of key

[8] Another example is the SaLüH!-project in Austria developed for the deep renovation of Multi Family Buildings

barriers that have limited the effectiveness of such efforts. Chief among these is the fact that many consumers have limited awareness of their water consumption patterns due to poor data availability, and/or are unmotivated to reduce their consumption due to low costs and split incentives. Two general categories for practices designed to increase water efficiency:

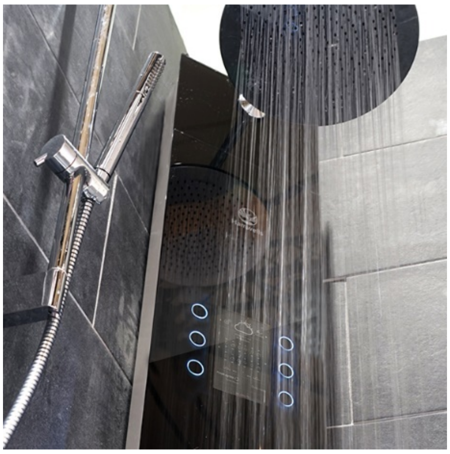
- Behavioural practices refer to changing users' habits irrespective of the technology being used.
- Technologies designed to passively reduce water irrespective of the user's behaviour, such as: water saving shower heads, low-flow toilets, etc.

This binary focus overlooks the conceptual area where technology and behaviour influence each other—an area that has seen much less attention, and is ripe for development.

Simple items informing the end user on their behaviour are available. Like a simple hour glass as Douche Coach or the more sophisticated Efergy Home Energy Monitor.

Fig. 6.9 Efergy display

Other simple solutions are the popular water saving shower head, reducing the water flow to 6 litres/minute at 38°C, this having in Netherland over 60% of the market.



A more advanced system is introduced by Hamwells Europe B.V. with the 'E-shower' which is a shower that recirculated and cleans the used water during showering.

With a classic shower, 10 minutes of showering takes about 70 to 90 litres of water. The water used during showering corresponds approximately to 30% of the total water use. The rain shower grows in popularity as comfort shower in modern bathrooms, but a rain shower uses 15 to 30 litres per minute! By recirculation more than 85% less water and thus 70% less energy is used. Each drop is recycled 9 times via a unique system that cleans water based on UV light.

Fig. 6.10 Hamwells E-shower

Combination with other technologies

Solar energy is traditional other technology that is combined with heat pump water heaters. The Workshop 'Heat Pumps and Solar Energy, a win-win combination' organized by the Annex at the 12th IEA Heat Pump Conference is evidence of this.

Several approaches are in the market, where the mainstream originated from the perspective of solar thermal energy with large storage systems and fresh water systems. The Annex 38/48 is exemplary of this. On the market a large number of systems is available an example of such a system by Heliopac (Fr) is given in the Annex 46 project overview of a newly built private collective housing in Marseille.

Significantly the main stream, as discussed in the Conference Workshop, is now tending towards combining solar photovoltaics with heat pump water heaters and heat pumps for space heating.

The concept of a low temperature non-glazed and non-insulated solar collector as source for a heat pump was already proposed in the thesis 'Theoretisch en experimenteel onderzoek aan warmwater zonnecollectoren', O.

Kleefkens M.Sc. September 1975, Leerstoel Klimaatregeling – Techn University of Delft.

In Switzerland the AquaPacSol-project is a recent example of such a development [32] where, the evaporator of the heat pump was coupled with the solar panels in order to maximize the solar energy efficiency and thus to increase the COP of the system up to 39%. The heat pump is operated only when the direct solar thermal power is not sufficient. In addition, the use of glass or vacuum solar panels allows a further increase in efficiency.

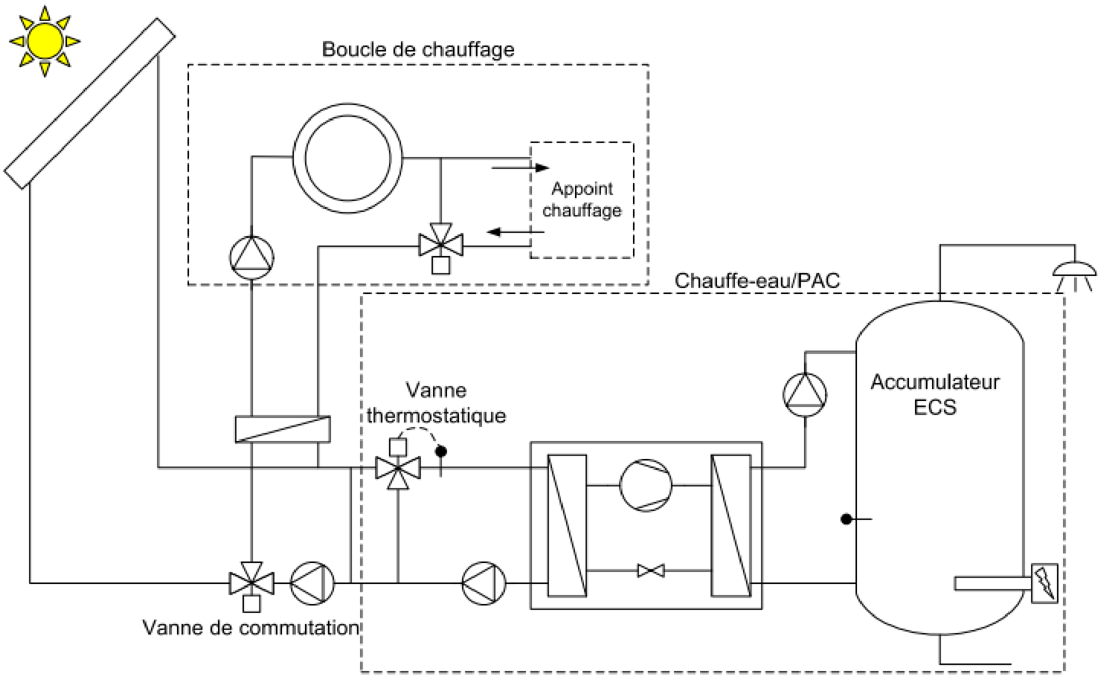
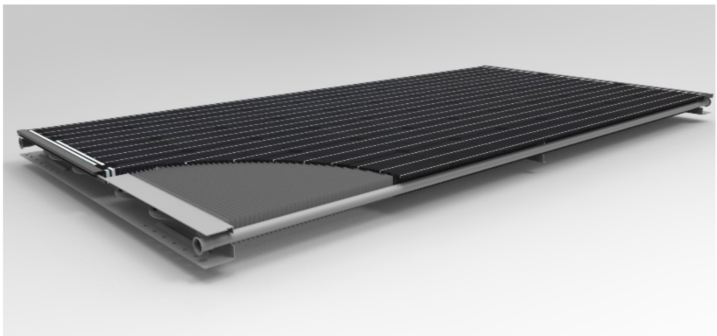


Fig. 6.11: Schematic of the AquaPacSol - Solar assisted Heat Pump Water Heater [32].



In Netherlands the developments has gone further into commercialization, where the Triple Solar®-system has got PVT heat pump panels. The front consists of photovoltaic cells (PV) that convert sunlight into electricity. The rear is a thermal exchanger (T). Together with the water/water heat pump, this provides space heating and domestic hot water.

Fig 6.12 - Triple Solar® PVT heat pump panels

This technology is applied in the recent Ronduit project as displayed in the Annex 46 project overview.

