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MODELLING AND DEVELOPMENT OF AN INNOVATIVE DUAL-MODE HEAT PUMP WITH HP2GRID FUNCTIONALITY

BY
CAROLINA MADEIRA RAMOS DO CARMO

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Modelling and Development of an Innovative Dual-Mode Heat Pump with HP2Grid Functionality

Ph.D. Dissertation

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Dissertation submitted September 13, 2016

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Preface

This Ph.D. dissertation was submitted to the Faculty of Engineering and Science at Aalborg University in partial fulfilment of the requirements for the Ph.D. degree in Energy Technology Engineering. The research was conducted from mid 2013 to mid 2016 in the Department of Energy Technology, Aalborg University as well as in Insero A/S. The project was industry-oriented, which enables a unique opportunity to perform research gathering insights from both the industry and the academia.

The project supervisors were Associate Prof. Mads P. Nielsen from the Department of Energy Technology, Aalborg University, and Associate Prof. Brian Elmegaard from the Department of Mechanical Engineering, Technical University of Denmark (DTU) and Nina Detlefsen from Insero A/S (currently at Grøn Energi). The project has been financed by Insero with support from the Danish Ministry of Science, Innovation and Higher Education.

In addition, the author had the pleasure of being a guest researcher at the Department of Aerospace and Mechanical Engineering, Faculty of Applied Sciences of the University of Liège in Belgium. During the stay abroad the author was able to get in touch with the novel heat pump/organic Rankine cycle (HP/ORC) prototype and obtain knowledge and results used to develop the dynamic model of the system.

Two bachelor projects have been supervised within the scope of this project.

Carolina Madeira R. do Carmo
Aalborg University, September 13, 2016

Acknowledgements

This Ph.D. dissertation aims at describing the main results of the work done for this PhD project. Yet, this project would not be possible without the support of several people, both experts on the research field and at the personal level. Thus, I would like to dedicate a part of this thesis to thank them.

I would like to thank...	for...
Mads P. Nielsen and Brian Elmegaard	for your expertise, guidance to avoid me getting sidetracked and valuable inputs commenting articles and thesis
Morten B. Blarke and Steen J. Kramer	*for enabling this opportunity and sharing your enthusiasm*
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Finally, I gratefully acknowledge Insero A/S and the Danish Ministry of Science, Innovation and Higher Education for the financial support that made this project a reality.

Abstract

For Denmark's transition towards a 100% fossil free energy system by 2050, while achieving 50 % wind power in electricity generation already by 2020, it is vital that energy systems are smart and efficient. By "smart" is meant that the consumption is linked to the availability of supply from intermittent renewables. Furthermore, the cost-effectiveness and energy efficiency of wind power calls for the electrification of other energy end-uses, that have been more difficult to de-carbonize. Initiatives that include the complete eradication of oil and gas-fired burners with renewable alternatives, like heat pumps, are in place. The electrification of heating introduces challenges of congestion in the power distribution system and power grid stabilization in case of unbalance between demand and supply. Thus, new heat pump solutions should be flexible, in a way that its time of energy use can be shifted from periods of low power supply to periods of excess power.

This PhD project aimed at contributing to the modelling and development of a novel dual-mode heat pump concept, called *HP2Grid*, from an integrated system level approach and at determining what the main benefits are both, in terms of renewable energy sources(RES) integration and improvement of domestic thermal energy conversion efficiency. The work is divided in four main parts: (1) role of residential heat pumps in the new energy system, (2) design of novel concepts,(3) modelling the HP2Grid system and (4) HP2Grid concept development.

The first part, consists of empirical studies of monitored data from heat pump installations operating under real-life conditions. The analyses reveal that the hourly heat pump power consumption profiles over the year coincide with wind power availability 70-80 % of the hours of the year, which indicates that 56-64 % of the total domestic energy demand is well suited to integrate wind power from the grid. In addition, domestic heat pumps show to be energy efficient with measured seasonal performance factors ranging from 2.4 to 3.5.

It is shown, through annual performance simulations, that the potential for RES integration increases when heat pumps are modified to use the excess solar thermal energy to cover both electrical and heat demand of the house.

Specifically, when a horizontal ground source modified heat pump is coupled with a solar thermal collector, the so-called heat pump - organic Rankine cycle (HP/ORC) unit. The energy demand covered by RES increases up to 63 % in a single-family passive house (140m^2) in Denmark equipped with the HP/ORC unit, also entitled as HP2Grid concept. Furthermore, the thermal conversion efficiency can be improved up to 32 % when compared to the traditional heat pump unit. The extension of this potential depends largely on the thermal characteristics of the building's materials and the hot water storage tank. The recommended sensible storage configuration is a 500 L hot water storage tank used exclusively for domestic hot water preparation.

Finally, this work shows that under the current Danish electricity market, the HP2Grid concept annual running costs are around 120€, which is not competitive with similar solutions in the market. However, buildings with a high heat demand can make the HP/ORC competitive with mature technologies like the combination of HP and photovoltaic panels. For instance, the HP/ORC system employed in buildings with different end-uses than single-family dwellings, like office buildings, hospitals, prisons, stadiums, etc.

Overall, it is concluded that the HP2Grid concept, in the form of a reversible ground source heat pump - organic Rankine cycle (HP/ORC) coupled with a solar thermal collector, can contribute to the future energy systems based on renewable energy sources, while increasing the thermal energy conversion efficiency of single-family houses.

Resumé

For Danmarks overgang til et 100 % fossilfrit energisystem i 2050, og samtidig opfyldelse af 50 % vindkraft i elproduktionen allerede i 2020, er det afgørende, at energisystemet er indrettet smart og effektiv. "Smart" betyder, at forbruget er forbundet med forsyning fra fluktuerende vedvarende energikilder. Desuden opfordrer omkostningseffektivitet og energieffektiviten af vindkraft til elektrificering af andre dele af energislutforbruget, der har vist sig vanskelig at dekarbonisere. Det er initiativer på plads, der omfatter en komplet udfasning af olie og gasfyrede brændere med vedvarende alternativer, ligesom varmepumper. Elektrificering af opvarmning fremkalder udfordringer i at balancere elnettet og produktionsbegrænsninger i tilfælde af knaphed på vedvarende energi i nettet. Det betyder, at nye varmepumpeløsninger skal være fleksible, således at forbruget kan flyttes fra perioder med lav strømforsyning til perioder med overskydende strøm.

Formålet med dette ph.d. projekt er at bidrage til modellering og udvikling af et ny dualmode varmepumpekoncept, kaldet *HP2Grid*, og at afdække de vigtigste fordele, både hvad angår, integration vedvarende energikilder og forbedring af termisk energi-konverteringseffektivitet. Arbejdet er opdelt i fire hoveddele: (1) individuelle varmepumpers rolle i det nye energisystem, (2) udformning af nye koncepter, (3) modellere HP2Grid systemet og (4) HP2Grid konceptudvikling.

Den første del, bestod af empiriske studier af overvågede data fra varmepumpeanlæg under virkelige forhold. Analyserne viste, at de varmepumpes elforbrug timeprofiler i løbet af året falder sammen med vindkraft tilgængelighed 70-80 % af årets timer. Dette indikerer, at 56-64 % af det samlede energiforbrug i hjemmet er velegnet til at integrere vindkraft fra nettet. Desuden viser individuelle varmepumper sig at være energieffektive med målte sæsonmæssige ydelsesfaktorer fra 2.4 til 3.5.

Det er vist, gennem årlige driftssimulering, at potentialet for vedvarende energi integration stiger, når varmepumper modificeres til at bruge den overskydende solvarme til at dække husets el- og varmeforbrug. Dette gøres ved at kombinerer modificeret varmepumpe med et solvarme anlæg og et jordvarme anlæg, det såkaldte HP/ORC-anlæg. Energibehov dækket af vedvarende energi stiger op til 63 % i et enfamilie passivhus (140m^2) i Danmark udstyret med HP/ORC-anlæg, også nævnt som HP2Grid koncept. Desuden kan termiske virkningsgrad forbedres op til 32 % sammenlignet med den traditionelle varmepumpeanlæg. Udvidelsen af potentiellet afhænger i høj grad af de termiske egenskaber af bygningens materialer og varmtvandsbeholder. Den anbefalede energilagringskonfiguration er en 500 L varmtvandsbeholder udelukkende anvendes til varmt brugsvand.

Endelig viser projektet, at under det nuværende danske elmarked, er HP2Grid konceptets årlige driftsudgifter omkring 120€, hvilket ikke er konkurrencedygtig med lignende løsninger på markedet. Men bygningerne med et høj varmebehov, kan gøre HP/ORC konkurrencedygtig med modne teknologier som kombinationen varmepumper og solceller. Det kunne eksempelvis være et HP/ORC-systemet i bygninger der ikk er enfamiliehuse, ligesom kontorbygninger, hospitaler, fængseler, stadioner, osv.

Samlet set konkluderes det, at HP2Grid koncept, i form af en reversibel jordvarmepumpe - organic Rankine cykle (HP/ORC) kombineret med en solvarme anlæg, kan bidrage til fremtidens energisystemer baseret på vedvarende energikilder, med samtidig forsøgelse af termiske virkningsgrad i enfamiliehus.

Contents

Thesis Details

Thesis Title:	Modelling and Development of an Innovative Dual-Mode Smart-Grid Heat Pump with HP2Grid Functionality
Ph.D. Student:	Carolina Madeira Ramos do Carmo
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The main body of this thesis consists of the following papers.

[a] Carolina Carmo, Nina Detlefsen, Mads Pagh Nielsen, "Smart Grid enabled Heat Pumps: an empirical platform for investigating how heat pumps can support large-scale integration of intermittent renewables," *Journal Energy Procedia*, vol. 61, pp. 1695–1698, 2014. *Published*

[b] Carolina Carmo, Toke H. Christensen, "Cluster analysis of residential heat load profiles and the role of technical and household characteristics", *Journal Energy and Buildings*, vol. 125, pp. 171–180, 2016. *Published*

[c] Carolina Carmo, Brian Elmegaard, Mads Pagh Nielsen, Nina Detlefsen, "Empirical Platform Data Analysis to Investigate How Heat Pumps Operate in Real-Life Conditions", *Proceedings of the 24th Int. Congress of Refrigeration (ICR2015) International Institute of Refrigeration IIF/IIR*, Japan, 2015. *Published*

[d] Carolina Carmo, Morten Boje Blarke, "Smart Dual-Mode Heat Pump With HP2Grid Functionality To Support Large-Scale Integration Of Intermittent Renewables", *Proceedings of the 3rd Int. 100% Renewable Energy Conference (IRENEC2013)*, Turkey, 2013. *Published*

[e] Carolina Carmo, Olivier Dumont, Mads P. Nielsen, Brian Elmegaard, "Assessment of Emerging Renewable Energy-based Cogeneration Systems for nZEB Residential Buildings", *Proceedings of the 12th REHVA World Congress (CLIMA2016)*, Denmark, 2016. *Published*

[f] Olivier Dumont, Carolina Carmo, François Randaxhe, Sylvain Quoilin, Vincent Lemort, "Simulation of a passive house coupled with heat pump/organic Rankine cycle reversible unit", *Proceedings of the 9th Int. Conference on System Simulation in Buildings (SSB2014)*, Belgium, 2014. *Published*

[g] Olivier Dumont, Carolina Carmo, François Randaxhe, Sylvain Quoilin, Vincent Lemort, "Performance of a reversible heat pump/organic Rankine cycle unit coupled with a passive house to get a Positive Energy Building", *Journal of Building Performance Simulation* , (in review). *Submitted*

[h] Olivier Dumont, Carolina Carmo, Rémi Dickes, Emeline Georges, Sylvain Quoilin and Vincent Lemort, "Hot water tanks: How to select the optimal modelling approach?", *Proceedings of the 12th REHVA World Congress (CLIMA2016)*, Denmark, 2016. *Published*

[i] Carolina Carmo, Toke H. Christensen, "Experimental Validation of a Domestic Stratified Hot Water Tank Model in Modelica for Annual Performance Assessment", *Proceedings of the 3rd Int. Seminar on ORC Power Systems(ASME ORC 2015)*, Belgium, 2015. *Published*

[j] Olivier Dumont, Carolina Carmo, François Randaxhe, Sylvain Quoilin, Vincent Lemort, "Performance comparison of two types of technologies associated with a positive energy building: a reversible heat pump/ORC unit and heat pump coupled with PV panels", *Proceedings of the ISES Solar World Congress (SWC2015)*, Korea, 2015. *Published*

[k] Carolina Carmo, Mads Pagh Nielsen, Brian Elmegaard, Olivier Dumont, "Performance Evaluation of a HP/ORC System with Optimal Control of Sensible Thermal Storage", *Purdue Conferences, 4th High Performance Buildings*, USA, 2016. *Published*

In addition to the main papers, the following publications have also been made.

[A] Carolina Carmo, Olivier Dumont, Mads Pagh Nielsen, Brian Elmegaard, "Energy Performance and Economic Evaluation of a HP/ORC (heat pump/organic Rankine cycle) system with different hot water tank storage configurations", *Proceedings of the 29th Int. Conference on Efficiency, Cost, Optimisation, Simulation and Environmental Impact of Energy Systems (ECOS2016)*, Slovenia, 2016. *Published*

[B] Olivier Dumont, Carolina Carmo, Emeline Georges, Sergio Balderrama, Sylvain Quoilin, Vincent Lemort, "Economic assessment of energy storage for load shifting in Positive Energy Building",*Proceedings of the 29th*

Int. Conference on Efficiency, Cost, Optimisation, Simulation and Environmental Impact of Energy Systems (ECOS2016), Slovenia, 2016.

This thesis has been submitted for assessment in partial fulfillment of the PhD degree. The thesis is based on the submitted or published scientific papers which are listed above. Parts of the papers are used directly or indirectly in the extended summary of the thesis. As part of the assessment, co-author statements have been made available to the assessment committee and are also available at the Faculty. The thesis is not in its present form acceptable for open publication but only in limited and closed circulation as copyright may not be ensured.

Nomenclature

1D	one-dimensional	
A	area of the tank segment	[m^2]
adc	average duty cycle	
AW	air-to-water	
BW	brine-to-water	
CHP	combined heat and power	
COP	coef.of performance	
COsP	coef.of system performance	
c_p	specific heat	[J/gK]
db	dead band	
DH	direct heating	
DHW	domestic hot water	
DL	discomfort level	
DSM	demand side management	
FH	floor heating	
ESCO	energy service company	
EU	European Union	
EV	electrical vehicle	
HP	heat pump	
h	specific enthalpy	[J/kg]
HP2Grid	heat pump to grid concept	
HP/ORC	reversible heat pump/organic Rankine cycle	
HP+PV	heat pump coupled with photovoltaic panels	
HX	heat exchanger	
LCPG	low capacity power generator	
$\dot{m}$	mass flow rate	[kg/s]
OccSB	occupancy setback control	
ODE	ordinary differential equation	
PDE	partial differential equation	
PI	proportional integral	
Q	heat demand	[kWh]
$\dot{Q}$	heat flow	[W]
RC	resistance and capacity	

RES	renewable energy source	
SPF	seasonal performance factor	
T	Temperature	[K]
t	time	[s]
TC	thermocouple	
U	heat transfer coef.	$[W/m^2K]$
USA	United States of America	
W	Power	[kWh]
WF	wind friendliness factor	
Δx	segment height	[m]
# cycles	number of cycles	

Greek letters

α	binary paramater	(-)
β	binary paramater	(-)
σ	artificial mixing term	$[W/mK]$
ρ	density	[kg/m^3]
γ_d	demand cover factor	
γ_s	demand supply factor	

Subscripts

amb	ambient	*cons*	consumption
cd	condenser	*dem*	demand
for	forward	*el*	electrical
ev	evaporator	*ex*	exhaust
high	high temperature threshold	*hx*	heat exchanger
HP	Heat Pump	*i*	tank segment number
in	indoor	*min*	minimum
L&Appl	light & appliances	*low*	low temperature threshold
p	priority	*prod*	production
out	outdoor	*ORC*	Organic Rankine Cycle
ret	return	*seg*	tank segment
su	supply	*sto*	storage
th	thermal	*unit*	HP/ORC unit
w	water		
wall	intermediate wall temperature between T_{in} and T_{out}		

Part I

Thesis

Thesis

1 Introduction

1.1 Motivation

Renewable energy growth

Over the last four decades, political, environmental and economical incidents have increased the interest to achieve a sustainable energy future. The word sustainable, in the context of energy technology, implies mitigation of greenhouse emissions, increment of local renewable energy sources use, higher energy conversion efficiency as well as lower energy cost [EU, 2015]. Figure 1 shows the primary energy sources in 1970 and 2014. It can be seen that - even though the energy demand as been doubled - to achieve the new goals, the global trend in energy systems is primarily the migration of supply based in fossil-fuel sources to renewable energy sources (RES) [BP, 2015].