Smart technologies(ZEB, smart grid, smart energy)

Grid operators are interested in the storage capacity of DHW Heat Pumps, although the capacity is smaller than with direct resistance heating and alternative storage technologies are coming on the market and are being researched. Domestic Hot Water Heat Pumps can contribute to solutions for several energy system-related obstacles. Within the Annex 46 working group, we distinguish five main smart heat pump contributions:

- Keeping grid load under control while renewable energy production grows to restrict or even avoid grid capacity investments.
- Keeping grid load under control during extreme conditions (i.e. 'coldest week'), again avoiding grid capacity investments.
- Increase self-consumption of renewable energy sources (achieving better grid balance and higher economic end user value).
- Selling flexibility to the grid, for the benefit of balance responsible parties, grid operators, traders, etc.
- Allowing for a higher share of heat pumps in the energy system without risking local overload problems. Enhancing the realization of these solutions has been the basic driver for the Annex 42 participants.

It turns out that there is a real – and often pressing – benefit in implementing smart grids in all participating countries. The table below summarizes the main recommendations and actions that should be considered when trying to stimulate further development of smart grids.

- Coupling of electricity and heat - Smart Grid Ready;
- Combination with photovoltaic self-consumption optimization;
- System integration in the living area;
- Increasing efficiency of partial load behaviour;

Switzerland developed the SmartGridready standard (Elektroplan Buchs & Grossen AG, 2017) (www.smartgridready.ch) as a supplement to the SIA 386.110 standard "Energy Efficiency of Buildings - Influence of Building Automation and Building Management", in order to dynamically integrate energy production, temporal energy load displacement, energy storage and energy costs into building automation. This provides a holistic view of energy consumption and production.

In Netherlands a number of projects have been supported under the Innovation Program Intelligent Grids (IPIN). From 2011 to 2016, 12 experimental gardens in the Netherlands experimented with smart grids. The testing grounds were completed at the end of 2015. Smart grids are electricity systems that influence the demand for electricity based on the moment supply. Under the HPT-Annex 42 this has been further developed.

7. Example projects (Task 5)

Example projects in countries participating in the Annex and some other countries:

- Example projects in New Buildings;
- Example projects in Existing Buildings;
- Example projects with Gas Driven Heat Pumps;
- Example Projects with CO2 as Refrigerant;
- Monitored Example Projects.

These examples are collected for Single Family Buildings as well as Multi-Family Buildings.

Example projects in New Buildings;

- Austria - Hot Ice – Weiz - Newly built block of passive houses as a pilot project with fresh water system and the use of latent heat with two ice storages.
- Netherlands - Ronduit – Utrecht - Terraced newly built Energy Zero houses with Solar PVT heat pump panels as source for individual heat pumps, providing hot water and space heating.
- Netherlands - Rijswijk Buiten - First Dutch housing quarter with Energy Costs Zero Houses.

Multifamily buildings

- Switzerland - DHW Supply in MF Dwellings - Pilot project Investigating the efficiency of domestic hot water generation, storage and supply systems for multiple family dwellings using heat pumps
- Switzerland - Suurstoffi - Risch-Rotkreuz – A district energy system with a low temperature network fed from a borehole field ground storage. This project high lights a ground source distribution system for the heat pumps and a number of different options for Domestic Hot Water distribution and generation.
- Switzerland – Plus Energy House – Rupperswil - “Plus Energy House with Electromobility”. The building produces more energy than needed for heating, hot water and household electricity. Part of the excess energy is used to operate an electric car.
- Switzerland – Reka Feriendorf – Blatten Belalp. Newly built holiday village with three central PVT-solar supported heat pumps and one booster heat pump delivering domestic hot water to seven individual fresh water stations in the separate apartment buildings.
- France - Bourderies - Nantes - Construction of 32 social housing units with very low energy consumption in line with the BEPOS Effinergie label, equipped with individual Heat pump water heater on collective exhaust air ventilation system.
- France - Dinetard student residence - Toulouse - A new student residential building heated by air source gas absorption heat pumps for space heating and solar support for domestic hot water, monitored.
- France - Villa Plaisance du Touch - Toulouse - New built low energy luxury apartment building with a collective hot water circulation on air source heat pump with CO2 as refrigerant.
- France – Les Jardins du Parc Résidence – Toulouse – A newly built luxury 4-storey apartment building with a centrally installed PVT supported domestic hot water heat pump.
- France - Roquebrune - The "Eco Quarter Capazur " brings together 7 buildings certified Low Consumption Building. They house 280 dwellings, including more than half of social housing, collective heat pumps on waste heat for space heating and special high temperature collective heat pumps for domestic hot water, boosting the low temperature wate heat source.
- France - La Novella - Marseille - New built private luxury housing with a collective hot water system with heat pump supported by non-glazed solar thermal energy as heat source.
- Nothern Ireland - St Thomas Hall - Belfast - New build apartment facility catering for the short-term city rental market. Domestic hot water provided by an air source sanitary hot water heat pump and space heating provided by electric instantaneous panel heaters. The build met the client’s requirements, i.e. complied with Building Regulations and provided a low cost hot water and space heating solution.

- England - Parkside Place - London - Forty newly built luxury apartments with Individual exhaust air source heat pumps for space heating and domestic hot water.
- United States - West Village - Davis, California - Central Heat Pump Water Heater installed on student apartments at the University of California, monitored by Alliance for Residential Building Innovation.
- Netherlands - De State - Amsterdam - Newly built 70 meters low energy high rise apartment building equipped with individual domestic hot water systems with the MultiBoiler heat pump concept for space heating and hot water.
- Netherlands - Zeewaarts - IJmuiden - Three identical towers house a total of 103 apartments heated by collective High Temperature double stage cascade heat pumps.
- Netherlands - Leyhoeve - Tilburg - Sustainable heating of an elderly home with special high temperature heat pump for safe sanitary hot water
- Netherlands - Sophia Staete - Hendrik Ido Ambacht - The first booster project in Netherlands in a collective system to produce individual domestic hot water.
- Netherlands - YOTEL Hotel – Amsterdam. - New BREEAM Excellent certified hotel built applying modular construction with prefabricated hotel rooms and technical system, with ground source heat pump.
- Netherlands - De Tas - Biddinghuizen - New Multi Family Building with individual double function heat pumps and individual ground sources.
- Germany - Herzo Base - Herzogenaurach - Booster heat pumps for hot water generation in 8 Row houses in the KfW Efficiency House 40 Plus standard.
- Germany - Strandstrasse - Kiel - Five newly built residential Multi-Family buildings, with collective hot water distribution, in combination with solar thermal energy and implemented using heat contracting

Example projects in Existing Buildings;

- England - Dartmoor - Farmhouse renovation makes use of cascade air source heat pump to meet hot water and space heating demand and reduce energy bills.
- Netherlands - Titus Brandsmastraat - ’s-Hertogenbosch - Plug & Play renovation by a Housing Corporation of six terraced houses to level of Energy Zero
- United States – Cocoa - Florida - Ducted heat pump water heater on Space Conditioning monitored in a single family house, tested side by side at the Flexible Residential Test facility laboratories
- United States - Redding - California - Summer indoor Heat Pump Water Heater installed in installed in two existing homes in Redding, California in a hot-dry climate, monitored and evaluated by the Alliance for Residential Building Innovation.

Multifamily buildings

- Switzerland – Stauffacherstrasse – Bern – Modular and fully equipped pre-wall units for bathrooms considerably simplify and noticeably accelerate the renovation of old buildings. The pre-wall units incorporate a decentralised hot water tank with a high-performance vacuum insulation, a low-power heat pump and an intelligent control system.
- France – Claude-Tournier residence – Brie-Comte-Robert – Renovation of 205 social housing units in 13 buildings, with small collective hot water heat pumps installed in each building.
- France - Rennes - Renovation of 21 collective dwellings Multi Family Building in Bédée with individual air source heat pump water heaters with propane as refrigerant.
- France - Soissons - Renovation in a Multi Family building in a social housing project connected to District Heating with individual domestic hot water heat pumps in 12 apartments.
- Netherlands – Paddepoel – Groningen – A first: Renovation of apartment complex becomes ‘zero on the meter’ for the energy use by installing individual air to water heat pumps in the 48 apartments and high-quality solar panels on the roof of the complex. The renovation is a plug & play building concept that did get Dura Vermeer the prestigious Dutch Sustainable Building Award in February 2016.
- Netherlands - Soendalaan – Leiden – A Plug & Play energy concept for renovation by a Housing Corporation to the level Energy Zero, with semi-individual heat pumps serving 2 or more apartments per heat pump.

- Netherlands - Collective HT HP – Jacques Urlusplantsoen – Leiden – Renovation of privately owned flats with a central heating system new type cascade ground source heat pump developed under the Dutch TKI-program Urban Energy.
- Netherlands - De Bomenwijk - Delft – Renovation of an existing mixed housing quarter owned by housing corporation Vestia, installing individual heat pumps with individual closed loop ground sources.

Projects with Gas Driven Heat Pumps;

Gas driven heat pump technologies can be split into sorption heat pumps and gas engine driven heat pumps. Efficient, gas driven heat pumps can reach high temperatures and therefore be used with existing distribution systems especially fit to produce domestic hot water in collective open systems.

- Absorption heat pumps can reach temperatures typically up to 75˚C.
- Gas engine driven heat pumps can reach temperatures up to 80˚C.

The main advantage of gas heat pumps in many markets is that, even if deployed widely, they would not constitute a significant burden on the electricity grid and as ground source heat pumps they need a smaller source.

- Canada – Social Housing complex - Toronto. Field Test by The Atmospheric Fund of air source absorption heat pumps in order to determine if GAHPs are a technology that can provide efficient heating and reduce carbon emissions in a cold climate. Two units were installed and monitored as part of a DHW system in a large multi-unit residential social housing complex in Toronto, Ontario consisting of two buildings with a combined 372 apartments for seniors, and a gross floor area of 16,258 m2.
- France – Dinetard student residence – Toulouse – A new student residential building heated by air source gas absorption heat pumps for space heating and solar support for domestic hot water, monitored. Similar projects are in 87 apartments in Annemasse and in Résidence Lyautey et Poncaré in Malauney
- France - Residence 9 Town - Lyon - New luxury housing project in the private sector for which the heat for space heating and domestic hot water is produced by a set of 4 gas absorption heat pumps.
- United States – Capital Manor Retirement Community – Salem, OR – Renovation and monitoring of the sanitary hot water system in a multi storey retirement home by installing a high temperature gas engine heat pump in the central technical room on an existing installation.
- Netherlands – 2 MegaWatt-project – Schalkwijk – Haarlem – Netherlands – Renovation of nine apartment blocks with a new heating system based upon solar thermal energy and the first large scale application of absorption heat pumps feeding a fresh water system for collective domestic hot water.
- Netherlands – Jannes van der Sleedenhuis – Hoogeveen. Newly built care home with a high temperature gas engine heat pump for domestic hot water and space heating as an example for further investments by the housing corporation Woonconcept in Heereveen and Meppel.
- United States – Park Forest a multifamily house in Jackson Michigan (United States) has an interesting combination of 18 ROBUR absorption air source heat pumps providing space heating and domestic hot water by individual risers in wintertime and 4 ROBUR gas fired chillers in summertime to provide domestic hot water from what is called waste heat from cooling.

Example Projects with CO_2 as Refrigerant;

- Koraku Onyado Fujiginkei – This hotel it built in Lake Kawaguchi Area at the foot of Mt. Fuji, now a registered world heritage site. When the refurbishment was done, they installed a low-cost, environmentally friendly commercial Eco Cute, out of consideration for the environment and the continued development of the area. Thanks to the system's cutting-edge technology, energy-saving performance and ability to reduce costs, they receive an energy-saving subsidy from the government in 2012, covering one third of the total cost.
- Tateyama Country Club – The new clubhouse was rebuilt in 2012. It is a fully electric building that combines safety and ease of maintenance, as well as protecting the environment and saving energy. For the hot water supply, load levelling was achieved by effective use of heat pump water heater combined with thermal storage tank which utilizes the less expensive overnight power. For air conditioning, high-efficiency heat pump system were installed for each room. The kitchens meanwhile are fitted with fully electric systems that maintain hygiene whilst also creating an excellent working environment.
- Sakakibara Heart Institute of Okayama - The concept of rebuilding this hospital was to save energy and improve the safety, comfort and cost of facilities, with the aim of improving management efficiency and reinforcing business continuity in the event of a disaster. In order to improve system efficiency air conditioning facilities combine high-efficiency heat pumps with Eco Ice and Eco Cute for hot water supply were installed.
- Abenobashi Terminal Building is a multi-purpose commercial facility in Abenosuji Itchome, Abeno-ku, Osaka, Japan. It consists of the New Annex (main tenants: Osaka Abenobashi Station, Abeno Harukas Kintetsu Main Store Wing Building), Eastern Annex (Tennoji Miyako Hotel), and a 300 m (984 ft) tall skyscraper Abeno Harukas. The reconstruction began in January 2010, and opened on March 7, 2014. The building is 300 meters tall and has 62 floors, making it the tallest building in Japan. It is the planned alternative station building of Ōsaka Abenobashi Station, the terminal of Kintetsu Minami Osaka Line. Its floor space is around 100,000 square meters, making it the biggest department store in Japan.[2] It contains the new Main Store of Kintetsu Department Store, Marriott International hotel, and new headquarters office of Sharp Corporation.
- France – Eco-Cute – Villa Plaisance du Touch in a suburb of Toulouse – New built low energy luxury apartment building with a collective hot water circulation on air source heat pump with CO_2 as refrigerant. This type of CO_2 system, in the deployment phase in France and in Europe, can be applied to capacities below 3kW and up to several tens of kW. This allows broad coverage on applications where DHW consumption is high, such as collective residential applications.
- Netherlands – The Albus Hotel – Amsterdam – This renovation of the Albus hotel in Amsterdam became the first completely CO_2-neutral hotel in Europe. The specially purchased state-of-the-art Mitsubishi Electric Multi R2 VRF system cools and heats all the rooms. In addition, it is also possible to heat the hotel's hot water up to a maximum of 90°C with a Mitsubishi Eco Cute QAHV. Thus the hotel's water is heated to more than 70°C in a sustainable manner.
- Netherlands - DUWO Studenthouse – Leiden – Renovation of sanitary hot water supply in a circulation system student home fed by a high temperature heat pump with CO_2 as refrigerant.

Monitored Example projects

Among the great number of example projects with domestic hot water systems withy heat pumps only a small number is monitored with knowledge available in the public domain.

- Canada – Gas Absorption Heat Pumps, a technology assessment and field test findings – This paper provides an overview of high-efficiency gas absorption heat pump (GAHP) technology, and presents The Atmospheric Fund's (TAF's) energy and emission findings from a detailed study of two GAHPs installed as part of a domestic hot water system in a multi-unit residential building in Toronto, Ontario. This paper also explores the cost and carbon effectiveness of GAHPs compared to alternative technologies such as electric heat pumps and condensing boilers.
- Canada – CO_2 & Integrated Heat Pump Water Heater Performance Report – This report presents the field test performance results of Sanden's CO_2 split system heat pump water heater (HPWH) and Rheem's

integrated HPWH. Energy 350 installed seven Sanden units and five Rheem units across three British Columbia locations including Kelowna, Rossland, and Vancouver Island. This report includes over a year of data for ten of the twelve sites. Submitted to Fortis BC in Partnership with BC Hydro, BC Ministry of Energy & Mines and Natural Resources of Canada, submitted by ENERGY350, 9/27/2018.