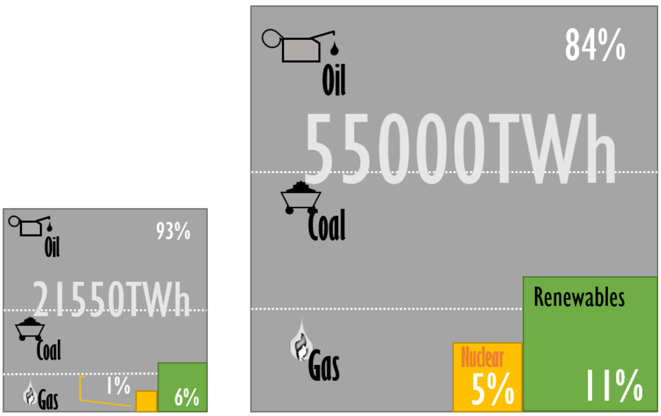

Fig. 1: World primary energy consumption sources in 1970 and 2014

The European Union (EU) has 7 % of the world's population (507 million) and ranks as the third largest energy market (18820 TWh) - after China (34570 TWh) and USA(26740 TWh). 13 % of its final energy consumption is supplied by renewable energy sources. Of this, biomass is the largest contributor to renewable energy sources (57 %) followed by hydro (18 %) and wind (17 %) power, solar (5 %) and geothermal (2.5 %) resources [EU, 2015] (Figure 2).

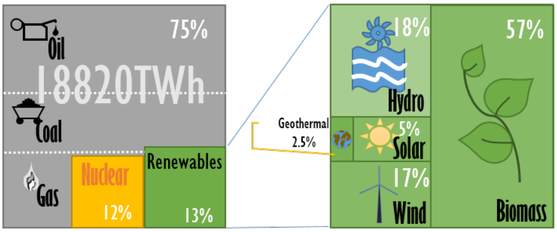

Fig. 2: EU-28 primary energy consumption sources in 2014. Figure based on data from [EU, 2015]

Yet, Figure 3 shows that the leading new installed capacity (MW) of renewable energy sources are predominantly wind and solar photovoltaic (PV) installations. This is primarily due to the cost and energy efficiency of wind and most recently solar power plants [EU, 2015] in comparison to the alternatives based on biomass. Over the past few years, the levelised costs of electricity generation from onshore wind and, specially, PV have fallen distinctly (around 6-8 % per year on average since 1998 [Feldman et al., 2014]).

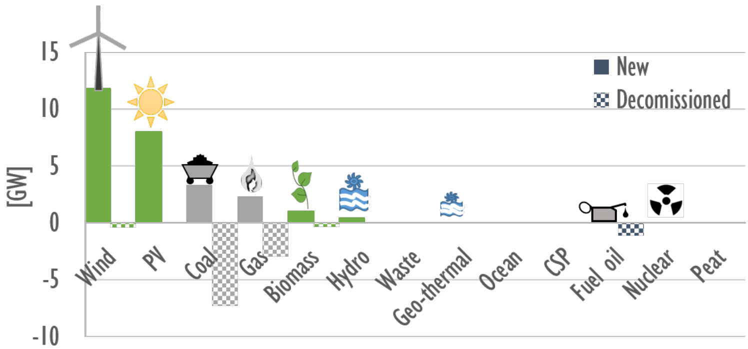

Fig. 3: EU-28 new installed and decommissioned capacity (GW) during 2014. Figure based on data from [I. Pineda, 2015]

Breakdown of end-use of energy

Its must be noted that this energy is used for three main end-uses: electricity, heating and cooling and transport. Detailed data on the breakdown of end energy use in EU-28 is illustrated in Figure 4. It reveals that 24 % of the final energy consumption in EU-28 is used for electricity, while heating and cooling represent the largest share 46 % and the remaining 30 % is used in the transport. In 2014, renewable energy provided already 26 % of the electricity used, but only 17 % of heating and cooling and 6 % of the European Union (EU) final energy consumption in transportation [EU, 2015].

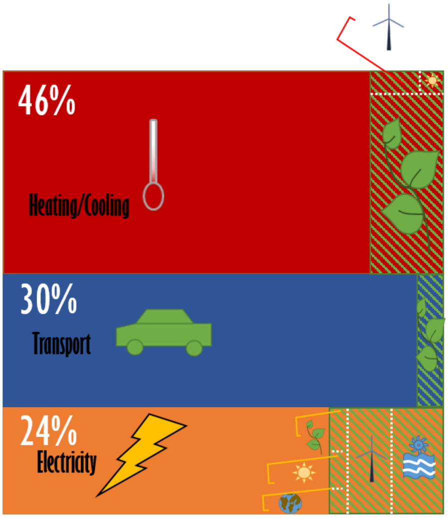

Fig. 4: EU-28 primary energy demand end-use in 2014. Figure based on data from [EU, 2015]

Also Denmark has been fully committed to the long-term target of 100 % fossil fuel- and nuclear-free power system by 2050 since October 2006 [Lund et al., 2009]. This target involves the conversion of oil- and coal- based power plants to renewable energy sources, largely covered by fluctuating wind, solar and wave power sources, but also supplied by renewable gas and biomass, as illustrated in Figure 5. Already by 2020, wind power should supply 50 % of the total electricity production. In addition, the other demand sectors should convert to biomass and hydrogen based energy supply systems.

In sum, two things can be concluded from the current energy outlook: First, we have witnessed an impressive technological development and uptake of renewable power and thus, there is tendency for the electrification of the future energy systems and secondly, the heating and cooling and transport sectors have proven more difficult to de-carbonise.

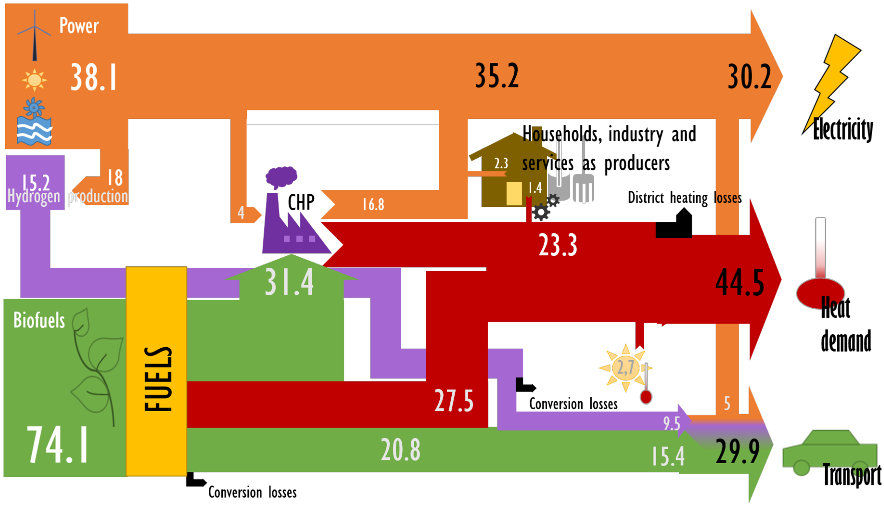

Fig. 5: Danish 100 % renewable energy based system from data in [Lund et al., 2009]

Sector coupling

In this electrification transition, energy systems increasingly face new and different challenges both technical and economical. Especially, the power system stability - conventionally ensured by the conventional fossil-fuel power plants which are used to cover the consumption baseload - is being pressed by fluctuating energy sources.

Bio-fueled and/or hydro power plants as well as electrical interconnections to neighbouring countries can partly provide the system-stabilizing ancillary services. However, on the one hand, the high levelised costs of bio-fueled based electricity generation and environmental impact limit their operation to peak-hours. On the other hand, the hydro power resources are restricted, around 20 % of the countries in the world have limited or no access to it [WEC, 2016]. And, finally, as shown previously, RES expansion is a global trend - thus, if neighbouring regions renewable power sources are the same, the power production from both regions is highly correlated-which reduces the interconnection benefits in terms of ancillary services [Energinet.dk, 2009].

Thus, the electrification trend calls for sector coupling, i.e. power should not only be used for the traditional electricity sectors, but also for the heating and cooling and the transport sectors.

Yet, it is important to remember that the electrification of heating and transport also increases the challenges of balancing the power grid and might contribute to grid capacity problems due to higher maximum loads in the morning and afternoon peak hours with risks of blackouts. Thus, the new technology solutions should be flexible, in the form of time shifting the energy use from periods of low power supply to periods of excess power supply, to support the system-stability.

Diffusion of renewable energy based technologies in the building sector

In total, households account for 27 % of EU-27 total final energy consumption [EU.Com., 2012], where heating and cooling demand represent up to 80 % of the total energy demand of the building sector and the building stock [EEA, 2012]. Furthermore, structures in EU-27 are dominated by residential buildings (75 %), of which 64 % are detached single-family houses [Economidou, 2011].

In Denmark, oil, natural gas, coal, coke and gas works gas made up 27 % of the final energy consumption for residential heating in 2013, while district heating represented 45 %, biomass 22 %, direct electric heating 4 % and heat pumps (HPs) 2 % [DEA, 2013]. This indicates that 50 % of detached dwellings rely on fossil fuel, while non-fossil fuel biomass represents 40 % and electric heating and heat pumps (HPs) only 7 % and 3 %, respectively.

The heating and cooling energy demand sector have proven difficult to further de-carbonise essentially due to scepticism about new technologies and high upfront investment costs [Energistyrelsen, 2015].

One of these technologies are heat pump units. In contrast with other heating technologies - which transform chemical energy into thermal energy - HPs are non-combustion technologies. In practice, for example, they transfer three units of free thermal energy at low temperature contained in the air, water and/or ground and use one unit electricity, to deliver two to four units of heat for heating and hot water supply (Figure 6). In this way, they reduce emissions and improve energy efficiency in heating and cooling buildings [HPJ, 2011].

Heat pump technology is based on thermal energy transfer, it absorbs heat from a heat source to a heat sink by means of heat exchange between a closed-loop working fluid, called refrigerant and two air/water/brine closed-loops that distribute this energy. In Figure 7, the heat transfer between working fluids (space heating loop water/brine and refrigerant) is shown. For example, in winter conditions, when the building requires heating, the free heat available from air, water and/or ground is used to evaporate the refrigerant, which is then compressed, increasing both pressure and temperature of the refrigerant vapour. The hot vapour then condenses, while it transfers heat to the water in the space heating loop or hot water tank. This increases the room temperature or the water tank temperature, respectively. Finally, the refrigerant - now in liquid form - undergoes an expansion process through the expansion valve. This process decreases both its pressure and temperature returning to the initial state. The temperature levels are not specified in Figure 7 because they depend on the thermodynamic properties of the refrigerant employed and the heating requirements of the building.

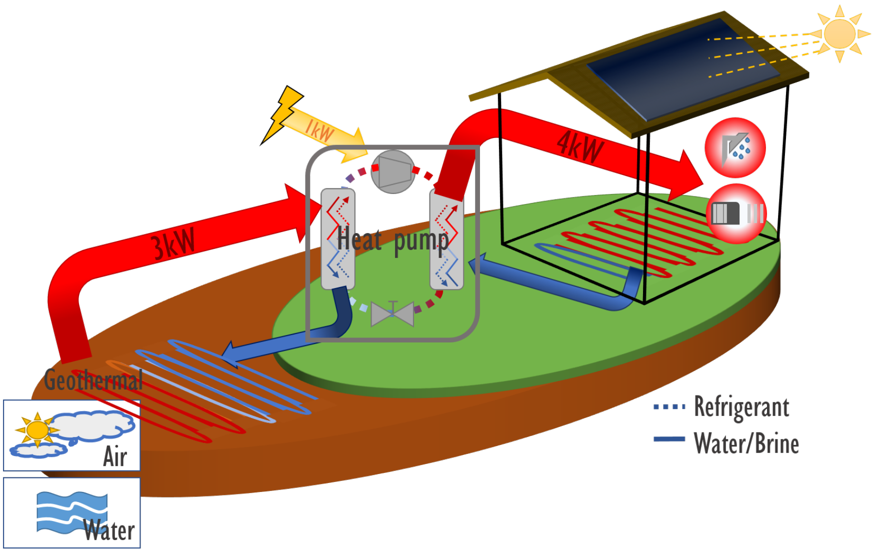

Fig. 6: Schematic ground-/air-/water-source water heat pump

Apart from increasing energy use efficiency and reducing emissions, HP units represent also a new possibility for including heating as a flexible load. Heat pumps own two important features that are crucial to handle both system balancing and network capacity challenges but have not yet been fully explored.

- They include the flexibility provided by heat storage, i.e. ability to shift energy demand from one period to another. This enables the use of demand-side management (DSM) solutions essential for system stability;
- and include the possibility of synergies with other technologies to enable cogeneration, which is considered as one of the best system solutions to further increase the use of renewable energy in the building sector.

In sum, the obstacles and prospects here introduced give the motivation for the topic of this work. Future sustainable energy systems call for attractive residential technology solutions that are highly energy efficient and enable to integrate non-dispatchable RES. Thus, the concept here referred as heat pump to grid, *HP2Grid*, is developed to embody both a high efficiency and flexible energy technology solution for detached single-family houses.

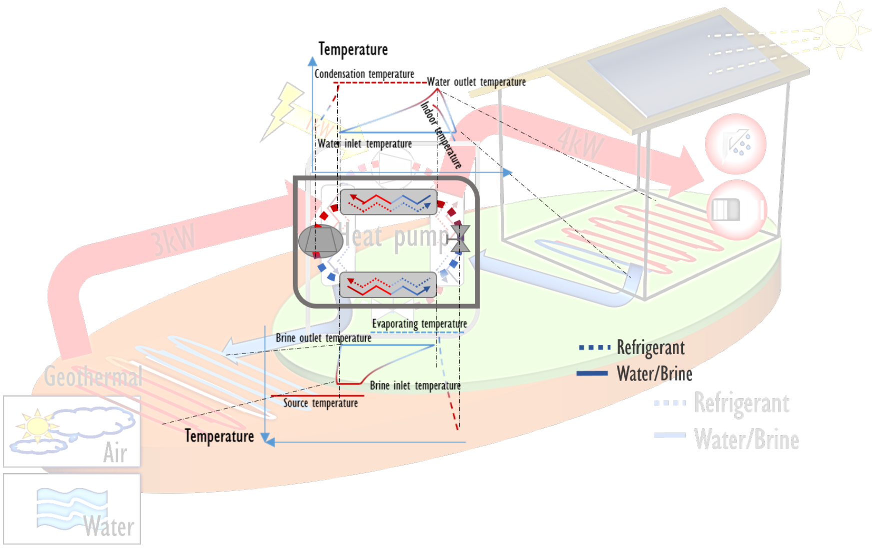

Fig. 7: Schematic heat transfer flows in heat pump

1.2 State-of-the-art and background

To provide the background related to the work presented in this thesis, this section gives an overview of ongoing works within the field of heat pump installations in single-family houses. It is divided into three main categories, which are relevant pillars of this thesis: (1) The first category focuses on studies that aimed at understanding and determining the *role of heat pumps* and its potential in supporting the future energy systems. (2) The second category, *energy efficiency and flexibility optimization synergies*, deals with the most recent works concerned with further improving the energy efficiency and flexibility optimization within heat pump installations. This covers the central point of this thesis, which is the development an innovative Dual-Mode Heat Pump. (3) Finally, the last category, involves studies that identified challenges in the introduction of new energy technologies in the residential sector. Together with the first category, the third category gives the ground for the effective development of *HP2Grid* functionality.

1. **Role of residential heat pumps in the energy system**

   Particularly in the Danish context towards a 100 % fossil-free energy system, while achieving 50 % wind power share in electricity generation already by 2020, it is vital that energy systems are "smart", flexible and efficient. By "smart" is meant that the flexible consumption is linked to the availability of supply from intermittent RES.

Numerous techno-economic studies suggest two alternatives of managing this balance with higher shares of RES, either by grid reinforcement (improving grid transmission capacity) or demand-side management (DSM), known as the "smart" concept of matching demand with supply. DSM methods have shown higher cost effectiveness [D. Bhatnagar et al., 2013, Energinet.dk, 2011b].

Within, DSM methods, several studies focus on the assessment of individual HPs potential as a resource in supporting high share of intermittent RES in the Danish energy mix indicate that HPs - even without the flexibility provided by heat storages − can contribute to *"increase wind power utilisation and reduce excess electricity production"* [K. Hedegaard and Heiselberg, 2012]. In 2012, Hedegaard et al. indicated that from 1.58 TWh to 1.46 TWh, i.e. 8 % of a system in 2020 with 16.5 TWh wind, were used by residential heat pumps. If additionally investing in heat accumulation tanks, moderately increased reductions are obtained (9-12 %). Furthermore, if instead investing in passive heat storage in the building thermal mass via the radiator emitting systems, equivalent larger reductions are achieved (12-19 %) [K. Hedegaard and Heiselberg, 2012].

In another study, Energinet.dk [Energinet.dk, 2011a] showed a prediction of the power balance during two weeks of high wind and sun production in 2050 (Figure 8). In this scenario, power is supplied by wind (17GW), sun (4GW), wave (1GW) power plants - marked with the red continuous line in Figure 8- while biomass and HPs (yellow area) secure 100 % of the thermal demand and electrical vehicles (EVs) (dark green area) 60 % of the electrified transportation. The total electricity annual production is estimated to be 80 TWh and the storage capacity of HPs and EVs 30-50 GWh. Furthemore, the interconnectors assure supply/demand balance. However, it can be seen by the number of periods with import values different than zero in Figure 8 (dark blue line) that the success of these methods in RES integration can only be partially provided by a mix of interconnectivity and flexible demand by means of HPs and EVs.

It is known that the performance of HPs and thus, their potential to provide demand-side flexibility is strongly dependent on external load conditions as well as end-users comfort needs [K. Gram-Hanssen, 2012]. For simplification, studies like these- at the energy system level- usually assume a constant coefficient of performance (COP) of the heat pump systems. It is therefore most relevant to consider real performance to better understand how to expand this flexibility.