- Switzerland – Warmwasserbereitstellung mittels Wärmepumpen in Mehrfamilienhäusern (Bernard Vetsch, NTB) – Pilot project Investigating the efficiency of Domestic Hot Water generation, storage and supply systems for Multifamily Buildings using heat pumps.
- Switzerland – Modelling the Suurstoffi district based on monitored data to analyse future scenarios for energy self-sufficiency (Prasanna and Vetterlin) – A district energy system with a low temperature network fed from a borehole field ground storage. This project which high lights a ground source distribution system and a number of different options for DHW is reported upon.
- Switzerland – Plus Energy House with Electromobility – The building in Rupperswil produces more energy than needed for heating, hot water and household electricity. Part of the excess energy is used to operate an electric car. Hall et.al extensively report upon the experiences in the article 'Optimierung des Eigenverbrauchs, der Eigendeckungsrate und der Netzbelastung von einem Mehrfamiliengebäude mit Elektromobilität', Bauphysik, 6. Jahrgang, Juni 2014, S. 117–129, ISSN 0171-5445
- Switzerland – Final report 2012 (in German – Zimmermann and Ritz) – School building in Krummbach renovation for sustainable second life. This renovation project can be seen as a pilot for industrialized plug & play renovation to a low Minergie®-P-Eco standard and has bee extensively monitored on DHW usage.
- Switzerland – Final report (in German, Sulzer and Summermatter) – Solar energy supply in the Alpine region in the Reka holiday village on Blatten-Belalp, consisting of 7 apartment buildings with 50 apartments. Its energy system with a solar supported heat pump and a fresh water system was monitored for two years with a focus on the regeneration of the ground sources. The overall use of domestic hot water was less than 50% of the estimated use according to standard calculation models.
- United States – Multifamily Heat Pump Water Heater Evaluation – Central Heat Pump Water Heater installed on student apartments at the University of California in West Village – Davis, monitored and reported upon by Hoeschele and Weitzel of the Alliance for Residential Building Innovation.
- United States – Effect of Ducted HPWH on Space-Conditioning and Water Heating Energy Use – Central Florida Lab Home – Ducted heat pump water heater on Space Conditioning monitored in a single family house in Cocoa (Florida), tested side by side at the Flexible Residential Test facility laboratories. This project focusing DHW is reported upon by NREL.
- United States – Summer Indoor Heat Pump Water Heater Evaluation Hot-Dry Climate – Installed in two existing homes in Redding, California, monitored and evaluated and reported upon by the Alliance for Residential Building Innovation.
- United States – Advanced Heat Pump Water Heater Research – (Eklund, Banks, Larson) – The CO_2 refrigerant, split-system heat pump water heater was tested in both lab tests and at four field sites representing the three heating zones in the Pacific Northwest. This report focuses on the field tests and the data and experience collected over almost two years of monitoring. This is a promising technology. The field tests demonstrated that the promise of the lab tests was carried out in the field, and that this technology has great promise as an efficient water heater in all climates of the Pacific Northwest.
- United States – Natural Gas Internal Combustion Engine Heat Pump Field Trial Final Report – The Northwest Energy Efficiency Alliance (NEEA) identified a natural gas internal combustion engine (ICE) heat pump water heater as a candidate for testing. NEEA selected the Capital Manor Retirement Community in Salem, OR as the location for the field testing. The report summarizes actions and performance results from the installation, operation and testing of this product in the field.
- United Kingdom – Strathclyde University – A significant part of the project also consisted in monitoring and analysing the Sanyo Eco Cute System in real conditions of operation.
- Netherlands – DUWO Studenthouse – Leiden – Renovation of sanitary hot water supply in a circulation system student home fed by a high temperature heat pump with CO_2 as refrigerant. One block of apartments has the heat pump as generator for DHW and a similar block next to it has a collective DHW system with a gas boiler. The energy use of both are monitored and compared.

OTHER Example projects

There is a number of other sites and information platforms where examples are shown, such as:

- Japan: Heat Pump and Thermal Storage Technology Center of Japan with some project videos.
- Switzerland: Deklarierte Plusenergie-Gebäuden, giving an extensive overview of declared Energy Plus Buildings and NzEBs in the Swiss area, with many examples of Energy Zero single family and multfamily buildings using heat pumps and solar supported Heat Pump Water Heaters
- France: L'Observatoire des Bâtiments Basse Consommation, not only focusing on heat pumping technologies, but still showing some nice examples.
- France: AFPAC (French Heat Pump Association) has published under the title 'La Pompe à Chaleur. Des solutions pour l'eau chaude sanitaire en habitat collectif', an extensive overview of technologies and example projects on Multi-family buildings.
- Netherlands: publication by Phetradico focused for the 12th IEA Heat Pump Conference, on high rise buildings in the Rotterdam Area under the title 'Heat Pumps in Rotterdam'. Not specifically focused on domestic hot water it gives a nice overview of projects.
- Germany: Wärmepumpe Regional, with over 1100 project examples.

Manufacturers and Energy Service Companies often have their own websites with examples.

8. Communication (Task 6)

Working Meetings

During the period the Annex has been running regular meetings at time intervals of 6 months were held between participants:

- 0th 2015 – Nuremberg (Germany) – a first meeting of potential participants defining the Tasks in order for the Operating Agent to write the Legal Text;
- 1st 2016 – Soesterberg (Netherlands), was a start-up meeting, with presentations by a number of Dutch manufacturers;
- 2nd 2016 – Belfast (United Kingdom), was a meeting discussing the Task 1 reports and markets. The laboratories of Ulster University were visited;
- 3rd 2017 – Rotterdam (Netherlands), adjacent to the 12th IEA Heat Pump Conference, presentations were held by the new participating country, Canada and two invited observers from Spain (dr. Carles Oliet from Universitat Politècnica de Catalunya on the Heat Pump Market in Spain) and Austria (dr. Fabian Ochs from UIBK – Unit for Energy Efficient Buildings on the Heat Pump Market in Austria
- 4th 2017 – Moret Sur Loing (France) – discussion on system models and visit to the laboratories of EDF at Les Renardieres;

- 5th 2018 – Tokyo (Japan), after the Workshop held at Waseda University the Working Meeting focused on the discussion on R&D and the technical modelling of the heat pump water heater;
- 6th 2018 – Buchs (Switzerland), after a number of presentations by Swiss experts, the final reports on Task 1 topics were discussed;
- 7th 2019 – Seoul (Korea), after the Workshop presenting the results to Korean experts, the final reports were discussed and the conclusions were agreed upon. A proposal was made to extend the Annex work on the topic of technical modelling;
- 8th 2019 – Montréal (Canada), after the Workshop at the ICR2019 Conference, a first discussion was held on the proposal for a new Annex and an extension in order to prepare for the Workshop at the 13th IEA Heat Pump Conference.

Workshops

- **1st Workshop - Soesterberg.** The first workshop focused on presenting the developments in Netherlands to the then still relatively small number of participating countries. The group went to visit the EnergyZero housing quarter in Soesterberg, invited by Mitsubishi/Alklima, showing their first prototypes of the Plug&Play Wattz.
- **2nd Workshop - Rotterdam** at 12th IEA Heat Pump Conference. The workshop at the Conference was titled 'Heat Pumps and Solar Energy, a win-win combination' and some 90 participants joined in the lively discussion after presentations by experts from a number of other TCP's. The workshop was organized by the Operating agent of this Annex together with experts from the Technical Collaboration Program on Solar Heating and Cooling. The conclusions of the workshop were presented by Jacob van Berkel at the plenary

closing session of the Conference.

- **3rd Workshop – Tokyo** - Before the 5th Working Meeting for the Annex a Workshop was held to discuss the concept reports from the participating countries. In the workshop the speakers were from the participating countries while the main attendants were from Japan and its National Team for the Annex. The first presentation was given by mr. Kenji Matsuda, General Manager of the Engineering Department within the Japan Refrigeration and Air Conditioning Industry Association (JRAIA). On the third day of the Working Meeting for the Annex a visit was made to the project of Tokyo Toshi Service Company at Harumi Island Triton Square. This being a large area project with district heating and a storage system for a number of high rise office buildings. A presentation by Tokyo Toshi Service Company was given.
- **4th Workshop - Seoul**. Before the 7th Working Meeting for the Annex a Workshop was held to inform Korean experts about the Annex work. In the workshop the speakers were from the participating countries while the main attendants were from Korea and its National Team for the Annex.

- **5th Workshop - Montréal at IIR Conference**. On Tuesday 27th August a successful workshop titled 'Heat Pump Water Heaters, a challenging future'. was held at the IIR Conference the ICR 2019 in the Palais de Congrès de Montréal. Over eighty participants joined in, where after the presentations by a number of invited experts and experts from the Annex 46, a lively discussion was held. Speakers invited from non-participating countries, were:
  - dr. Pavel Makhnatch MSc., KTH Royal Institute of Technology, Sweden,
  - Prof. Pedro G. Vicente Quiles, Universidad Miguel Hernández, Spain;
  - Prof. Emilio Navarro Peris, Universitat Politècnica de València, Spain.

It is envisaged to hold a workshop at the 13th IEA Heat Pump Conference in JEJU.

Publications

A number of papers have been published by participants in the Annex and authors invited by the Operating Agent.

[01] - Kashif Nawaz, Bo Shen, Ahmed Elatar, Van Baxter, Omar Abdelaziz, R1234yf and R1234ze(E) as low-GWP refrigerants for residential heat pump water heaters, Building Equipment Group, Oak Ridge National Laboratory, International Journal of Refrigeration. 82. 10.1016/j.ijrefrig.2017.06.031

[02] - Kashif Nawaz, Bo Shen, Ahmed Elatar, Van Baxter, Omar Abdelaziz, R290 (propane) and R600a (isobutane) as natural refrigerants for residential heat pump water heaters, Building Equipment Group, Oak Ridge National Laboratory, Applied Thermal Engineering 127 (2017) 870–883

[03] - Kashif Nawaz, Bo Shen, Ahmed Elatar, Van Baxter, Omar Abdelaziz, Feasibility Analysis of a Commercial HPWH with CO2 Refrigerant, Building Equipment Group, Oak Ridge National Laboratory, Report for the US Department of Energy under contract DE-AC05-00OR22725, July 2017

[04] - Kyle Gluesenkamp, Viral Patel, Omar Abdelaziz, Bracha Mandel, Valmor de Almeida, High Efficiency Water Heating Technology Development – Final Report Part II: CO2 and Absorption based Residential Heat Pump Water Heater Development, Oak Ridge National Laboratory, report Report for the US Department of Energy under contract DE-AC05-00OR22725

[05] - Kashif Nawaz, Bo Shen, Ahmed Elatar, Van Baxter, Omar Abdelaziz, Performance optimization of CO2 heat pump water heater, Building Equipment Group, Oak Ridge National Laboratory, Oak Ridge,TN 37831 - International Journal of Refrigeration 85 (2018) 213–228

[06] - Deutz, Kevin, Cauret, Odile, Rullière, Romuald, Haberschill, Philippe. (2016). Modeling and Experimental Study of a Heat Pump Water Heater Cycle 16th International Refrigeration and Air Conditioning Conference at Purdue, July 2016, USA.

[07] - K. R. Deutz - Optimisation des chauffe-eau thermodynamiques, 6ème Congrès Français des Pompes à Chaleur INPAC, Paris, France.

[08] - Kevin Ruben Deutz, A. D'Angelo, O. Cauret, R. Rullière, Ph. Haberschill – Performance Evaluation of a Heat Pump Water Heater by means of Thermodynamic Simulation, paper at 12th IEA Heat Pump Conference 2017, May 15-18 2017, Rotterdam – Netherlands

[09] - Jacob van Berkel, Onno Kleefkens, Felix Lacroixc, Solar Heat Pump Standard Assessment Model, paper at 12th IEA Heat Pump Conference 2017, May 15-18 2017, Rotterdam – Netherlands

[10] - Onno Kleefkens, Jacob van Berkel, Charles Geelen, Martijn Bos, Booster Heat Pump, development of test procedure and calculation methodology in order to estimate the energy performance in various domestic applications, paper at 12th IEA Heat Pump Conference 2017, May 15-18 2017, Rotterdam – Netherlands

[11] - N.J. Hewitt, M.J. Huang, N.N. Shah, Vapour Compression Heat Pump Technologies for Domestic Hot Water Heating, Centre for Sustainable Technologies, Ulster University, Newtownabbey, BT37 0QB, UK, 12th IEA Heat Pump Conference 2017, Rotterdam, Holland.

[12] - N.N. Shah, N.J. Hewitt- Ulster University, S. Patton, Glen Dimplex, Overview of Domestic Hot Water Heat Pump: Advancements, Policy and Challenges, United Kingdom, 12th IEA Heat Pump Conference 2017, Rotterdam, Netherlands

[13] - Alan Abela, Performance Testing of Domestic Hot Water Heat Pumps, BRE, United Kingdom, 12th IEA Heat Pump Conference 2017, Rotterdam, Netherlands

[14] - Vishaldeep Sharma, Bo Shen, Patrick Geoghegan, Chris Keinath, Michael Garrabrant, European Regional Climate Zone Modeling of a Commercial Gas Absorption Heat Pump Hot Water Heater, Oak Ridge National Laboratory, Stone Mountain Technologies Inc., United States, 12th IEA Heat Pump Conference 2017, Rotterdam, Netherlands

[15] - Martin Kegel, Justin Tamasauskas, Daniel Giguère, Roberto Sunyé, Heat pump water heaters in the Canadian residential market, Natural Resources Canada, Canada, 12th IEA Heat Pump Conference 2017, Rotterdam, Netherlands

[16] - Chul Woo Roh, Gilbong Lee, Young-Jin Baik, Hyungki Shin, Beomjoon Lee, Junhyun Cho, Korea Institute of Energy Research, Minsung Kim, Chungang University, Thermodynamic performance and economic feasibility of booster heat pumps in low-temperature district heating, Korea South, 12th IEA Heat Pump Conference 2017, Rotterdam, Netherlands

[17] - Stephen Harrison, The Potential and Challenges of Solar Boosted Heat Pumps for Domestic Hot Water