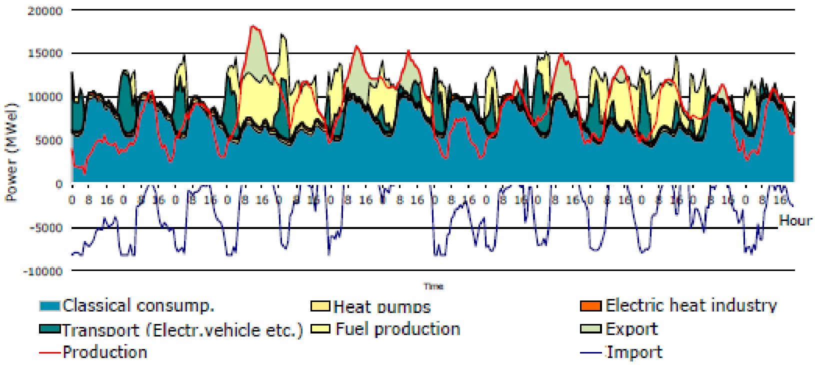

Fig. 8: Power balance in two weeks in 2050 scenarion in [Energinet.dk, 2011a]

Furthemore, these studies as well as national policies tend to think of domestic consumers as economic rational agents. This conceptualization of the residential demand can mitigate the envisaged outcomes of DSM methods as everyday practices and social contexts important factors in the domestic context are not taken into account [Christensen et al., 2013].

2. **Energy efficiency and flexibility optimization synergies: thermal storage and Low temperature power generators (LTPG)**

Although heat pump (HP) systems can provide heating, cooling and domestic hot water at high energy conversion efficiencies, also known as coefficient of performance (COP), it has been shown that synergies with other renewable energy based technologies can further improve both their COP and flexibility potential.

On the performance improvement aspect, different concepts of hybrid systems combining heat pumps with solar thermal systems exist and have proven their potential to enhance the heat pump systems performance [Hadorn, 2015].

On the other hand, other studies have focused on integration of thermal storage in heat pump systems with regard to both energy performance improvement and flexibility within the demand side framework [A.Arteconi, 2012, A. Floss, 2015].

Moreover, combined heat and power generation is the most efficient way to produce electricity with a small environmental footprint [Phent et al., 2006] and they maximize the integration of renewable energy sources in the energy system.

In domestic combined heat and power (CHP) applications, during the recent years, the Organic Rankine Cycle (ORC) has become increasingly popular. These systems are similar to HP systems using the same components (heat exchangers, turbomachinery – compressor or expander) but reversing the cycle to generate power. Although "reversible" HPs are not a novelty and have been considered since 1924, reappearing after the oil crisis of the $1970's$, the scientific body has recently showed increased interest to review and improve low capacity power generators (LCPG) [R. Almanza, 1998, Oliveira et al., 2002, M.Orosz et al., 2009, E. Georges et al., 2013].

In comparison with PV and HP systems, HP/ORC systems offer economic advantages, further potential for heat and electrical flexibility and similar or higher energy efficiencies [S.Schimpf, 2014, O.Dumont, 2015].

Finally, to extend their flexibility and thus, potential of RES integration, other works have addressed the DSM methods in the form of logic control strategies [A. Arteconi, 2013, S.H. Widder et al., 2013, A. Floss, 2015]. The objective parameters of these controls, in the case of HPs, tends to be the increase of flexibility by running costs reduction considering thermal comfort quantified by humidity levels, air quality and/or indoor temperature. The large amount of publications in these topics is echoed in the number of review papers [Shaikh et al., 2014b, B.Priya Esther, 2016].

3. Factors impacting the diffusion of heat pumps

Finally, within the framework of developing new technologies, it is important to call attention to the importance of external factors that dictate the adoption of new energy technologies. Low levels of dissemination of new technologies in the domestic sector might jeopardize the transition to sustainable energy systems.

A number of scientific and popular contributions have discussed this challenge [Kaur, 2012, K. Bettgenhäuser et al., 2012, Bergmann, 2013]. Despite the great energy performance of the domestic heat pump installations, the domestic consumers primary choice might not be a heat pump. The immediate challenge is the high installation costs [H. Singh, 2010]. Yet, some national markets have demonstrated that factors like national policies, complex historical processes, the complexity of the technology and the civil society shape the number of units sold in a country [S. Nyborg, 2015]. The holistic approach of these studies intends to identify issues and challenges for the large deployment of heat pumps and, in general, new energy technologies. Subsequently,

> they propose new mechanisms that are expected to provide some impetus to the heat pump market growth. These range from stable policies, suitable building regulations, to craftsmen education and user-involvement. In addition, they also call special attention to the aforementioned interaction between the heat pumps and the everyday practices in households.

This thesis seeks to incorporate the most promising mechanisms to the best of authors' knowledge based on the above literature review. In sum, the hypothesis is that combining these different state-of-the-art mechanisms to improve energy efficiency and increase flexibility in single-family buildings: intelligent HP operation, optimal integration of heat storage with the HP and power generation from thermal energy will become a key instrument for reaching extreme penetration levels for intermittent renewables.

1.3 Objectives

The overall objective of this work is to unveil a new type of bulk electricity and thermal storage heat pump technology to support renewable energy integration while improving the residential thermal supply system efficiency.

Developing such a novel technology includes primarily technical advances. Yet, economical and business-oriented aspects are also essential for the uptake of new technologies in the domestic sector. Thus, this issue is also briefly explored in this thesis.

From a technical point of view, it is a goal of the project to examine how HP systems are configured and operate under real-life conditions. Following this, the novel integrated residential energy system solution is modelled and developed at component and system level.

From the economical and business oriented-perspective, competitive investment, operating and maintenance costs as well as promising policies and regulations are discussed to support market development.

1.4 Research questions

The state-of-the-art and the objectives of this work are used to form the research questions which this thesis seeks to answer. The questions are made such that they address end-users and future sustainable energy system stakeholders' needs and electrical grid interaction requirements. These needs and requirements were presented in the Motivation section.

- **Research question 1:** *How much can the single family dwellings' consumption contribute to the future energy system renewable energy integration without compromising comfort needs?*

- **Research question 2:** *Which low capacity power generator (LCPG) should be implemented and developed? Why? And How?*
- **Research question 3:** *How to optimize the interaction between HP2Grid system components for energy efficiency, especially considering thermal storage? And is that, also, the best control strategy for smart grid integration?*
- **Research question 4:** *What are the estimated benefits and costs of the HP2Grid concept at local and national level?*

1.5 Overview of contributions

This section reveals an overview of the main contributions of this thesis, which are embodied in a total of 11 articles. The articles are branched in four main topics, which answer the research questions, respectively:

1. Role of residential heat pumps in the energy system: 3 articles
2. Design of novel concepts: 2 articles
3. Modelling the HP2Grid system: 4 articles
4. HP2Grid concept development: 2 articles

Each article is presented with a brief summary. A detailed summary of the content is provided in Chapter 2.

1. Role of residential heat pumps in the new energy system

The three papers under this topic report on monitored heat supply, power demand and coefficient of performance of residential heat pumps(HPs) installed in single-family houses in Denmark. The goal is to examine the current energy efficiency of domestic HP units, their potential for power wind integration and flexibility available of residential energy demand under real-life conditions.

Paper 1

Title: Smart Grid enabled Heat Pumps: an empirical platform for investigating how heat pumps can support large-scale integration of intermittent renewables

Authors: Carolina Carmo, Nina Detlefsen, Mads Pagh Nielsen
Published in: Journal Energy Procedia, Vol.61, 2014, p. 1695-1698

In Paper 1 [C.Carmo et al., 2014], the fit between domestic heat pumps power demand and wind power supply is studied. A novel simple parameter, the so-called wind friendliness coefficient (WF), is introduced to assess the potential of demand-side managament (DSM) tools. The analysis is based on hourly power consumption gathered over a period of up to 3 years for 283 residential heat pumps installed and operating in Denmark and wind power production data.

Paper 2

Title: Cluster analysis of residential heat load profiles and the role of technical and household characteristics

Authors: Carolina Carmo, Toke H. Christensen
Published in: Journal Energy and Buildings,Vol.125, August, 2016, p.171-180

Paper 2 [C.Carmo and Christensen, 2016] assesses the potential for demand-side management in residential space heating demand. This paper uses data mining techniques to identify typical space heating demand profiles in single-family homes and explores their associations with building and household characteristics.

Paper 3

Title: Empirical Platform Data Analysis to Investigate How Heat Pumps Operate in Real-Life Conditions

Authors: Carolina Carmo, Brian Elmegaard, Mads Pagh Nielsen, Nina Detlefsen
Published in: Proceedings of the 24th Int. Congress of Refrigeration (ICR2015), International Institute of Refrigeration IIF/IIR, Yokohama, Japan, August 2015

In the same line as Paper 1, Paper 3 [C.Carmo et al., 2015a] is an analysis based on operational data of heat pumps installations in residential buildings. The focus is a benchmarking study of heat pump installations in single-family houses in Denmark. Results of a statistical analysis on the different types of configurations, their heating capacity and the most common thermal storage solution are presented. Also results on average operating temperatures and seasonal performance factor (SPF) are shown. In addition, the flexibility potential of heat pumps in terms of shifting the time of energy use are presented.

2. Design of novel concepts

This topic focus on the state-of-the-art developments of heat pump technology to answer the *research question 2* and on giving an overview of the emerging micro combined heat and power (μ- CHP) technologies. Furthermore, the main barriers for market diffusion are identified and a change of the regulations is proposed to streamline the incorporation of renewable energy based technologies in the residential sector.

Together with topic 1, the findings of these papers are used as guidelines for the development of the novel heat pump concept in terms of relevant components, relevant control logics and, more briefly, it also introduces contexts to ensure effective market diffusion of novel μ- CHP technologies.

Paper 4

Title: Smart Dual-Mode Heat Pump With HP2Grid Functionality To Support Large-Scale Integration Of Intermittent Renewables

Authors: Carolina Carmo, Morten Boje Blarke
Published in: Proceedings of the 3rd Int. 100 % Renewable Energy Conference (IRENEC2013), Istambul, Turkey, June 2013

Paper 4 [C.Carmo and M.Blarke, 2013] describes the overall concept of utilizing Heat Pumps (HPs) as a resource for RES integration and, thus as a resource of the future energy systems. The focus is to give an overview of the state-of-the-art developments of the heat pump system components and its role in the future smart grids. The system components discussed are working fluids, heat exchangers, thermal storage, control strategies and organic Rankine cycle coupling to enable cogeneration by thermal energy conversion to electrical energy. In sum, it briefly introduces the heat pump to grid (*HP2Grid*) concept, materialized in the form of the novel cogeneration concept heat pump/organic Rankine cycle unit.

Paper 5

Title: Assessment of Emerging Renewable Energy-based Cogeneration Systems for nZEB Residential Buildings

Authors: Carolina Carmo, Olivier Dumont, Mads P. Nielsen, Brian Elmegaard
Published in: Proceedings of the 12th REHVA World Congress (CLIMA2016) , Aalborg, Denmark, May 2016

Paper 5 [C.Carmo et al., 2016a] puts the novel cogeneration concept, heat pump/organinc Rankine cycle unit in perspective. It gives an overview of state-of-the-art developments on novel micro combined heat and power (μ- CHP) for single-family house applications to enable nearly Zero Energy Buildings (nZEB). Four main technologies are considered in this review: fuel cells, photovoltaic thermal, solar thermal reversible HP/ORC and cogeneration thermoelectric generators. Additionally, it discusses the strengths and weaknesses of these technologies in order to identify disruptive strategies to stimulate the diffusion of μ- CHP technologies in the residential sector.

3. Modelling the HP/ORC system

The four papers of this topic describe the models developed to mimic the dynamic performance of the innovative ground source HP/ORC system integrated in a passive single-family house with a solar thermal collector. These models enabled the annual performance analyses made. At the same time, they were used to further develop the HP2Grid concept discussed in the articles from topic 4.

Paper 6

Title: Simulation of a passive house coupled with heat pump/organic Rankine cycle reversible unit

Authors: Olivier Dumont, Carolina Carmo, François Randaxhe, Sylvain Quoilin, Vincent Lemort
Published in: Proceedings of the 9th Int. Conference on System Simulation in Buildings (SSB2014), Liège, Belgium 2014

An underlying assumption in Paper 4 is that heat pump systems coupled with solar collectors and converted to low-temperature heat recovery systems can enhance the potential for RES integration in the energy system. Based on this, Paper 6 [Dumont et al., 2014b] presents the dynamic model of a novel ground source heat pump/organic Rankine cycle (ORC) system for residential building applications. Results of the operation of the unit in three characteristics days of the year (winter, spring/fall and summer) are reported with two different storage temperature set-point control strategies.

Paper 7

Title: Performance of a reversible heat pump/organic Rankine cycle unit coupled with a passive house to get a Positive Energy Building

Authors: Olivier Dumont, Carolina Carmo, François Randaxhe, Sylvain Quoilin, Vincent Lemort
Published in: Journal of Building Performance Simulation (in review)

Paper 7 [Dumont et al., rev] is an extended version of Paper 6, which was selected for journal publication. In Paper 7, the annual performance of HP2Grid system results are assessed as well as running costs. Additionally, a sensitivity analysis of the system under different climates, insulation materials and occupant behaviour is discussed and a performance comparison between the HP/ORC unit and the conventional combination of HP and photovoltaic panels is made.

Paper 8

Title: Hot water tank: How to select the optimal modelling approach?

Authors: Olivier Dumont, Carolina Carmo, Rémi Dickes, Emeline Georges, Sylvain Quoilin and Vincent Lemort
Published in: Proceedings of the 12th REHVA World Congress (CLIMA2016), Aalborg, Denmark, May 2016

Paper 8 [Dumont et al., 2016] is the background of paper 6. It discusses different hot water tanks modelling approaches and develops a flow chart for the selection of the right model choice.

Paper 9

Title: Experimental Validation of a Domestic Stratified Hot Water Tank Model in Modelica for Annual Performance Assessment

Authors: Carolina Carmo,Olivier Dumont, Brian Elmegaard, Mads Pagh Nielsen, Nina Detlefsen
Published in: Proceedings of the 3rd Int. Seminar on ORC Power Systems (ASME ORC 2015), Brussels, Belgium, October 2015

To support the findings in papers 6, 7 and 8, paper 9 [C.Carmo et al., 2015b] shows the validation of the stratified hot water tank model in Modelica.

4. HP2Grid concept development

The HP2Grid concept is explored in the two papers of this topic. This topic is an extension of the findings in topic 1 in terms demand-side management employment in the future energy systems utilizing residential supply systems as well as an amplification of topics 2 and 3 in terms of defining the potential of the new HP2Grid system to support them.

Paper 10

Title: Performance comparison of two types of technologies associated with a positive energy building: a reversible heat pump/ORC unit and heat pump coupled with PV panels

Authors: Olivier Dumont, Carolina Carmo, François Randaxhe, Sylvain Quoilin, Vincent Lemort
Published in: Proceedings of the ISES Solar World Congress (SWC2015). International Solar Energy Society, ISES, Daegu, South Korea, November 2015

The promising results from Paper 6 and Paper 7 give the motivation for the investigation made in this paper. Following the discussion of the innovative HP2Grid concept and the development a dynamic model of the system, Paper 9 [C.Carmo et al., 2015c] focus on comparing the annual performance of this novel concept (HP/ORC) with a more conventional energy supply system solution for residential buildings, a ground source HP coupled with PV system (HP+PV). A study of influence at 5 different climates is performed.

Results are given in terms of gross electrical production, net electrical production, running benefits and self-consumption and - production rates.

Paper 11

Title: Performance Evaluation of a HP/ORC System with Optimal Control of Sensible Thermal Storage

Authors: Carolina Carmo, Mads Pagh Nielsen, Brian Elmegaard, Olivier Dumont
Published in: Purdue Conferences, 4th High Performance Buildings, West Lafayette, Indiana, USA, July, 2016

Paper 11 [C.Carmo et al., 2016b] addresses one of the barriers to accommodate RES in the residential energy use. It focuses on simulating the HP2Grid system dynamics and performance with real load control logics. Four different controls are tested. These controls are characterized by considering the actual load conditions of the thermal supply system.

2 Summary of contributions

This chapter summarizes the main contributions of the 11 papers that are included in this thesis. For further details, the reader is encouraged to refer to the actual papers.

2.1 Role of residential heat pumps in the new energy system

This section addresses *research question 1*, which is concerned with assessing the potential of the domestic heating demand to support the future of energy systems.

Heat pumps to make up to 80 % of the residential demand flexible

In order to enable reliable energy systems with intermittent energy sources, the demand-side management is expected to play a crucial role of activating demand when supply is available. The realization of this new role of the demand depends on its flexibility, i.e. the ability to shift energy demand to periods of energy supply availability. In this work, to study the potential to activate this flexibility, the operation of residential heat pumps (HPs) providing both space heating (SH) and domestic hot water (DHW) - which represent up to 80 % of households energy consumption in EU-27 - is examined based on monitored data of residential HP installations all over Denmark.

In Figure 9, the results of the methodology employed in Paper 1 [C.Carmo et al., 2014] are shown. To assess the potential of wind integration in the residential heating demand, the normalized power demand of a residential HP - in relation to maximum power demand during 2012 - is compared with the normalized wind power - in relation with the maximum wind power supply in whole Denmark in 2012. The data is shown for every hour of the year. It can be seen that the HP power demand is higher mostly at the beginning and end of the year. This corresponds to colder months. On the other hand, the wind power supply is distributed equally over the year with a random cyclic behaviour. It is characterized by periods of high wind power followed by periods of low wind power availability.