Heating, Solar Calorimetry Laboratory, Dept. of Mechanical and Materials Engineering, 12th IEA Heat Pump Conference 2017, Rotterdam, Netherlands
[18] - Krystyna Dawson, Residential PV replacements offer an opportunity that heat pumps should not miss, Krystyna Dawson, BSRIA, United Kingdom, 12th IEA Heat Pump Conference 2017, Rotterdam, Netherlands
[19] - Brian Fronk, Oregon State University, Christopher M. Keinath, Stone Mountain Technologies Inc., Comparison of Primary Energy Consumption of Vapor and Non-Vapor Compression Natural Refrigerant Heat Pumps for Domestic Hot Water Applications, 12th IEA Heat Pump Conference 2017, Rotterdam, Netherlands
[20] - Cordin Arpagaus, Daniel Gstöhl, Stefan Bertsch, IEA HPT Annex 46: Domestic Hot Water Heat Pumps, Gut zu Wissen, planer+installateur 06/07-18
[21] - Kevin Ruben Deutz, b , Gaspard-Louis Charles, Odile Cauret, Romuald Rullière, Philippe Haberschill, Detailed and dynamic variable speed air source heat pump water heater model: Combining a zonal tank model approach with a grey box heat pump model, Université de Lyon, EDF R&D, International Journal of Refrigeration 92 (2018) 55–69.
[22] - Kevin Ruben Deutz, Odile Cauret, Romuald Rullière, Philippe Haberschill, Multi-criteria Air Source Heat Pump Water Heater optimization combining optimized thermodynamic performance and control, Université de Lyon, EDF R&D, 10th International Conference on System Simulation in Buildings, Liege, December 10-12, 2018.
[23] - Ming Jun Huang, Yan Jun Dai, Nikhilkumar Shah, Christopher Wilon, Neil J.Hewitt, Performance Analysis on Developed EVI Air Source Heat Pump with Seasonal Heat Demand, Ulster University, Shanghai Jiao Tong University, Paper TS-114.4, ICR2019 - 25th IIR International congress of refrigeration, Montréal
[24] - Le, Khoa; Huang, M.J.; Shah, Nikhikumar; Wilson, Christopher; Artain, Paul; Byrne, Raymond; Hewitt, Neil. (2019). High Temperature Air Source Heat Pump Coupled with Thermal Energy Storage: Comparative Performances and Retrofit Analysis. 10th International Conference on Applied Energy (ICAE2018), Hong Kong
[25] - Vorushylo Lytvyn, Inna; Keatley, Patrick; Shah, Nikhikumar; Green, Richard; Hewitt, Neil. (2018). How heat pumps and thermal energy storage can be used to manage wind power: A study of Ireland. Energy. 157. 10.1016/j.energy.2018.03.001.
[26] - Le, Khoa Xuan; Huang, Ming Jun; and Hewitt, Neil J., Domestic High Temperature Air Source Heat Pump: Performance Analysis Using TRNSYS Simulations (2018). International High Performance Buildings Conference. Paper 315. https://docs.lib.purdue.edu/ihpbc/315
[27] - Khoa Xuan Le, Nikhilkumar Shah, Ming Jun Huang, Neil J. Hewitt, High Temperature Air-Water Heat Pump and Energy Storage: Validation of TRNSYS Models, Proceedings of the World Congress on Engineering and Computer Science 2017 Vol II, WCECS 2017
[28] – Cordin Arpagaus, et al, Field performance of domestic heat pumps for heating and hot water in Switzerland, NTB University of Applied Sciences and Technology Buchs, 13th IEA Heat Pump Conference 2020, Jeju, Korea
[29] – Christopher Keinath, et al, GAHP with Combined Heating and Cooling for Full Service Restaurants, Stone Mountain Technologies, Inc, 13th IEA Heat Pump Conference 2020, Jeju, Korea
[30] – Ahmed Elatar, et al, HPWH with integrated energy storage for peak-load shaving, Oak Ridge National Laboratory, 13th IEA Heat Pump Conference 2020, Jeju, Korea
[31] – Ahmed Elatar, et al,HPWH peak-load shaving by using the system water tank with a mixer, Oak Ridge National Laboratory, 13th IEA Heat Pump Conference 2020, Jeju, Korea
[32] – Takaoki Suzuki, et al, Annual Performance Assessment of Heat Pump Water Heater Technology based on Thermodynamic Properties of Various Refrigerants, Waseda University, 13th IEA Heat Pump Conference 2020, Jeju, Korea
[33] – Kashif Nawaz, Alternate refrigerants for Heat Pump Water Heater Applications Oak Ridge National Laboratory, 13th IEA Heat Pump Conference 2020, Jeju, Korea
[34] – Muhamad Yulianto, et al, Energy and CO2 Emission Assessment of Heat Pump Water Heaters in Tropical Climates, Waseda University, 13th IEA Heat Pump Conference 2020, Jeju, Korea
[35] - Justin Tamasauskas, et al, A techno economic Comparison of Air Source Heat Pumping Technologies in the Canadian Residential, Canmet ENERGY-Varennes, 13th IEA Heat Pump Conference 2020, Jeju, Korea
[36] - Elatar, Ahmed; Nawaz, Kashif; Shen, Bo & Baxter, Van; Abdelaziz, Omar. (2017). Characterization of Wrapped Coil Tank Water Heater During Charging/Discharging. ASME 2017 International Mechanical

Engineering Congress and Exposition
[37] - Yasuaki Bando; Hironori Hattori; Yoshiharu Amano, A Status-transition Model for CO2 Heat Pump Water Heater Based on Modified Lorentz cycle. (Waseda University). (2019). International Journal of Thermodynamics. 22. 26-33. 10.5541/ijot.499185.
[38] - Bertsch, Stefan S. & Büchel, Elias. (2017). Idee, Projekt und Produkt - Kompakte und dezentrale Warmwasserbereitstellung, bauRUNDSCHAU, 2017, 2, 34–38.
[39] - Khoa Xuan Le, Ming Jun Huang, Christopher Wilson, Nikhilkumar N. Shah, Neil J. Hewitt (2020), Tariff-based load shifting for domestic cascade heat pump with enhanced system energy efficiency and reduced wind power curtailment, Applied Energy Volume 2571 January 2020
[40] - Khoa Xuan Le, Ming Jun Huang, Nikhilkumar N. Shah, Christopher Wilson, Neil J. Hewitt (2019), Techno-economic assessment of cascade air-to-water heat pump retrofitted into residential buildings using experimentally validated simulations, Applied Energy Volume 25015 September 2019 Pages 633-652
[41] - Khoa Xuan Le, Ming Jun Huang, Nikhilkumar Shah, Christopher Wilson, Neil J. Hewitt (2019) High Temperature Air Source Heat Pump Coupled with Thermal Energy Storage: Comparative Performances and Retrofit Analysis, Energy Procedia Volume 158 February 2019 Pages 3878-3885
[42] - Nikhilkumar N. Shah, Christopher Wilson, Ming J. Huang, Neil J. Hewitt (2018) Analysis on field trial of high temperature heat pump integrated with thermal energy storage in domestic retrofit installation, Applied Thermal Engineering Volume 143 October 2018 Pages 650-659
[43] - Neil J Hewitt, Nik Shah, Donal Cotter, Chris Wilson, Khoa Le, Raymond Byrne, Paul MacArtain, Ming Jun Huang (2020) Domestic Demand-Side Response: The Challenge for Heat Pumps in a Future UK—Decarbonised Heating Market, Renewable Energy and Sustainable Buildings, 2020, 735-745, Springer Cham
[44] - MJ Huang, NJ Hewitt (2020) Enhancing Energy Utilisation in Building with Combining Building Integrated PV and Air Source Heat Pump for Underfloor Heating Using Phase Change Materials, Renewable Energy and Sustainable Buildings, 2020, 813-823, Springer Cham
[45] - K Le, M Huang, N Hewitt (2019) Demand-side management study for cascade air-water heat pump coupled with thermal energy storage in the UK domestic sector SusTEM2019, 2019, Zhejiang University (ZJU) in Hangzhou, China
[46] - Khoa Le, M Huang, Nikhilkumar Shah, Paul MacArtain, Raymond Byrne, Neil Hewitt (2018,) High Temperature Air Source Heat Pump Coupled with Thermal Energy Storage: An Analysis of Demand-Side Management Designed for Flattening the Grid Demand, 17th International Conference on Sustainable Energy Technologies
[47] - Khoa Le, Nikhilkumar Shah, M Huang, Neil Hewitt (2017) High Temperature Air-Water Heat Pump and Energy Storage: Validation of TRNSYS Models, 2017, Proceedings of the World Congress on Engineering and Computer Science 2017 Vol II WCECS 2017
[48] – Sebastiaan Knepper, Ivo Pothofa, Laure Itard, Carlos Infante Ferreir, Low temperature district heating based on low temperature geothermal heat (30ºC), Technical University of Delft, 13th IEA Heat Pump Conference 2020, Jeju, Korea

9. Conclusions

Policy

Throughout the developed world, the heating of water for domestic use is one of the largest consumers of energy in the household sector (10 to 20% energy share). Applying heat pumping technology as one of the possible heat generators to reduce the energy usage significantly. Although there are some noticeable successes in the market developments, heat pump water heaters are still having a relatively small market share with a much larger potential. Traditionally however policy makers are reluctant to make choices, thus except for Japan in the past with the Top Runner program, there seems to be no direct specific support for optimisation of domestic hot water with heat pumping technologies. In general, mandating the installation of high efficiency water heaters is the main policy tool used to ensure that high efficiency water heaters are installed regardless of any short-term inconvenience issues.

In the end it is the end-user, either private or collective through housing corporation, but also the building constructor and its engineers having to comply with the Energy Efficiency demands of a building, that decide on the choice of water heating technology to be applied in a new building or a renovation project. The renovation project can be a simple replacement of an old heater or system. And it is the end-user that is not well informed about the advantages of heat pump water heaters.

This all needs a more clear and focused energy policy from national governments on heat pump water heaters as already advised upon by the IEA TCP on ‘4E Mapping and Benchmarking’.

The overall efficiency of heat pumps in a domestic application is largely influenced by the strategy used to generate domestic hot water, specifically in buildings with a decreasing demand for space heating and multifamily buildings with a collective central system. A widespread uptake of heat pumps would require a much greater emphasis on these two aspects and an evolution of ‘business as usual’ approaches to building services design.

Boundary Conditions

There is a number of boundary conditions that will have to be addressed:

- **Legionella** - Harmonisation of legislation is needed as well as a strategy to get acceptance of alternatives in low temperature systems based upon the 3-litre concept. Heat pumping technologies for the safe generation of hot water in line with current legislation for legionella is widely available, however not always necessary if the 3-litre rule is widely accepted.
- **Test procedures** - The ISO Working Group 12 on Heat pump water heaters of ISO/TC 86/SC 6/WG 12 on HPWHs has developed a harmonisation framework, for drafting a test procedure now available as standard ISO 19967-1:2019. A process has to be set into motion to get this accepted by individual countries.
- **Calculation models** - Currently, the biggest challenge for every user of building and plant simulation is the large number of different simulation tools. Every simulation software has a main area of application and is optimized for this specific problem. Even software with a wide range of applications or specialized multi-physics software cannot calculate every problem in an accurate and efficient manner. If DHW is not included based on objectively verified values, it will not be possible to assess future systems that are predominantly dimensioned around tap water for their energy performance.
- **Refrigerants** – Less work has been done on specific HPWH research with refrigerants. Important for the short term to base the approach for policy on TEWI/LCCP as methodology and less on the GWP. For the longer term with a large renewable share for power generation the GWP will have to be the policy basis.

Future Work

For future work under the IEA TCP on Heat Pumping Technologies and/or the IIR Working Group on Heat Pumps, the focus will be on collaboration on a number of topics to be developed further:

- **Refrigerants**, a great leap forward has been achieved on natural refrigerants in the past four years at Waseda, Oakridge, KTH and Universitat Politècnica de València. This has to be continued with a strong focus on increasing the efficiency of heat transfer to the water and smaller refrigerant charges.
- **Smaller**, where it is of importance to integrate into small spaces of the building structure. In Switzerland and Austria some remarkable small plug & play solutions for renovation have been developed, whereas the Dutch technologies are in general much smaller in tank size than traditional tank sizes worldwide. Smaller storage can be opposed to the needs in smart grid developments.
- **Optimizing the double function**, whereas in large parts of the world the heat pump water heater is seen as a stand-alone monobloc technology an increasing market share will develop for small double function heat pumps.
- **Cold weather applications**, where especially air source heat pump heaters are in focus.
- **Plug & Play** installer focused concepts for easy and simple installation in renovation projects.
- **Optimizing collective systems** for renovation as well as new buildings with a focus on decentralisation of hot water generation.

Modelling making the heat pump water heater technologies more efficient is the basis of the three first bullet points and therefore it is proposed to develop a new HPT-Annex.

Participants

Japan

Prof. Kiyoshi Saito	Waseda University
Katsumi Hashimoto	Central Research Institute of Electric Power Industry
Ryohei Yokoyama	Osaka Prefecture University
Ryo Akasaka	Kyushu Sangyo University
Shigeru Koyama	Kyushu University
Yasuo Kuwasawa	Building Reserch Institute
Masayuki Mae	Tokyo University
Eiji Hihara	Tokyo University
Yasuyuki Miyamoto	Toyama Prefectural University
Kenji Matsuda	Japan Refrigeration and Air Conditioning Industry Association
Kazuaki Shikichi	Kansai Electric Power Company,Incorporated
Yasushi Osagawa	Sanden Living & Environmental Systems Corporation
Yuuji Horiuchi	DAIKIN INDUSTRIES,LTD
Kei Hayakawa	CHUBU Electric Power Co.,Inc.
Hisayoshi Sakakibara	DENSO Corporation
Takeshi Fujinawa	Central Research Institute of Electric Power Industry
Akio Morita	TEPCO Energy Partner, Inc.
Tsukasa Takayama	Toshiba Carrier Corporation
Ryota Hirata	Japan Air Conditioning and Refrigeration Testing Laboratory
Masaki Toyoshima	Mitsubishi Electric Corporation

South KOREA

Jeongsik Seo	Korean Refrigeration and Air Conditioning Assessment Center
Dae-Hoon Kim	Korean Refrigeration and Air Conditioning Assessment Center
Minsung Kim	Chung-Ang University

Canada

Justin Tamasauskas	CanmetÉNERGIE/CanmetENERGY
Roberto Sunyé	CanmetÉNERGIE/CanmetENERGY
Daniel Giguère	CanmetÉNERGIE/CanmetENERGY

United States

Kashif Nawaz	Oak Ridge National Laboratories
Patrick Geoghegan	Oak Ridge National Laboratories
Micheal Garrabrant	Stone Mountain Technologies
Stephen Memory	AO Smith
Kyle Gluesenkamp	Oak Ridge National Laboratories
Van D. Baxter	Oak Ridge National Laboratories

France

Mihai Radulescu	Électricité de France
Odile Cauret	Électricité de France
Kevin Rubin Deutz	Électricité de France
Philippe Rivière	Mines Paris Tech
Michèle Mondot	Centre Technique des Industries Aérauliques et Thermiques (CETIAT)

United Kingdom

Neil Hewitt	Ulster University
Nikhilkumar Shah	Ulster University
Martin Betz	Glen Dimplex
Stephen Patton	Glen Dimplex

Switzerland

Cordin Arpagaus	Interstaatliche Hochschule für Technik Buchs (NTB)
Stefan Bertsch	Interstaatliche Hochschule für Technik Buchs (NTB)
Daniel Gstöhl	Interstaatliche Hochschule für Technik Buchs (NTB)
Michael Eschmann	Interstaatliche Hochschule für Technik Buchs (NTB)

Netherlands

Onno Kleefkens	Phetradico
Charles Geelen	Infinitus
Martijn Bos	ECOON
Marijn Beekman	Techneco
Erwin Janssen	Nathan
Imco Janssens	NIBE
John Braakman	Zon Energie
Jacob van Berkel	ENTRY

References

[01] - IEA 4E Mapping and Benchmarking: Benchmarking Report for domestic gas and electric, storage, instantaneous and heat pump water heaters

[02] - SEAD, Heat Pump Water Heaters: Potential for Harmonization of International Test Standards Final Report, October 2013, Super-efficient Appliance and Equipment Deployment (SAED) report for Initiative of the Clean Energy Ministerial.