In the same paper [C.Carmo et al., 2014], to further understand the flexibility requirement, the wind friendliness indicator (*WF*) is introduced. It is simply defined as the difference between the normalized wind power production and the normalized HP power demand. The indicator ranges from -1 to 1, where negative *WF* values indicate the need for shifting the demand to a period where *WF* is positive (Figure 10). Although *WF* does not represent effective values of power balance need, it gives an indication of when and how to avoid grid congestion and increase the integration of wind power in the energy mix.

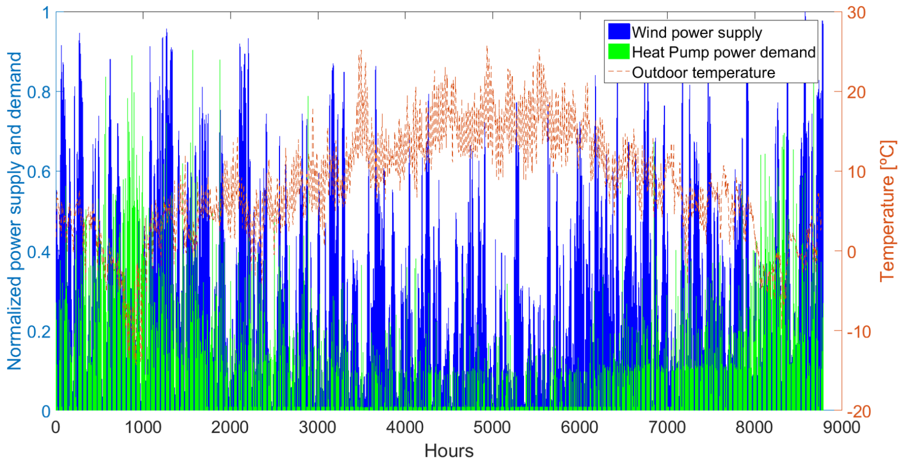

Fig. 9: HP power demand vs. wind power supply

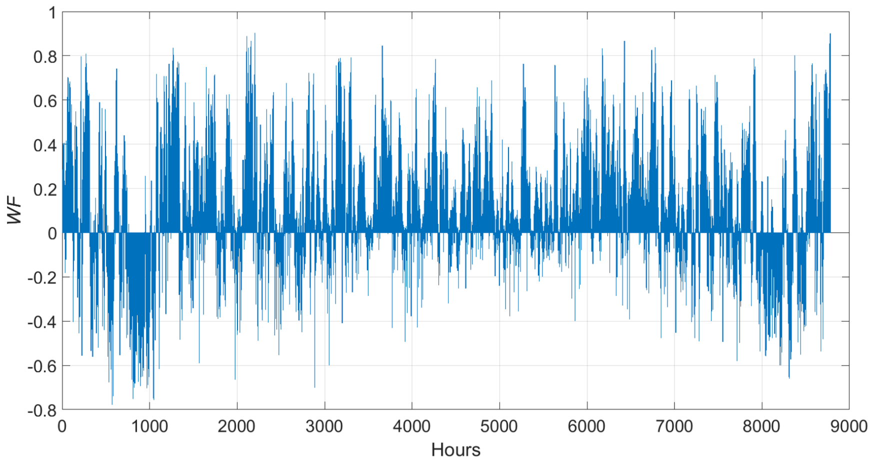

Fig. 10: Variation of wind-friendliness (*WF*) during 2012

The same analysis was made for 6 different types of HP installations, grouped by heat source (air (*AW*) or ground (*BW*) source) and heat emitting system (radiators (*Rad*), floor heating (*FH*) or combined (*combi*)). The results are summarized in Figure 11 and indicate that 70 to 80 % of the hours in a year the HP power demand should not represent an extra stress to the Danish electrical grid with high shares of wind power. Additionally, results revealed that, depending on the HP type, around 50 % of the negative *WF* occur during unoccupied periods, in other words, periods when inhabitants are not at home (from 8 AM to 7 PM). Hence, if controlled adequately HP installations in households could further support the integration of wind energy. In sum, it can be expected that this match between heat pump power consumption and wind power availability will support the progressive increase of intermittent renewable power in the Danish energy system by 2050 and that active control will be able to avoid eventual unbalance problems.

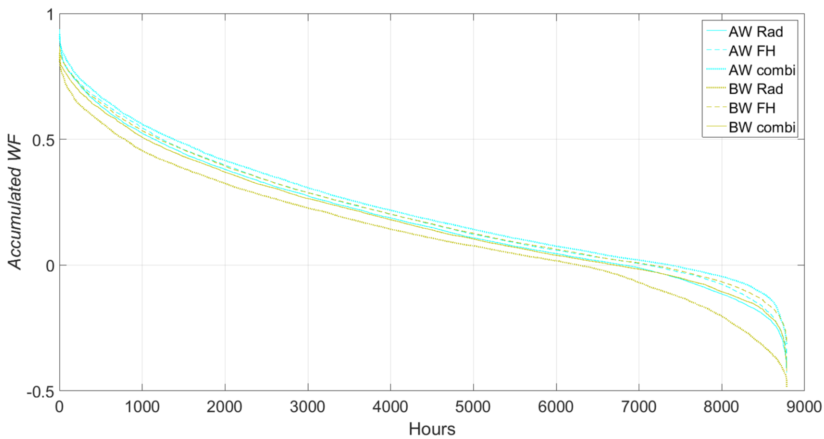

Fig. 11: Accumulated *WF* during 2012 for the 6 different HP installations

Finally, looking at the frequency of consecutive positive and negative *WF* one can have an indication of the expected flexibility needs in terms of duration. In Figure 12, it is shown that 30 % of the around 1800h when *WF* is negative remain negative for not more that 3h. Contrarily, the frequency of consecutive positive is dispersed and can go up to several hundreds of hours where no energy shift is needed. This suggests that the flexibility needs in terms of duration are not expected to exceed 3h in most periods of a year and that, most likely, HP installations coupled with the thermal mass of the building and hot water tank can provide this flexibility.

This example prepares the ground for the opportunity of activating advanced controls to allow domestic SH and DHW demand - provided by the HPs - to be put forward or postponed according to the circumstances. In

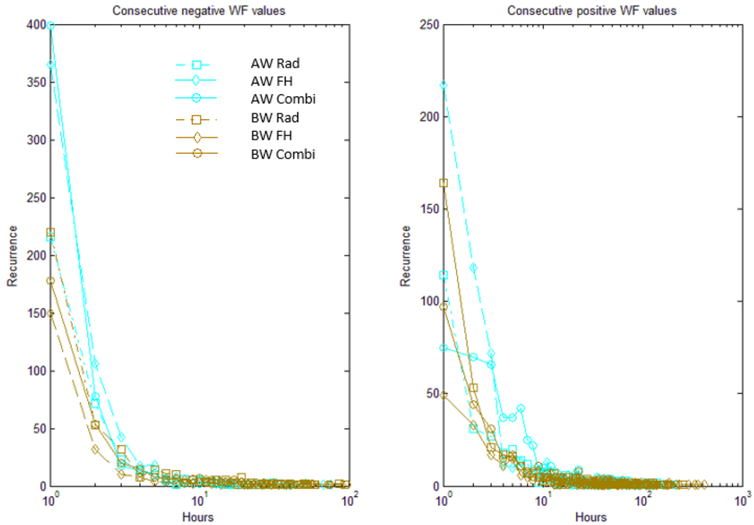

Fig. 12: Frequency of consecutive negative and positive *WF* during 2012

other words, to activate demand-side management (DSM) methods in the domestic sector.

Yet, the mentioned flexibility and the ability to provide future energy system stabilizing ancillary services through deployment of DSM methods appeal to awareness on the associations between residential heating time-patterns socio-technical characteristics of the households to ensure that inhabitants thermal comfort is not disturbed. This is studied in Paper 2 [C.Carmo and Christensen, 2016] by using data mining methods of space heating hourly profiles combined with social and technical data of the characteristics of the households. The study shows that hourly space heating load profiles in single-family dwellings equipped with heat pumps exhibit less diversity compared with electricity patterns for lighting and appliances in households. The space heating load profiles with heat pumps are mainly driven by buildings characteristics (age, floor heated area and heat emitting system) and external conditions. This points that space heating temporal patterns are less closely linked with the household members' daily activities, than electricity used for other appliances in households.

Figure 13 shows the two main clusters identified for both weekdays and weekends and across three different load segments (high, medium and low demand). The most common cluster (Cluster 1)- both in high and medium load segments - has a relatively constant load profile, i.e. with small variation during the day, while the other cluster (Cluster 2) has a more distinct variation. The latter is characterized by a sharp morning peak, low mid-day demand and increasing demand during the afternoon/evening. It can be inferred by the regression results that older single-family dwellings relate to Cluster 1 and that each increase in square meters in the house area also increases the odds of the load profile to be similar to Cluster 1. No clear correlation between the heat emitting system type and the space heating profiles was found in high load segments. Still, the heat emitting system, radiator or floor heating systems, are found to be significant variables in medium and low load segment. Dwellings equipped with radiator systems are positively correlated with Cluster 1 in the medium load segment. Yet, in low load periods, they are associated with Cluster 2, while floor heating systems are positively associated with Cluster 1. The nature of radiator systems - normally equipped with manual thermostats which can be easily manually regulated according to weather transitions - might explain this. In the case of floor heating systems, the invariability of demand in low load segments could be related to their circulation pumps, usually running all-year-round.

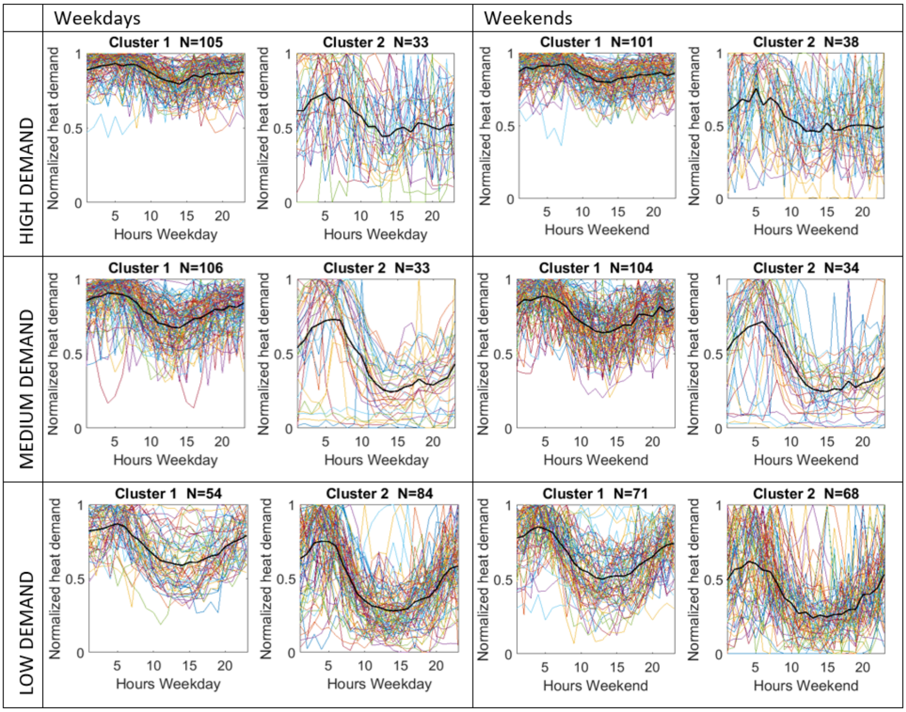

Fig. 13: Normalized heat load profiles of the three baseline load segments

Besides the building characteristics, two socio-economic household characteristics showed to be significant to explain differences between space heating profiles. Teenagers effects are evident peculiarly in high load periods and younger children are more noticeable during medium load segments.

The household variable number of teenagers is associated with Cluster 1, which points that a higher and constant space heating load is expected in dwellings with teenagers. On the other hand, the number of children is also associated with a larger demand in the morning (Cluster 2) in the medium load segment. This morning peak might be related with the fact that households with small children are more likely to have fixed schedules when all family members leave the home.

This knowledge reinforces the hypothesis that residential space heating demand can be flexible and that DSM methods are viable while considering the inhabitants comfort. Additionally, these results can contribute to the development of strategies and technical solutions tailored to specific groups of households with similar social and building characteristics. Particularly, newer buildings with high thermal inertia emitting systems present a one peak in their daily space heating demand profile. This reveals that the heat demand is concentrated in the morning and released continuously during the day and thus, it unfolds a flexibility potential. This peak could be shifted to another time of day according to the conditions. Nonetheless, this flexibility might be limited by household characteristics, like existence of teenagers and children.

Heat pumps to improve domestic energy efficiency

The implementation of sustainable energy systems implies not only the increment of the local renewable energy sources in the energy mix, but also higher energy conversion efficiency to ensure the best use of renewable energy sources. Thus, following Paper 1 [C.Carmo et al., 2014], Paper 3 [C.Carmo et al., 2015a] assesses the performance of heat pump installations in single-family households in terms of energy efficiency conversion based on monitored operational data between 2012 and 2014. Results of this analysis show that residential HP installations performance varies widely with the outdoor conditions, as exemplified in Figure 14. However, they can perform as recommended by the Danish Energy Authority [Aggerholm, 2013] to achieve the energy goals with seasonal performance factors (SPF) ranging from 2.4 to 3.5 depending on heat source, heating emitting systems and installed capacity . Yet, proper sizing of these units is vital to ensure that they fulfil the requirements in terms of energy efficiency as well as in the realization of flexible alternative sources of balance in the power grid. The results report that unsuitable sizing, specially under-sizing, can jeopardize the expected energy efficiency performance.

Additionally, supplementary lessons learned from the systems studied in Paper 3 [C.Carmo et al., 2015a] are listed below:

- The configurations of residential HP installations vary in terms of the heat source (air and ground) and heat distribution system (radiators,

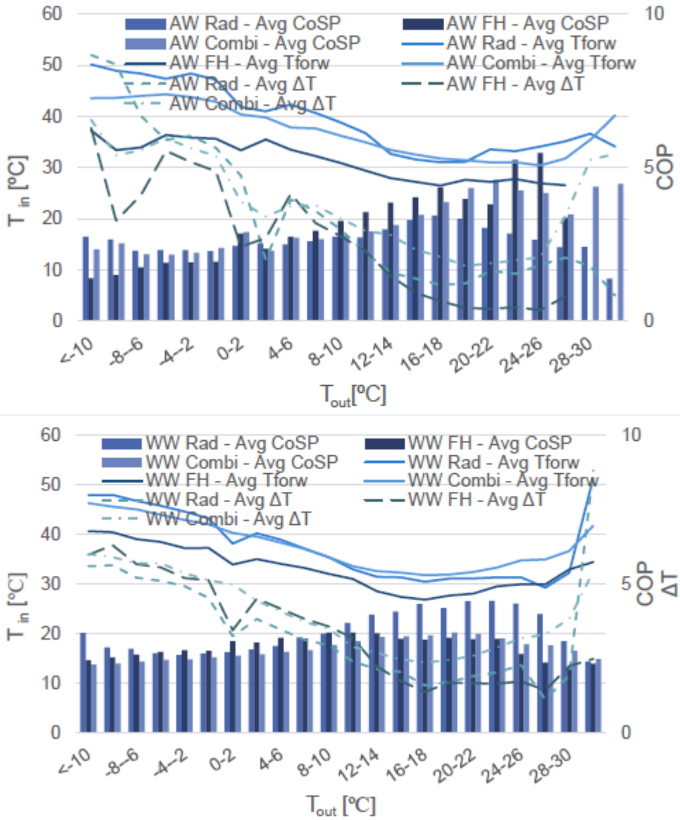

Fig. 14: Average forward temperature (T_{in}) in the heating circuit, ΔT and coefficient of performance (COP) at different outdoor conditions (T_{out})

floor heating and combined). The most common installation type in the sample studied is ground source heat pumps (80 %). While, in regards to the emitting system, 63 % of the houses combine radiators with floor heating systems - usually the floor heating loop is limited to the bathroom area;

- It was found that all the heat pump installations considered are equipped with hot water storage tanks. Four different design configurations were identified, as illustrated in Figure 15. Units equipped with two sensible thermal storage tanks, one for domestic hot water (DHW) and another for space heating (SH) -supply design 4, present higher performances, followed very closely by double mantle tanks -supply design 2- and tanks for exclusively DHW -supply design 3- than other system configurations (buffer tanks for SH and DWH);
- There seems to be no clear relation between the installed HP heating capacity and hot water storage volume, and the expected building heat demand;
- Along these lines, the load time-shifting potential of residential HP units coupled with sensible storage in the form of hot water tanks varies between 2 and 22 hours depending on the ambient temperature and installed heat capacity (Figure 16).

An example is used in Figure 17 to illustrate the two last supplementary lessons. This figure presents the relationship between installed HP capacity, daily ON hours, number of HP starts and average duty cycle (adc) of an on/off controlled HP installation as well as the heat demand of the building and indoor temperature at different outdoor temperatures. The HP installation, in the example, is a ground source unit coupled with both radiators and floor heating.