[03] - Yunho Hwang, et al, Guideline for Life Cycle Climate Performance 2015, International Institute of Refrigeration, Published by the LCCP Working Group

[04] - Kashif Nawaz, Bo Shen, Ahmed Elatar, Van Baxter, Omar Abdelaziz, Feasibility Analysis of a Commercial HPWH with CO2 Refrigerant, Building Equipment Group, Oak Ridge National Laboratory, Report for the US Department of Energy under contract DE-AC05-00OR22725, July 2017

[05] - P.Makhnatch, R.Khodabandeh and B.Palm, Effekterna av F-gasförordningen oroar värmepumpsindustrin, KTH Royal Institute of Technology, Stockholm, 2018.

[06] -Piotr A. Domanski, Riccardo Brignoli,J. Steven Brown, Andrei F. Kazakov,Mark O. McLinden, Low-GWP refrigerants for medium and high-pressure applications, International Journal of Refrigeration, December 2017

[07] - K. Andersson, B. Palm, P. Fernando, P. Lundqvist, , O. Samoteeva, Designing a Heat Pump for minimum Charge of Refrigerant, KTH Sweden

[08] - K. Andersson, E. Granryd and B. Palm, Water to water heat pump with minimum charge or propane, 13th IIR Gustav Lorentzen Conference on Natural Refrigerants, Valencia, Spain, 2018.

[09] - Chen, Yun-Guang. (2016). Pinch point analysis and design considerations of CO2 gas cooler for heat pump water heaters. International Journal of Refrigeration. 69. 10.1016/j.ijrefrig.2016.05.003

[10] - Miquel Pitarch i Mocholí, High capacity heat pump development for sanitary hot water production PhD Thesis, 2017

[11] - Tammaro, M; Montagud, Carla; Corberan, Jose; Mauro, Alfonso; Mastrullo, R. (2016). Seasonal performance assessment of sanitary hot water production systems using propane and CO2 heat pumps. International Journal of Refrigeration. 74. 10.1016/j.ijrefrig.2016.09.026.

[12] - Martina Longhini, Next generation of refrigerants for residential heat pump systems, Thesis report Stockholm 2015

[13] - Presentation by Japan Refrigeration and Air Conditioning Industry Association at the 5th Three Associations Meeting in Seoul November 2011

[14] - Makhnatch, P., Khodabandeh, R., 2014. The influence of climate conditions on Life Cycle Climate Performance of low GWP refrigerant based heat pumps. Presented at the ASHRAE 2014 Annual Conference, Seattle, WA.

[15] - Makhnatch, P., Khodabandeh, R., 2016. Uncertainty of life cycle climateperformance (LCCP) analysis. Presented at the 12th IIR Gustav Lorentzen natural working fluids conference, Edinburgh, UK.

[16] - Per Jonasson etr.al., Svenska Kyl & Värmepumpföreningen, Undantag för värmepumpar – annars nås inte miljömålen, Svenska Kyl & Värmepumpföreningen, 01 Feb 2018.

[17] - Linita Karlsson; Klara Ottosson. Overcoming issues with Legionella in DHW in LTDH systems; thesis at Lunds Tekniska Högskola; 2018 Lund

[18] - Domestic High Temperature Heat Pumps; Evidence gathering – Low Carbon Heating Technologies, Prepared for DECC by the Carbon Trust and Rawlings Support Services, © Crown copyright 2016

[19] - Michel Haller, Validation of assumptions concerning Legionella prevention in drinking water installations, November 2018 - Hochschule für Technik Rapperswill (Switzerland)

[20] - Félix Iglesias and Peter Palensky, Profile-Based Control for Central Domestic Hot Water Distribution, Austrian Institute of Technology (AIT), IEEE Transaction on Industrial Informatics, Vol. 10, No. 1, February 2014

[21] - Xiaochen Yang, Hongwei Li and Svend Svendsen; DTU; Alternative solutions for inhibiting Legionella in domestic hot water systems based on low-temperature district heating; Journal of Building Services Engineering Research & Technology 37(4)

[22] - Linita Karlsson; Klara Ottosson. Overcoming issues with Legionella in DHW in LTDH systems;; thesis at Lunds Tekniska Högskola; 2018 Lund

[23] – Bernard Vetsch, Warmwasserbereitstellung mittels Wärmepumpen in Mehrfamilienhäusern, NTB Interstaatliche Hochschule für Technik Buchs, BFE-Vertrags- und Projektnummer: SI/500574-01
[24] - Onno Kleefkens et al.; Booster Heat Pump, development of test procedure and calculation methodology in order to estimate the energy performance in various domestic applications, paper at 12th IEA Heat Pump Conference 2017, May 15-18 2017, Rotterdam – Netherlands
[25] - Axel D'Angelo, Techno-Economic Study of Air Source Heat Pump Water Heaters, TESI DI LAUREA 836621, Politecnico di Milano, 2015.
[26] - Kevin Ruben Deutz, Odile Cauret, Romuald Rullière, Philippe Haberschill, Multi-criteria Air Source Heat Pump Water Heater optimization combining optimized thermodynamic performance and control, Université de Lyon, EDF R&D, 10th International Conference on System Simulation in Buildings, Liege, December 10-12, 2018.
[27] - Le, Khoa Xuan; Huang, Ming Jun; and Hewitt, Neil J., Domestic High Temperature Air Source Heat Pump: Performance Analysis Using TRNSYS Simulations (2018). International High Performance Buildings Conference. Paper 315. https://docs.lib.purdue.edu/ihpbc/315
[28] - Jacob van Berkel, Onno Kleefkens, Felix Lacroixc, Solar Heat Pump Standard Assessment Model, paper at 12th IEA Heat Pump Conference 2017, May 15-18 2017, Rotterdam – Netherlands
[29] - Friedl, M, Wärmepumpen mit Gaskühlung im Zweiphasenkompressor, 20. Tagung des BFE-Forschungsprogramms «Wärmepumpen und Kälte» 25. Juni 2014, HTI Burgdorf
[30] - Schiffmann, J. (2005) 'Radialverdichter für Wärmepumpen mit R134a', in 12. Tagung des Forschugnsprogramms Umgebungswärme, Wärme-Kraft-Kopplung, Kälte des Bundesamts für Energie (BFE), 22. Juni 2005, HTI Burgdorf, pp. 61–68.
[31] - Büchel, E. et al. (2016) 'Kompakte, dezentrale Warmwasserbereitstellung aus Fortluft und Solarstrom (KoDeWa)', in 19. Status-Seminar 'Forschen für den Bau im Kontext von Energie und Umwelt', 8./9. September 2016 - ETH Zürich, pp. 1–15.
[32] - Bony, J. et al. (2015) 'AquaPacSol VD (LESBAT) Avenue des Sports 20 CP521 CH-1401 Yverdon-les-Bains jacques.bony@heig-vd.ch www.lesbat.ch Sanitaire, Projet AquaPacSol - Couplage d'une PAC avec capteurs solaires thermiques pour la production d'eau chaude', in 21. Tagung des BFE-Forschungsprogramms Wärmepumpen und Kälte, 17. Juni 2015, HTI Burgdorf, pp. 61–74.
[33] - Dai, Baomin; Li, Minxia; Dang, Chaobin; Ma, Yitai. (2014). Thermodynamic performance assessment of carbon dioxide blends with low GWP working fluids used for heat pump water heater. 11th IIR Gustav Lorentzen Conference on Natural Refrigerants, Hangzhou, China, 2014, At Zhangzhou, China
[34] - J. Calm, G. Hourahan, Physical, safety, and environmental data for current and alternative refrigerants, Proceedings of 23rd International Congress of Refrigeration, Prague, Czech Republic, 2011,

www.heatpumpingtechnologies.org

Heat Pump Centre
c/o RISE - Research Institutes of Sweden
PO Box 857
SE-501 15 BORÅS
Sweden
Tel: +46 10 516 5512
E-mail: hpc@heatpumpcentre.org

www.heatpumpingtechnologies.org

Report no. HPT-AN46-1