When sizing HP units capacity, installers are recommended to calculate it based on the following: *"the capacity of the unit should match 80 % of the building heat demand to mantain an indoor temperature of 20°C at a specific design temperature (-12°C in Denmark)"*. This was the case until March, 2013, when a new normative for heat supply systems was introduced [Dansk Standard, 2013]. This new normative indicates that small heat pump installations (<20kW) should be dimensioned to cover 100 % of the building space heat demand at -7°*C*, also known as the balance point. If the outdoor temperature is lower than the balance point, an auxiliary electrical or gas heater should supply the remaining demand. On the contrary, when the outdoor temperature is higher than the balance point, the on/off controlled heat pump will be operating in its cycling region. In this region, the number of start increases but the adc decreases and thus, the daily ON hours decrease.

However, as shown - and the general trend in the systems studied - indicated that the recommendations are not always respected. In Figure 17, it is

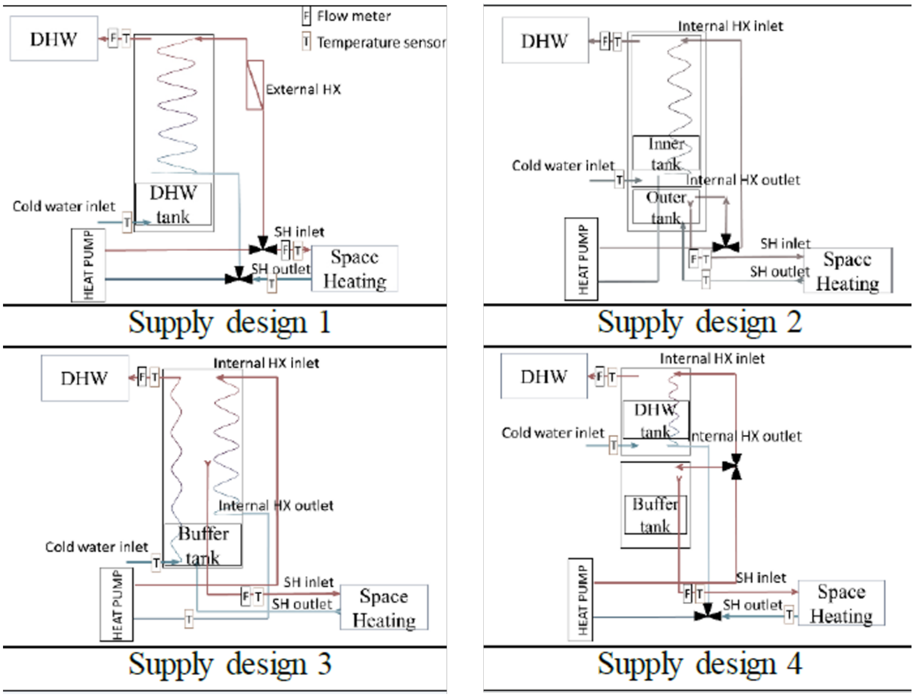

Fig. 15: Hydraulic diagrams of the different HP units configurations in regard to hot water storage tank

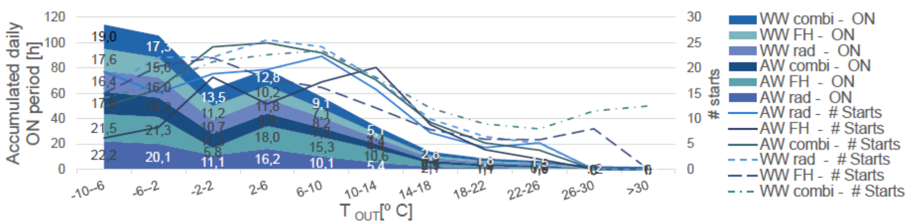

Fig. 16: Operating hours and number of starts according to the outdoor temperatures

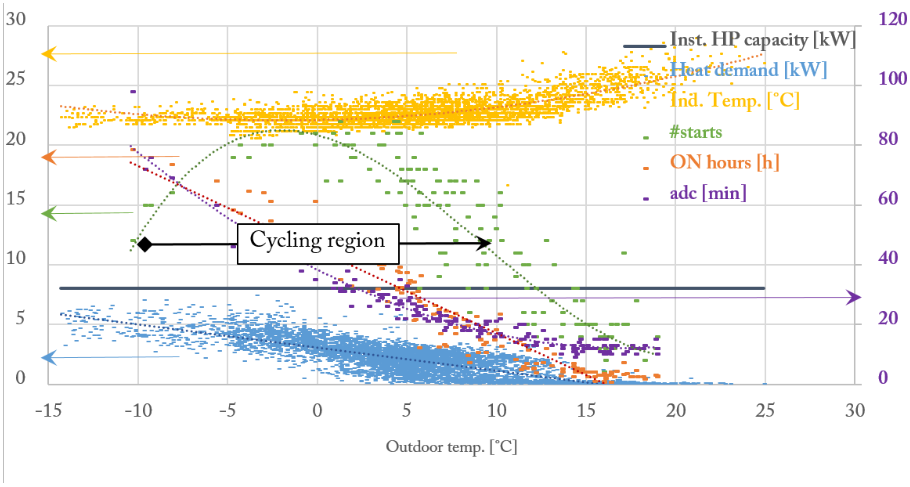

Fig. 17: Installed HP capacity, building heat demand,indoor temperature, ON daily hours, number of starts and average duty cycle (adc) of a single-family house in Denmark [180 m^2 household composed of two adults and built in 2010]

shown that, despite the recommendations, the installed HP capacity (8kW) is higher than the building heat demand at any of the operation conditions, which yields to an increase number of HP compressor starts (cycling region between -10°C and 10°C). Yet, this does not seem to affect negatively the COP and the heat pump unit is capable of delivering the heat required maintaining the indoor temperature at >20°C all-year-round. On the other hand, the number of starts and the COP factor decreases at an outdoor temperature of around 18 °C (Figure 14). This is due the nearly zero building heat demand at those temperatures. After all, the heat pump operates exclusively to supply occasional domestic hot water but this energy is delivered at high temperatures which de-gradates the energy efficiency.

Finally, the average duty cycle (adc) and daily ON hours of the unit give an indication of the flexibility - in terms of duration - that the residential heat pump units can provide. The duration of each on/off cycle, here called duty cycle, varies between 9 and 98 min with more or less number of starts to match the heat demand. This turns out in a hourly potential to shift energy consumption.

In conclusion, outdoor conditions and installed capacity affect both the energy conversion efficiency as well as has the flexibility potential of residential HP installations which can vary from 2h to 23h in terms of duration. This fulfils the expected flexibility needs to ensure the vital balance in the power grid according to the results from Paper 1 [C.Carmo et al., 2014]. With respect to energy efficiency over-sizing of residential heat pumps capacity is preferred than under-sizing.

Like discussed in the introduction chapter, there have been and still are attempts to forecast the future of energy systems by assuming scenarios of the mix of the energy sources, technologies employed and consumption levels. However, the discussion of flexibility potential in this thesis is purposely limited to duration terms. This is because, it has been witnessed that the absolute values in terms of the amount of energy that can be shifted depend on several unexpected and unregulated factors.

Firstly, as identified in the studies presented above, the flexibility depends on the heat pump capacity installed and the heat demand of the building, which ultimately are driven by end-users and/or installers preferences.

Secondly, at the energy system level, these predictions are expected to be less realistic when stable framework conditions of energy systems can no longer be assumed, as it has happened in the recent years with successive energy policy changes. Not only driven by fossil fuel free policies, but closely related to the liberation of markets formerly monopolized.

2.2 Design of novel concepts

This section debates *research question 2*. It introduces the latest developments within heat pump (HP) technology and argues possible improvements related to energy efficiency and increase of renewable energy integration. The concept of combined heat and power based on the heat pump technology coupled with a low capacity power generator (LCPG) is suggested and set side by side with similar solutions in the domestic context. In addition to that, it discusses a set of factors and perspectives that need to be taken into account when introducing new energy appliances in the domestic sector.

Heat pump technology is improving

Compression HP is a mature technology and the most efficient form of electric simultaneous heating and cooling. HPs deliver two to four times more thermal energy for heating than the equivalent amount of electrical power they consume, and on the other side, they simultaneously deliver two to three times thermal energy for cooling. However, research efforts to maximize their performance are continuously increasing due to their role in the future energy systems, as explained in the previous section.

A review of the latest technical developments on this regard is presented in Paper 4 [C.Carmo and M.Blarke, 2013]. At the component level, it is concluded that new refrigerants should be considered for environmental, regulatory and energy conversion improvement. Furthermore, the introduction of variable speed compressors is also discussed. This feature allows to match the heat pump capacity with the building heat demand and eliminate the adverse effects of intense cycling and ease the power demand regulation of the HP units. However, it is found - based on previous studies - that this solution would only be competitive to the mature on/off control in retrofitting under-dimensioned HP units - units designed to cover less than 65 % of the peak buildings heat demand.

Secondly, at the HP system level synergies between solar collectors and HPs are encouraged with potential to improve the energy performance of the heat pump system.

Finally, at the energy system level, it is postulated that - apart from increasing the efficiency of HP units - the integration of thermal storage and coupling with the low-temperature heat recovery power generator technologies will increase the flexibility potential. Like this, highly efficient HP units will not only be able to supply the heating demand with high energy conversion efficiency but also to cover the electricity demand of households. Altogether, these developments pave the way for the introduction of the HP2Grid concept illustrated in Figure 18.

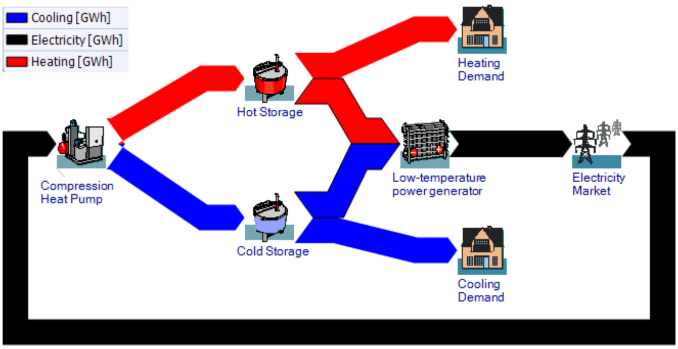

Fig. 18: Illustration of the preliminary HP2Grid concept

In practice, the novel HP2Grid concept is, in this work, defined as a slightly modified ground source HP unit - with a horizontal ground heat exchanger (HX). The scroll compressor of the HP unit is modified to allow the reversion of the cycle and a pump is added to the original HP unit. The reversible compressor and pump allow the unit to operate as an expander in an Organic Rankine cycle (ORC) mode and thus, generate electricity to supply the building. In addition, the reversible HP unit is hydraulically connected to a flat solar thermal collector installed with the roof of the building- in a hybrid solar collector roof solution. This ensures that the ORC unit is supplied with reasonably high temperature source (>70°C). In sum, the system can operate in three modes (see Figure 19):

- The normal **heat pump mode**, when the outdoor temperature is low and the building demands heating;

- the **direct heating mode**, when the roof temperatures are not high enough for starting the ORC (>70°C) and there is heating demand ;
- and finally, in **ORC mode**, in the absence of building's heating demand and high roof temperatures, to supply electrical power. The excess heat is then used to charge the ground source loop.

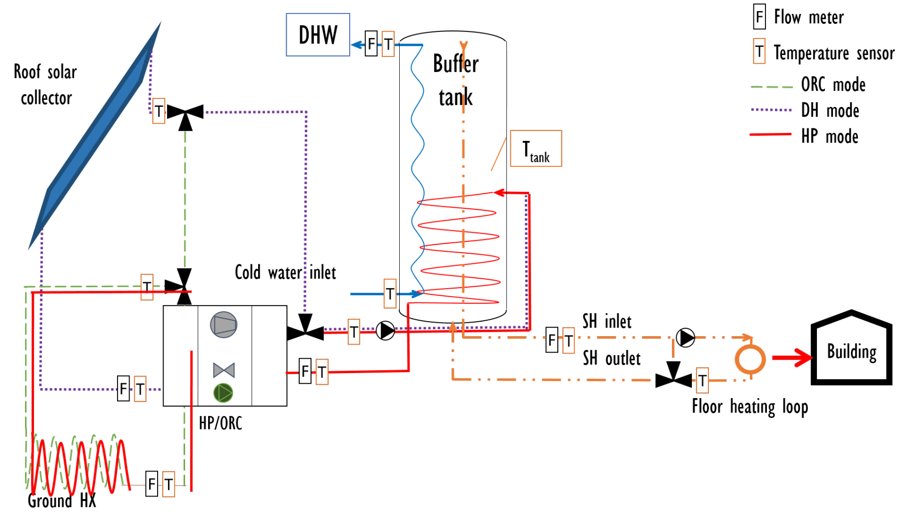

Fig. 19: Hydraulic scheme of the HP2Grid concept

What influences the diffusion of new combined heat and power (CHP) appliances in the domestic sector?

In the residential sector, cogeneration *"the process of producing both electricity and usable thermal energy (heat and/or cooling)"*, in particular, micro combined heat and power (μ- CHP) have proven to be superior to traditional systems, in total energy conversion efficiency [Phent et al., 2006]. Still, in the introduction of new energy concepts in the domestic sector, it is paramount to consider other perspectives than the technical state-of-the-art, such as economy and market context. In the previous section, it was revealed that the flexibility potential in the residential buildings sector depends strongly on the acceptance and diffusion of flexible appliances in the domestic heating market.

The study performed in Paper 5 [C.Carmo et al., 2016a] examines relevant drivers and barriers that determine the uptake of new cogeneration appliances. This is quite an ambitious task. Thus, this study is narrowed down to review case studies of analogous cogeneration units that can lead to delineate the appropriate conditions for the market growth of the HP2Grid concept (in Paper 5 [C.Carmo et al., 2016a] called solar thermal heat pump/organic Rankine cycle, HP/ORC).

A significant amount of experimental and modelling research has recently been presented on emerging micro combined heat and power (μ- CHP) technologies based on renewable energy sources. Based on the state-of-the-art review and the technology readiness level, four main technologies are considered in Paper 5 [C.Carmo et al., 2016a]: Fuel Cells (FC), Photovoltaic thermal (PV/T), solar thermal reversible heat pump /organic Rankine cycle (HP/ORC) and cogeneration solar Thermoelectric generators (TEG). Figure 20 emphasizes the wide variety of electrical and thermal conversion efficiencies that can be found in emergent μ- CHP domestic units. The reader is referred to Paper 5 [C.Carmo et al., 2016a] for a more elaborated description of these technologies operation principles and characteristics.

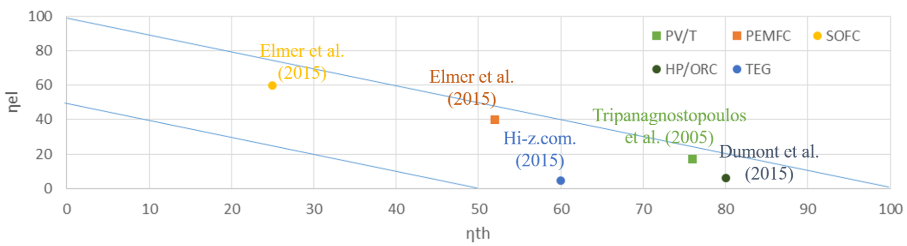

Fig. 20: Representative electrical and thermal efficiency for each μ- CHP unit

Less extensively, a market research in terms of investment, operation and maintenance costs of novel domestic cogeneration units has also been done. Yet, it should be noted that it is quite daunting to make a conclusive techno-economical comparison of these technologies due to their small market development. Thus, the results presented in Paper 5 [C.Carmo et al., 2016a] on current investments costs are considered preliminary.

Following, 6 key performance indicators gave the framework to guarantee the diffusion of new energy supply technologies in homes. The parameters chosen reflect house-owners essential criteria to acquire a new heating appliance to their home. These criteria are: reliability and energy efficiency, climate protection, low operation costs, user-friendliness and low maintenance. Figure 21 illustrates the scores of the different μ- CHP technologies with respect to these parameters.

In general terms, this study argues that technical, economical, market conditions as well as end-user preferences are vital to the suitable introduction of novel energy technologies in the domestic sector. Subsequently, the study demonstrates the compatibility of μ- CHP based on renewable sources - which have a diversified electric to thermal supply ratio (Figure 20) - with

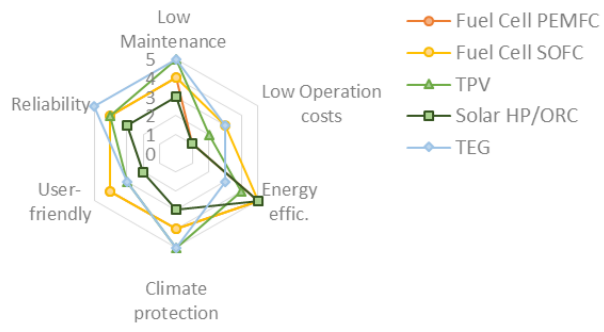

Fig. 21: Radar chart showing the rating of each μ- CHP unit for the most relevant criteria for residential end-users acceptance

the different shares of thermal and electricity demand found in the domestic sector in EU-27 (Figure 22). In addition, due to their low maintenance, reliability and climate protection nature when compared to well-established cogeneration technologies (like internal combustion engines), they are undisputed winners in the realization of house-owners requirements when thinking about their home energy supply technology.

However, and specially with respect to the prospects of the HP2Grid concept, the study suggests that a set of conditions need to be in place to establish its acceptance and diffusion. The immediate answer is the reduction of upfront installation costs (represented in operation costs in the radar chart). Yet, other mechanisms have proven to trigger the dissemination of novel and costly technologies:

- Implementation of financial incentives from governments (subsidies, dedicated tariffs by tax reduction) and/or utilities (loans,feed-in tariffs);
- Stable regulations and policies that favour and ensure the correct sizing and installation of renewable energy based appliances;
- Business model reorientation to allow the end - user to purchase high quality energy services. These innovative business models require a energy service company (ESCO) to own the costly energy supply appliances and guarantee its optimal operation. The revenue streams of the ESCOs depend on the optimal management of existent feed-in tariffs and/or dedicated tariffs;
- Expansion of sales and distribution channels. Use of well-established energy suppliers and online channels.

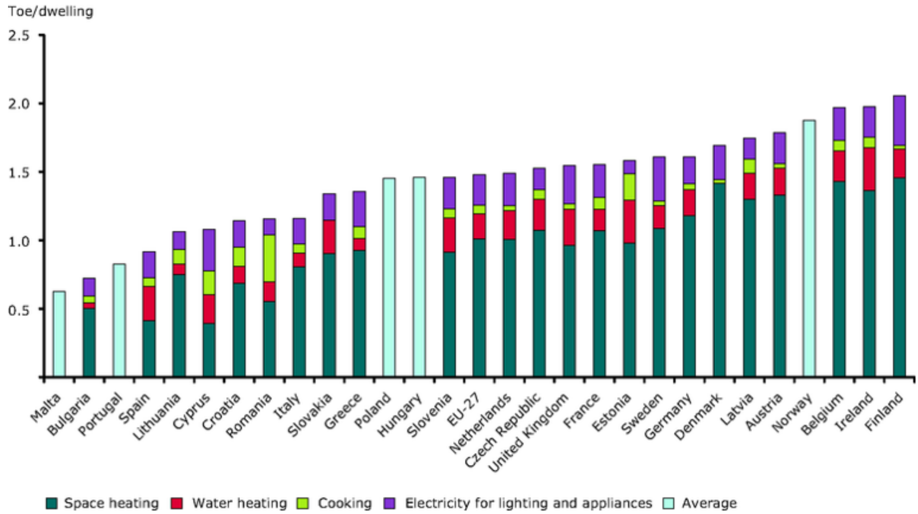

Fig. 22: Diversity of household energy consumption by end-use in EU-27 [EEA, 2012]

2.3 Modelling the HP2Grid concept

In this section, the model of the HP2Grid concept, materialized in the form of a solar thermal ground source HP/ORC system is described and discussed in detail. The model includes several sub-models such as the HP/ORC unit, the building,the ground and solar energy collectors and the thermal storage tank. The model also takes occupation behaviour and climate into account. Collectively, the section constitutes the backbone of *research questions 3* and *4*. The simulation model is developed in Dymola environment based on Modelica language. The selection criteria for the simulation tool is discussed in Paper 7 [Dumont et al., 2014b], sub-section 2.1.

Model boundaries and complexity selection

Simulation models are developed to be fast and cost-effective tools to mimic the system performance as close to the real system performance as possible. They can be used for several purposes: components of a system improvement, energy performance of a system studies, operation costs assessment, among other applications. In the development process of a model, the developer needs to answer two key questions:

- What are the system responses (outputs) and specific controllable variables and other disturbances (inputs) to be studied?
- What parts of the system need to be modelled in order to predict these responses with tolerable accuracy?

The answers to these questions will frame the boundary level of the system and the level of model complexity needed, respectively.

In other words, the model selection is determined by the general objectives and required accuracy. The accuracy of the prediction very often is related with the level of complexity of the model. However, complex models are computational resourceful and time demanding. Therefore, the model selected should be as simple as possible without losing the capability to capture the responses of the real system with satisfactory accuracy. Considering a good compromise between complexity and accuracy, Figure 23 shows the most common model types for different types of analyses applied to heat pump systems [Lundqvist, 2011].

The boundary level should be limited to the component level when the aim of the study is the performance of a new component. For example, to study the behaviour of a heat exchanger when subject to different boundary conditions. With regards to the complexity level, if the aim is to calculate the performance at a specific range where grey box models and black box models are available, they should be used due to their simplicity. However, if the aim is to test the component performance out of the identification data set (experimental data) both white box and grey box models are recommended. They require some prior knowledge of the system and parameters with a physical meaning but they yield to an accurate component performance evaluation out of the measured range. Another type of analysis example could be, the calculation of energy consumption and supply of a new system. For instance, for heat pump systems several black models, in the form of data sheets provided by manufacturers, are available. They are calculated based on standard testing at specific operational conditions (EN14511:2007,EN15316-4-2:2008, EN14825:2013 and the old, EN 255-1+2:1997 [B.Klein, 2012]). However, both white box or a simple grey box model of the different components with simplified equations with parameters with physical meaning are recommended, as these models are fast enough and accurate even out of the ranges of the identification data set. Finally, more rough models are recommended when considering complex systems that include numerous sub-systems, like a new energy system with different energy sources.

Following this framework, the following sub-section intends to clarify the aim of the model developed, which defines the boundary level and the complexity level of each of the sub-models. At the end, the results of daily and annual HP2Grid performance analysis based on the simulation are shown and discussed.

Global model objectives and sub-model types

The aim of the model developed in this research is to evaluate how the entire system, including building, HP/ORC unit, solar and ground collector as well

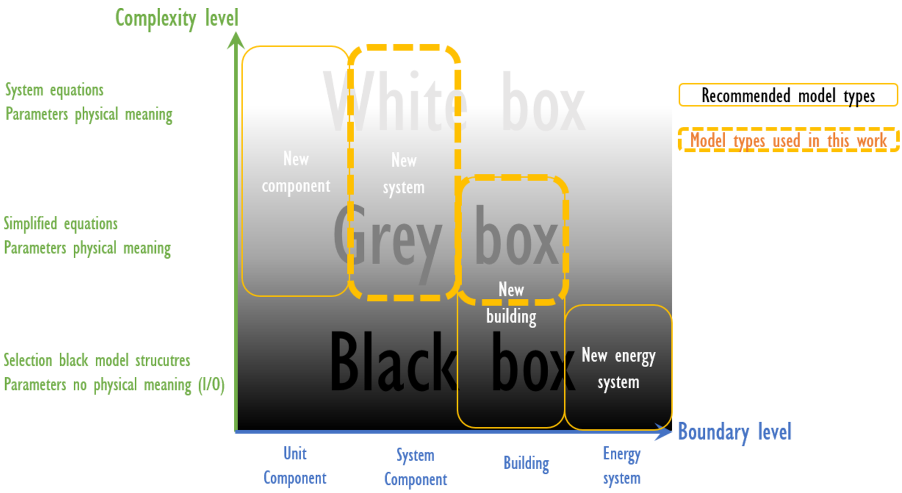

Fig. 23: Simulation models types and recommended box model type depending on the aim of the analysis

as thermal storage, behaves under different boundary conditions (like climate and user demand) as well as to test the effect of different system configuration (like different thermal storage tanks) and control strategies (for example, domestic hot water priority and/or space heating demand oriented). Altogether, the model should enable to assess the energy demand and supply of the HP2Grid concept in a residential building and to optimize the operation given the boundary conditions in terms of energy efficiency and/or running costs reduction.

The system responses studied are instantaneous energy flows between the system components. These responses will enable to calculate total energy demand and supply of the unit but also to identify components and control strategies that can optimize the energy conversion performance of the system. In order to predict those flows, several sub-models were built, which are shortly described in this sub-section.

A detailed explanation of the each sub-model is given in Paper 6 [C.Carmo et al., 2016a] and Paper 7 [Dumont et al., 2014b]. In Paper 8 [Dumont et al., 2016], the background for the multi-node stratified 1D-model choice is given and the experimental validation of the hot water storage model is presented in Paper 9 [C.Carmo et al., 2015b]. Figures 24 and 25 show the prototype and the laboratory facilities used to validate the HP/ORC unit and hot water tank model, respectively.

Building model A building model written in the Modelica language was integrated in the system model. This model is a result of the research efforts of

Fig. 24: HP/ORC prototype

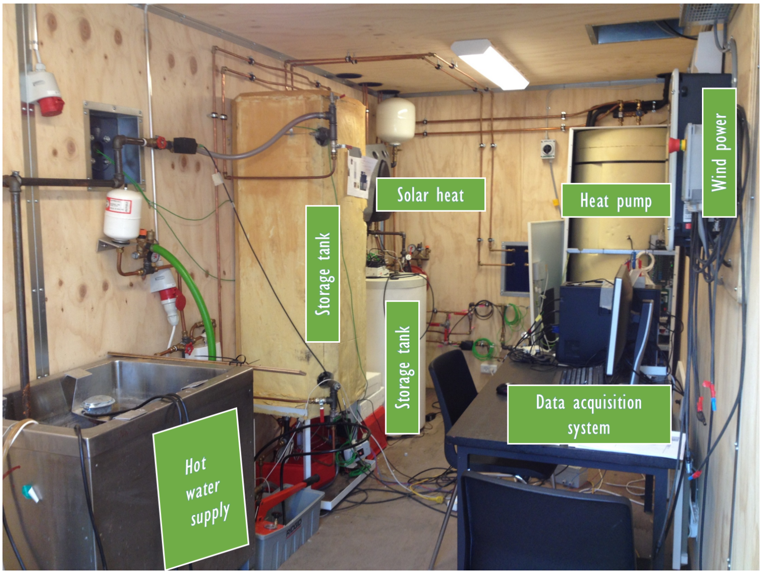

Fig. 25: Experimental set-up used for hot water tank model validation

IEA - EBC Annex 58- Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurements [IEA, 2015, Masy, 2007]. This model was chosen due to its computational cheapness, accuracy and flexible structure. The modelling method used is defined as zone simplified dynamic model or RC - networks, where the thermal conductance (inverse of thermal resistance) and heat capacity of walls and windows are modelled through a series of analogous electrical components, resistances (R) and capacities (C). An example of an RC- network model of internal or external wall is illustrated in Figure 26 along side with its appearance in Dymola environment. The building model inputs are the geometry and constructive characteristics of the building as well as the arrangement of the rooms, thus any residential building can easily be modelled. The heat demand is calculated based on the equations of conservation of mass and energy within adjacent zones of the building and the exterior. Lastly, a radiant slab model from the Buildings library [M.Wetter et al., 2014] is linked to supply heating to meet the building heating demand.

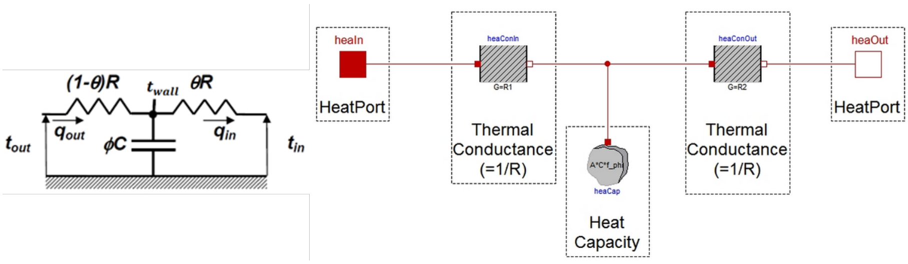

Fig. 26: Wall model RC-network diagram (left) and equivalent model in Dymola environment (right)

The heat flux q_{in} injected into the zone is calculated as follows:

$$q_{in} = \frac{1}{R\theta}(T_{wall} - T_{in}) \quad (1)$$

$$q_{out} = \frac{1}{R(1-\theta)}(T_{out} - T_{wall}) \quad (2)$$

and

$$q_{out} - q_{in} = \varphi C \frac{dT_{wall}}{dt} \quad (3)$$

HP/ORC unit model Experimental results of the proof-of-concept design of the HP/ORC unit with refrigerant R134a at different operating conditions are used to validate a dynamic model of the HP/ORC unit. The HP/ORC unit semi-parametric model (Equations (4)- (8)) was primarily developed by the research group at the Thermodynamics Laboratory, Aerospace and Mechanical Engineering Department of the University of Liège. Research efforts to characterize such systems started during the early 2000's [Lemort, 2009] and continued until today [Quoilin, 2011, Quoilin et al., 2013, Dumont et al., 2014a, Quoilin et al., 2015, O.Dumont, 2015]. Subsequently, thanks to a close collaboration with the laboratory staff, this knowledge was integrated in the HP2Grid system model developed during this project (see coefficients of the semi-parametric model in annexes of Paper 6 [Dumont et al., 2014b]). The validity range of these regressions is presented in [O.Dumont, 2015].

$$T_{w,ev,ex,HP} = a_1 + a_2 . T_{w,cd,su} + a_3 . T_{w,cd,su}^2 + a_4 . T_{w,ev,su} + a_5 . T_{w,ev,su}^2 \quad (4)$$

$$\dot{W}_{el,ORC} = b_1 + b_2 . \dot{m}_{w,ev} + b_3 . \dot{m}_{w,ev}^2 + b_4 . \dot{m}_{w,cd} + b_5 . \dot{m}_{w,cd}^2 + b_6 . T_{w,cd,su} + b_7 . T_{w,cd,su}^2 + b_8 . T_{w,ev,su}\ b_9 . T_{w,ev,su}^2 \quad (5)$$

$$T_{w,ev,ex,ORC} = c_1 + c_2 . \dot{m}_{w,ev} + c_3 . \dot{m}_{w,ev}^2 + c_4 . \dot{m}_{w,cd} + c_5 . \dot{m}_{w,cd}^2 + c_6 . T_{w,cd,su} + c_7 + c_8 T_{w,ev,su} + c_9 . T_{w,ev,su}^2 \quad (6)$$

$$\dot{W}_{el,HP} = d_1 + d_2 . \dot{m}_{w,ev} + d_3 . \dot{m}_{w,ev}^2 + d_4 . sc + d_5 . sc\text{^}2 + d_6 . \dot{m}_{w,cd} + d_7 . \dot{m}_{w,cd}^2 + d_8 . T_{w,cd,su} + d_9 . T_{w,cd,su}^2 + d_{10} T_{w,ev,su} + d_{11} . T_{w,ev,su}^2 + d_{12} . \dot{m}_{w,ev} . sc + d_{13} . \dot{m}_{w,ev} . \dot{m}_{w,cd} + d_{14} . \dot{m}_{w,ev} . T_{w,cd,su} + d_{15} . \dot{m}_{w,ev} . T_{w,ev,su} + d_{16} . sc . \dot{m}_{w,cd} + d_{17} . sc . T_{w,cd,su} + d_{18} . sc . T_{w,ev,su} + d_{19} . \dot{m}_{w,cd} . T_{w,cd,su} + d_{20} . \dot{m}_{w,cd} . T_{w,ev,su} + d_{21} . T_{w,cd,su} . T_{w,ev,su} \quad (7)$$

$$\dot{Q}_{cd,HP} = e_1 + e_2 . \dot{m}_{w,ev} + e_3 . \dot{m}_{w,ev}^2 + e_4 . sc + e_5 . sc^2 + e_6 . \dot{m}_{w,cd} + e_7 . \dot{m}_{w,cd}^2 + e_8 . T_{w,cd,su} + e_9 . T_{w,cd,su}^2 + e_{10} . T_{w,ev,su} + e_{11} . T_{w,ev,su}^2 \quad (8)$$

Ground and solar collector models The flat solar thermal roof collector model is based on classical white box model based on physical parameters [Klein, 1975]. In the case of the ground source heat exchanger, a reduced order model [Fontaine, 2015] validated against TRNSYS model (Type 997 [TRNSYS, 2006]) is used.

Stratified hot water tank model Finally, in this work, a novel 1D model for representing stratified water tank systems was developed and validated using experimental data under different charging and discharging conditions following prEN12977-3:2008 [CEN, 2008].

The real water tank (250 L) to be modelled is shown Figure 27. It consists of a stainless steel cylinder with two built-in spiral heat exchangers (HXs), 3 L and 9.6 L respectively – one going from mid-height to bottom of the tank and another going from bottom to the top of the tank. When charging the store, the working fluid in the HP/ORC unit (HP/ORC HX in Figure 27) is circulated through the mid-height helical heat exchanger. During discharging, the cold water from the grid is circulated through the all-through heat exchanger to supply DHW. Furthermore, a direct inlet (bottom) and outlet (top) on the tank form part of the space heating loop (FH HX in Figure 27). In periods of space heating demand, the water from the house floor slab enters the inlet and supplies hot water from the outlet in the top.

This type of hot water storage tank and its geometry was selected considering two essential characteristics for hot water storage tanks designed for solar domestic hot water systems: maintenance of thermal stratification and legionella growth prevention [W.Duff et al., 1996, Furbo et al., 2004, Dansk Standard, 2012].

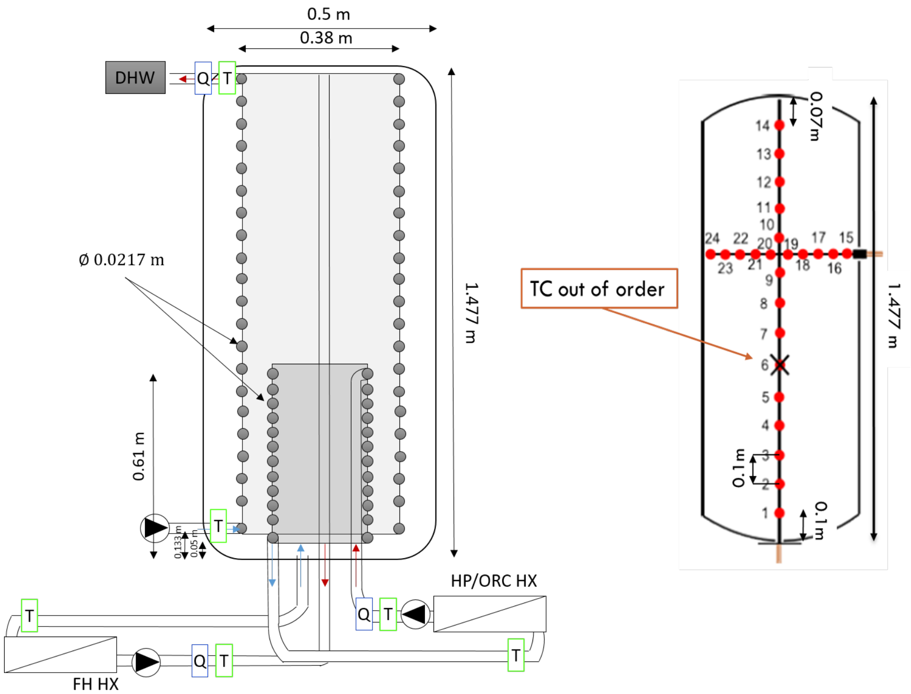

Fig. 27: Hydraulic scheme of the tank test rig, which also was modelled in Modelica language (left). Thermocouples (TC) position inside the tank (right)

The model used is based on an existing model in ThermoCycle library, *Heat Storage Water Heater* [S.Quoilin et al., 2014]. It is an 1-D lumped parameter model based on the finite volume discretization. This means that, in order to solve the spatial temperature dependencies, the flow is discretized into *i* interconnected cells in series. This discretization is an approximation method, in which each of the *i* cells, are modelled by equations of energy and mass conservation and a static momentum balance. This method makes the tank model compatible with the other sub-models of the system.

The original tank model was then modified to account for the two heat exchangers ($\dot{q}_{hx}$), heat transfer and mixing between adjacent cells ($\dot{q}_{i-1}$ and $\dot{q}_{i+1}$), thermal losses to the ambient ($UA_{amb,i}(T_i - T_{amb})$) and heat release to the load ($\dot{m}(h_{ex,i} - h_{su,i})$). The dynamic temperature profile of the tank is represented by a set of i ordinary differential equations that approximately represent the energy balance of the tank:

$$\begin{aligned} A_i \Delta x_{seg} \rho_i c_p \frac{dT_i}{dt} = \dot{m}(h_{ex,i} - h_{su,i}) + A_{hx,unit,i}\dot{q}_{hx,unit} + \\ A_{hx,DHW,i}\dot{q}_{hx,DHW} + \alpha_i A_{i+1}\dot{q}_{i+1} + \\ \beta_i A_{i-1}\dot{q}_{i-1} - UA_{amb,i}(T_i - T_{amb}) \end{aligned} \tag{9}$$

where

$$\dot{q}_{hx,unit,i} = U_{hx}(T_{i,hx} - T_i) \tag{10}$$

and

$$\dot{q}_{i-1} = \sigma \frac{(T_{i-1} - T_i)}{\Delta x_{seg}} \tag{11}$$

In Equation (9) α is 0 if the i-th node is the top of the tank and 1 otherwise and β is 0 if the i-th node is the bottom node and 1 otherwise.

In addition, the model includes the mixing parameter (σ, with units of thermal conductivity in Equation 11) in order to represent the combined effect of the different mechanisms of heat transfer that can occur between tank nodes (diffusion, advection or axial mixing due to flow) as well as the mixing that occurs due to temperature inversion. This parameter is issued whenever there is temperature inversion in the tank. This parameter is estimated by minimization of errors between simulated and measured temperatures in the tank from experimental tests at operation conditions identical to the conditions in which the storage tank is operated in HP/ORC system. In practice, a much higher mixing parameter is used when this situation arises. However, in case the tank is in stand-by mode ($\dot{m} = 0$), this mixing parameter is computed as suggested by J. Fan et al. [J. Fan, 2012, Fan et al., 2015] to include the transient fluid flow and heat transfer phenomena that are induced by the ambient heat loss at the tank walls. The mixing parameter, in this case, depends on the temperature gradient and the geometric characteristics of the tank (diameter, height, insulation and material). Figure 28 presents a table from Paper 9 [C.Carmo et al., 2015b] with the different charging and discharging conditions tested, identified as cases 1-5.

Figures 29-33 show the validation of the model discretized in i=20 cells against experimental results. It should be highlighted from Figure 30 that the error between calculated and measured values increases when there is flow inside the tank. Especially, in case 2 - when the tank is discharged via the outlet placed on the top of the tank and simultaneously charged by the inlet

Mode	Case	$\dot{m}_{HP/ORC,in}$ [kg/s]	$\dot{m}_{FH,in}$ [kg/s]	$\dot{m}_{DHW,out}$ [kg/s]	$T_{HP/ORC,in}$ [ºC]	$T_{FH,in}$ [ºC]	$T_{DHW,in}$ [ºC]	$T_{tank,in}$	Duration [min]
Charging	1	0,04	-	-	45	-	-	18	300
Discharging	2	-	0,034	-	-	18	-	40	151 (2,5H)
	3	-	-	0,034	-	-	20*	40	365,5 (6H)
	4	-	-	0,07	-	15	-	40	150(2,5H)
	5	-	-	-	-	-	-	40	2880 (48H)

Fig. 28: Charging and discharging conditions. Experimental tests cases

at the bottom of the tank with cold water. This is because the discretization method used, which is an approximation of the spatial partial derivatives equations (PDE) into i ordinary differential equations (ODEs) - see Equation (9), exhibits a negative effect called numerical diffusion with systems with flow. This effect causes the model to exhibit higher diffusivity than the true physical system. To minimize the negative effect when using spatial discretization using a finite difference method, a different discretization scheme could be the solution to handle the convection phenomena and maintain the integrity of the results.

In general, it is difficult to make a fair comparison of the simulation model performance and this work intends by no means to make a comprehensive study of computational efficiency. However, for the purpose of the studies performed in this work, the model with i=20 is considered to present reasonable accuracy with a maximum RMSE of 2.58(K) during the entire experiment period and takes around 24 seconds to simulate 24 hours. Thus, it is considered reasonable to apply in annual simulations. The error (RMSE) was calculated as a root-mean-square of a difference of the simulation value and the experiment value at each time step of the simulation and for all cells.

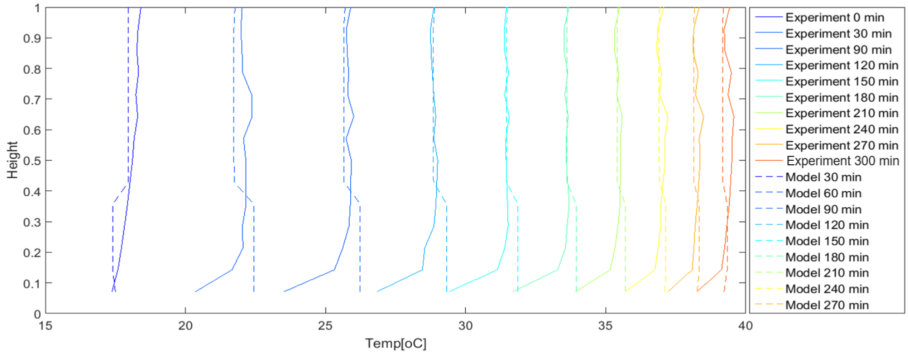

Fig. 29: Validation of the stratified hot water tank model under charging through small spiral conditions (Case 1)

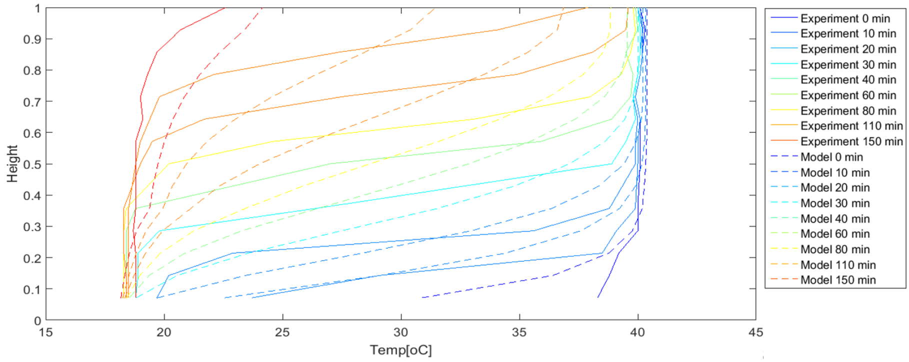

Fig. 30: Validation of the stratified hot water tank model under discharging through direct outlet conditions (Case 2 – low flow)

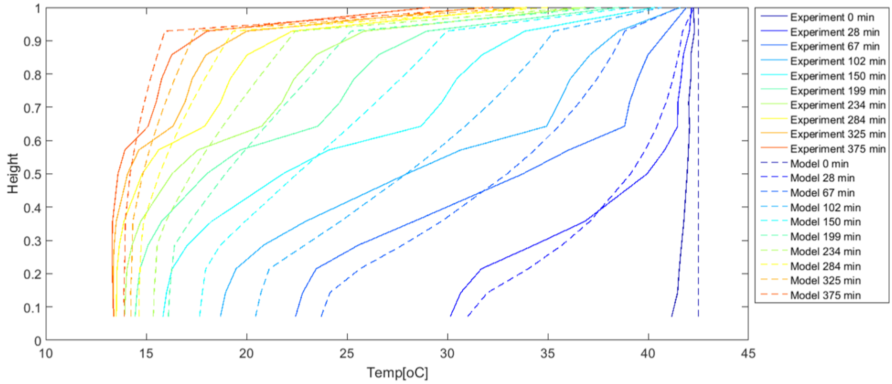

Fig. 31: Validation of the stratified hot water tank model under discharging through immersed spiral conditions (Case 3 – low flow)

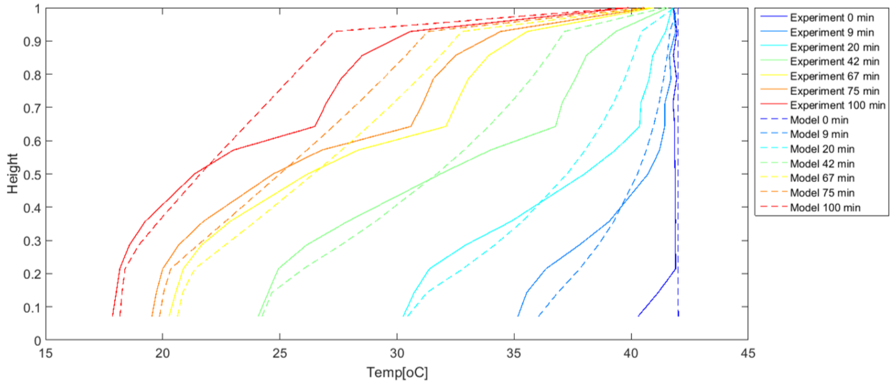

Fig. 32: Validation of the stratified hot water tank model under discharging through immersed spiral conditions (Case 4 – high flow)

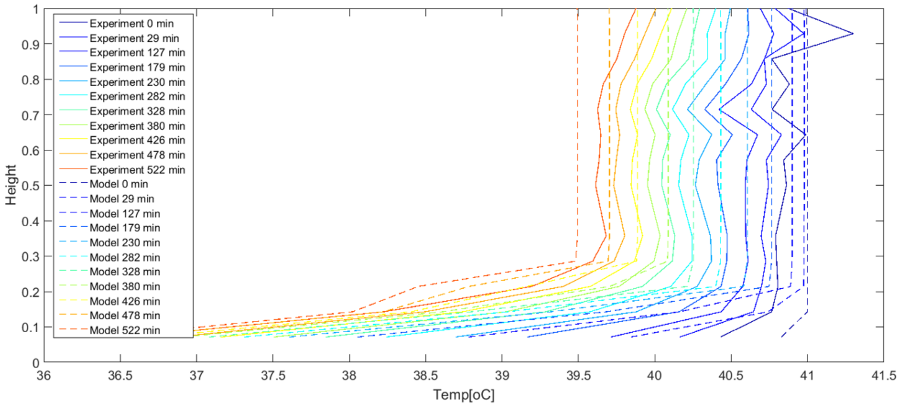

Fig. 33: Validation of the stratified hot water tank model under steady-state ambient loss during 48 h (Case 5)

HP2Grid control model

Traditional control for building systems are rule-based control (RBC) algorithms. These control strategies are based on a combination of logic rules, *IF condition THEN action*. The condition generally implicates the comparison of a measured state with a threshold value. This heuristic approach is easily interpreted and has been the state-of-the-art in building automation [C.Carmo et al., 2016b].

For heating and cooling systems, the traditional control primarily lies in accurately predicting the heating load based on predefined heating load curves. These curves define the right amount of heat need to satisfy the thermal comfort requirements with minimal primary energy consumption. Conventionally and for simplification for heat pump systems, the thermal comfort is a function of the forward and/or return temperatures which varies according to the outdoor temperature. The relation between them is given by the predefined heating load curves. An example of the heating curves is given in Figure 34. The heating curve parameters, curve slope number, are traditionally set by a technician when the heat pump is installed. In the example presented, curve slopes between 2 and 4 are the normal setting for floor heating systems and 4-6.5 for radiators while 7-10 exist in cases of high temperatures demand. Subsequently, small adaptations can be performed by the house owner if necessary. For instance, in Figure 34 slope 4 gives a return temperature (T_{ret}) of + 35°C, when this temperature is reached the heat pump, which supplies the temperature at a constant condensation temperature switches off. To avoid abrupt switches between on and off, a dead band (db) or hysteresis method is commonly introduced in the feedback controller. This method assures that the heat pump unit starts when the T_{ret} reaches $T_{ret} - (db)/2$ and stops when T_{ret} is equal to $T_{ret} + (db)/2$.

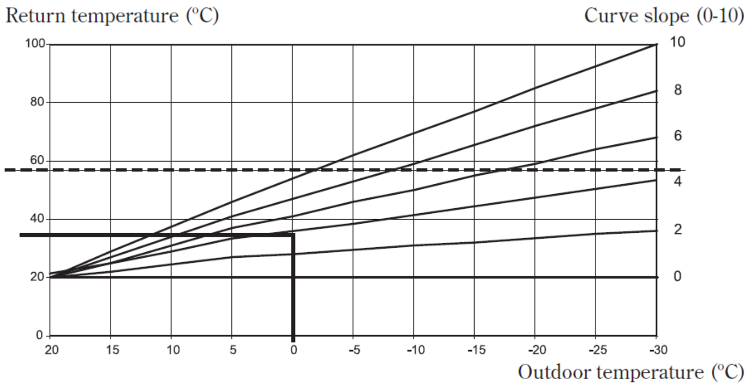

Fig. 34: Example of heating curves design by an European heat pump manufacturer

However, the HP/ORC unit prototype is connected to hot water storage tank as shown in Figure 35, in such a way that the control is driven by both space heating (SH) and domestic hot water (DHW) demand instead and therefore, the temperature inside of the tank is used for control purposes alternatively. As for the installation level control, also simple changes are proposed to the other HP2Grid system components and levels. They are summarized below:

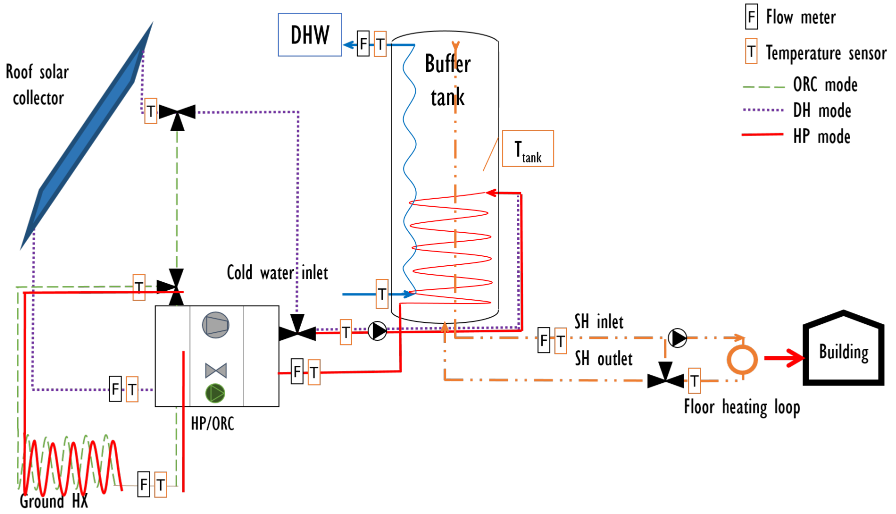

Fig. 35: Hydraulic scheme of the HP2Grid concept

- **Building level control**: The conventional PI-control strategy is found to be acceptable for floor heating systems due to their inherently self-regulating nature. The air temperature in the rooms is monitored and used to regulate zone valves (the valve on the right hand side of Figure 35) that are opened or closed to supply the required heat to the rooms. A proportional- integral (PI) controller regulates the temperature of a designated room to a set point, 20°C, using a pump to adjust the hot water flow in the floor heating loop. The flow varies from 0.0 L/s to 0.4 L/s. In practice, to perform this control room thermostats are used.

- **Installation level control**: Figure 36 illustrates the reference control strategy at HP/ORC unit level. T_{sto} is the hot water tank control temperature at height 0.6m – middle of the tank,$T_{sto,low}$ is the lower limit of temperature allowed in the tank (40°C), $T_{sto,high}$ is the higher limit of temperature allowed in the tank (60°C), $W_{ORC,min}$ is the lower limit of the power to start the ORC (2 kW) and T_{roof} is the roof temperature in the outlet.

If the storage control temperature (T_{sto}) is below a fixed low temperature threshold ($T_{sto,low}$) and the temperature in the roof solar collector (T_{roof}) also, the heat pump mode is activated to cover the space heating (SH) and the domestic hot water (DHW) demand. It is then switched off when T_{sto} reaches the high temperature threshold ($T_{sto,high}$). The heat pump heat source is the ground heat exchanger or the solar roof depending on which one is the warmest.

In case, T_{roof} is higher than T_{sto} and T_{sto} is lower than $T_{sto,low}$ the direct heating mode is enhanced.

The ORC mode is activated whenever the T_{sto} is higher than $T_{sto,high}$ and the roof temperature is above the minimum power to get a net electrical production ($W_{ORC,min}$). The former mode is kept when the T_{sto} lies between the high and low threshold, to minimize chattering between modes, which reducing performance and reliability of the system.

Lastly, the by-pass mode is active when T_{sto} is between $T_{sto,low}$ and $T_{sto,high}$ and there is no solar heat to activate the ORC mode. The roof pump is running whenever in the by-pass mode to homogenize the roof temperature. This control strategy is implemented in Modelica language in the form of state diagram, that uses the various outputs (T_{sto},T_{roof}, etc.- Figure 36) of the different sub-models to activate the different operation modes.

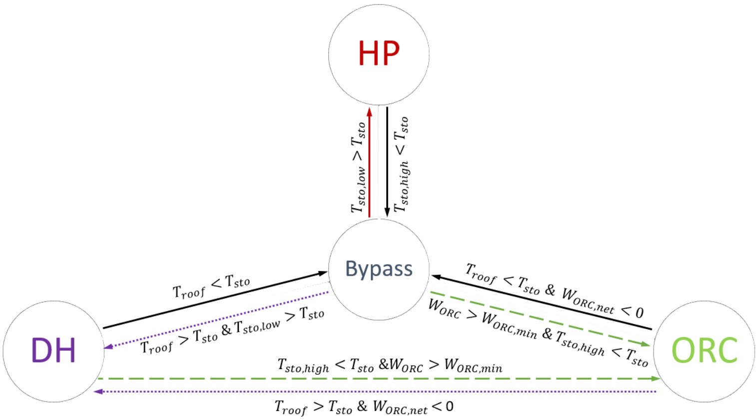

Fig. 36: State diagram illustrating the HP2Grid unit level control

Annual simulation of the integrated system

Subsequently, the sub-models described above are combined in a model employed to study the annual performance of the HP/ORC system in different climates, with different system configurations and controls.

A theoretical investigation of the dynamic performance of the HP/ORC unit integrated in a residential household during three characteristic days (winter, transition and summer season) is illustrated in Figures 37, 38 and 39. Using the aforementioned components, system configuration and two different control strategies the results - further discussed in Paper 6 [Dumont et al., 2014b] - demonstrate the feasibility of the HP2Grid concept. Installed in a residential house, the HP/ORC unit is able to integrate renewable energy sources at high energy conversion efficiencies. Two different set temperatures of the water temperature inside of the tank are tested: a low set temperature (50°C) and a high set temperature (60°C). A maximum coefficient of performance (COP) of 5.85 is achieved with the low set temperature control during a typical summer day. This is mainly due to free heating supplied by the solar roof. Furthermore, the results indicate that this concept might enable positive Energy Buildings.

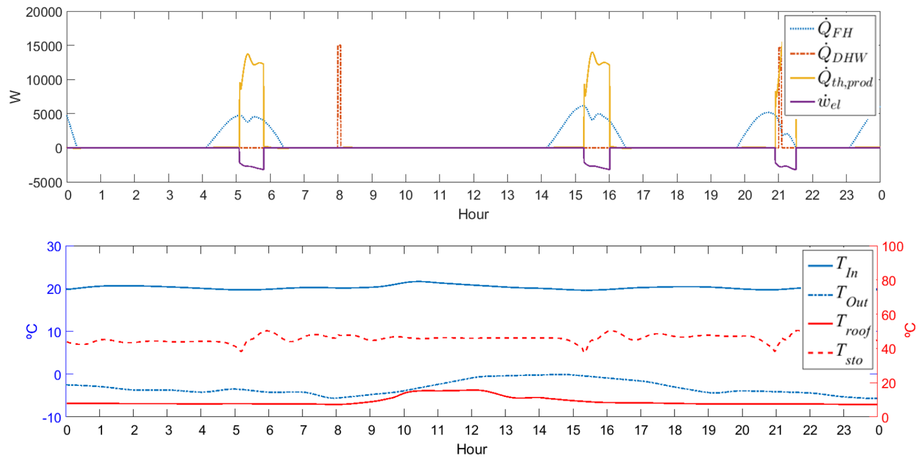

Fig. 37: Dynamic simulation results of the HP/ORC unit coupled to a passive house for a typical winter day

The successful preliminary results of Paper 6 [Dumont et al., 2014b], motivated the annual performance assessment of the HP2Grid system described in Paper 7 [Dumont et al., rev]. The annual simulation results - reveal the potential of HP2Grid concept in form of HP/ORC reversible unit to achieve Positive Energy Buildings in the Danish climate. The annual electrical production of the ORC is 3012 kWh while the total annual electrical consumption is only 2318 kWh. The monthly energy demand and supply of the HP2Grid system is drawn in Figure 40.

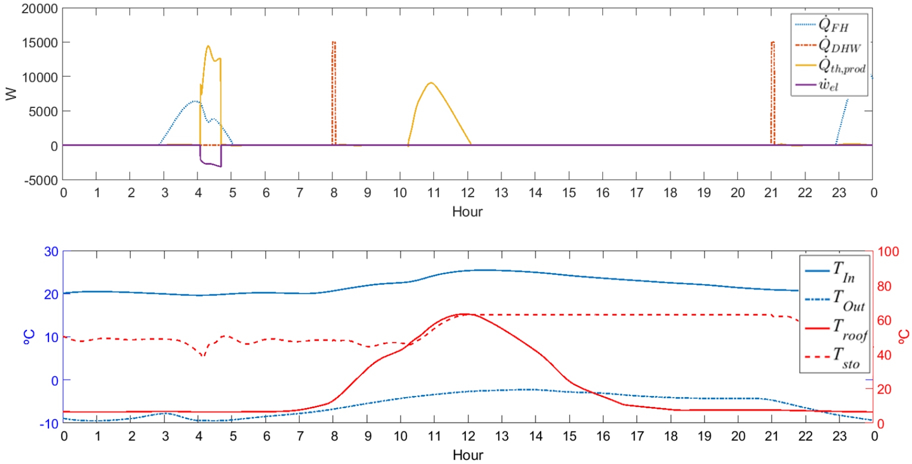

Fig. 38: Dynamic simulation results of the HP/ORC unit coupled to a passive house for a typical transition season (spring or fall) day

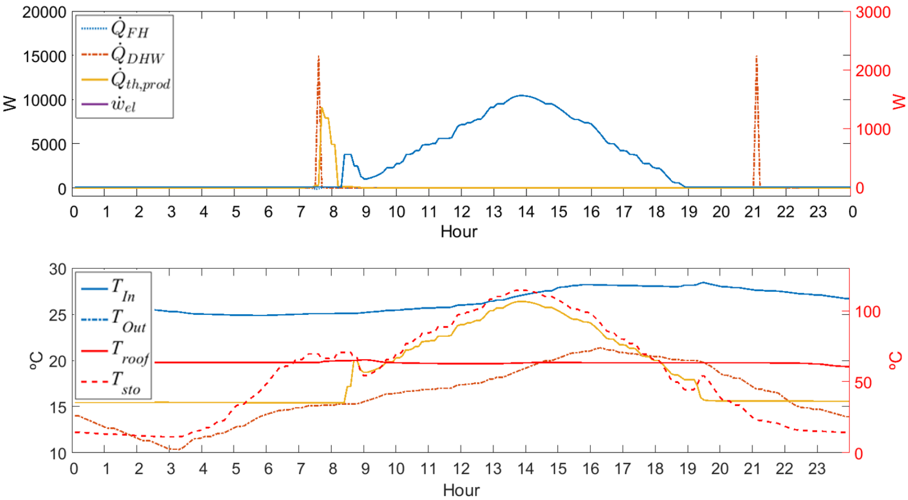

Fig. 39: Dynamic simulation results of the HP/ORC unit coupled to a passive house for a typical summer day

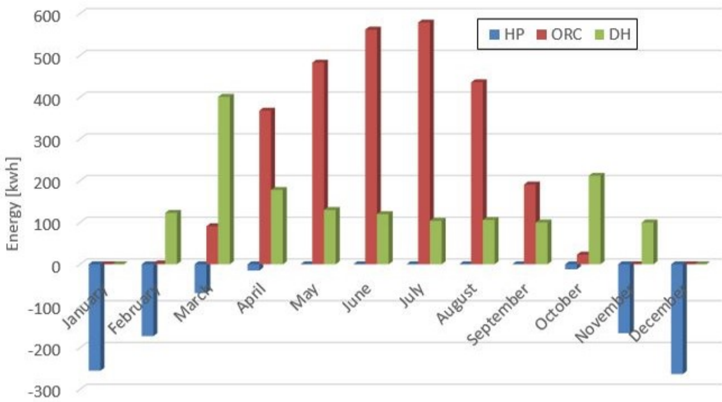

Fig. 40: Dynamic simulation results of the HP/ORC unit coupled to a passive house for each month under Danish climate conditions in 2013

Furthermore, an extensive sensitivity analysis of the system's performance under 5 different climates, 3 different light and appliances demands and 3 different insulation standards is performed and the summary of the results is presented in Figure 41. Its performance parameters are defined as following:

- $Q_{th,prod}$ [kWh], is the annual thermal energy produced by the HP/ORC unit corresponding to the building SH and DHW;
- $W_{el,prod}$ [kWh], is the gross electrical HP/ORC production when operating in the ORC mode;
- $W_{el,HP}$ [kWh], is the annual electricity demand of the HP/ORC unit in HP mode;
- W_{net} [kWh], is the difference between the gross electrical production and the gross electrical production for both heat pump and light and appliances;
- Benefits [€], they are evaluated according to Danish market conditions and do not take into account investments costs. Where, $P_r \sim 0.28$ €$/Wh$ is the retail price considered when the net electrical power is negative, $P_{r,HP}$ is the retail price for the heat pump only $\sim$ 0.22 €$/Wh$ and P_{bb} is the buy-back tariff $\sim$ 0.17 €$/Wh$ considered when the net electrical power [W_{net}] is positive;

$$Benefits = \begin{cases} \int_0^t (P_{bb} \cdot \dot{W}_{net} - P_{r,HP} \cdot \dot{W}_{HP})dt, & \text{if } W_{net} > 0 \\ \int_0^t (P_r \cdot \dot{W}_{net} - P_{r,HP} \cdot \dot{W}_{HP})dt, & \text{otherwise} \end{cases}$$

- Supply cover factor or self-production rate (γ_s), is the ratio of energy produced by the HP/ORC which is use to cover instantaneous electrical consumption;
- Demand cover factor or self-consumption rate (γ_d), is the ratio of electrical energy demand which is covered by ORC instantaneous electrical production.

Building	L&A	Location	$Q_{th,prod}$ [kWh]	$W_{el,prod}$ [kWh]	$W_{el,hp}$ [kWh]	W_{net} [kWh]	Benefits [€]	γ_s	γ_D	Q_{dh} [kWh]
		Copenhagen	3597	3015	690	-675	-501	0,13	0,13	1057
		Frankfurt	3291	3609	572	37	-368	0,119	0,14	1180
	2010	Torino	2243	5379	189	2190	38	0,1	0,18	1523
		Roma	1072	6646	16	3630	312	0,1	0,23	990
		Palermo	861	8597	0	5597	666	0,096	0,27	845
		Copenhagen	4289	3012	827	694	-119	0,071	0,138	1207
		Frankfurt	3879	3607	699	1417	15	0,065	0,15	1292
Danish	Danish	Torino	2700	5371	251	3629	422	0,054	0,185	1726
		Roma	1301	6639	35	5113	695	0,053	0,226	1148
		Palermo	889	8597	0	7106	1046	0,049	0,27	872
		Copenhagen	4025	3014	783	231	-260	0,093	0,133	1134
		Frankfurt	3652	3609	647	962	-125	0,084	0,145	1254
	2030	Torino	2545	5374	226	3148	281	0,071	0,181	1671
		Roma	1211	6643	26	4617	553	0,07	0,22	1088
		Palermo	875	8596	0	6596	904	0,065	0,26	859
		Copenhagen	2887	3021	535	995	-38	0,047	0,096	912
		Frankfurt	2685	3615	447	1677	81	0,042	0,1	1034
K15	Danish	Torino	1772	5386	120	3775	464	0,036	0,131	1304
		Roma	980	6648	12	5145	708	0,036	0,159	917
		Palermo	863	8596	0	7105	1048	0,033	0,19	847
		Copenhagen	8667	2987	1723	-227	-318	0,046	0,092	2031
		Frankfurt	7804	3573	1457	625	-156	0,041	0,098	2206
K30	Danish	Torino	5956	5334	803	3040	300	0,035	0,128	2837
		Roma	3254	6585	196	4898	655	0,035	0,155	2468
		Palermo	1670	8562	15	7056	1038	0,032	0,187	1586

Fig. 41: Sensitivity analysis results of the HP/ORC unit coupled to a passive house with 3 different building insulation, 3 different light and appliances (L&A) profiles subject to 5 different climates

This analysis unveils the fact that the HP/ORC solution becomes economically interesting only if installed in buildings with a large heating demand and/or restrictions to buy electricity from the grid. For further comments, the reader is referred to Paper 7 [Dumont et al., rev].

2.4 HP2Grid concept development

As previously revealed, the energy systems transition from fossil fuels to renewable energy encompasses changes both on the supply and on the demand side. On the supply side, dispatchable fossil-fuel based technologies have been substituted with intermittent renewable energy based technologies. Thus, to implement a 100 % renewable energy systems, it is paramount that demand side is able to use energy when it is available, i.e. that the demand side is flexible.

Hence, this section is concerned with the HP2Grid concept development as a mean to achieve the main objectives of this work: increase the energy efficiency and integration of renewable energy in the domestic energy demand side through the implementation of the HP2Grid concept.

Design issues to tackle the objectives involve proper sizing -as already mentioned in sub-chapter 2.1- but also proper controls and the need for thermal storage.

In this section, the model described in the previous section is used to study different system configurations and control methods as well as perform a comparative analysis of the performance of the HP/ORC unit with competitive existent solutions. These analyses intend to answer *research questions 3* and *4*. In other words, they aim at the improvement of the system energy conversion performance and estimating running costs and/or benefits.

Improved configurations and control strategies

On the one hand, the findings of the real-life heat pump systems monitoring campaign in Paper 3 [C.Carmo et al., 2015a] revealed a link between energy efficiency and hot water tank configurations. On the other hand, several studies on small solar heating systems point at the essential role of thermal storage with regard to thermal performance, flexibility potential and self-consumption enhancement also as the price of the solar heating system [Furbo et al., 2004, D.Parra, 2016].

Side by side with effective storage solutions, intelligent control strategies are a key instrument to reach energy savings and intermittent renewable energy sources integration. For this reason, another approach to enhance the performance of the HP2Grid concept was testing different control strategies.

Finding an optimal control input trajectory for residential energy supply systems boils down to find easily implementable and adaptable control strategies that operate considering the actual load and supply conditions.

In the last years, Model-based Predictive Control (MPC), multi-agent system technology (MAST), Fuzzy and ON/OFF controls have been considered the most encouraging strategies [Shaikh et al., 2014a]. However, the lengthy model development process and challenges to obtain trusty information for each application are often considered prohibitive. On the other hand, users are perceived as a major challenge for successful implementation due to the poor user friendliness (not intuitive) of these methods. Yet, traditional Rule-based control (RBC) algorithms, like ON/OFF control methods, have proven to deliver similar results to the aforementioned methods if enhanced with adaptive controls driven by occupancy and DHW consumption information.

On this basis, Paper 11 [C.Carmo et al., 2016b] aims at studying the effect of enhanced RBC methods complemented with occupancy information. Three different HP2Grid thermal mass configurations cases- passive house, poor insulated house both equipped with a 250 L buffer tank and house equipped with a 500 L buffer tank - are investigated under three different control strategies:

1. **Occupancy setback (OccSB):** this control minds occupancy information to adapt the indoor comfort temperatures from 20 °C when occupied, to 16.5 °C when non-occupied.

2. **DHW priority (DHWp):** in this case the space heating distribution pump is turned off when the HP/ORC unit is supplying DHW. This control logic intends to ensure higher energy efficiency by minimizing the mixing inside the storage water tank when it delivers high temperature water for domestic end-uses.

3. **Combined Occupancy setback and DHW priority (OccSB+DHWp):** this variant terminates the space heating supply both when people are not at home or in case they are taking a shower.

The simulation results of the annual performance of HP2Grid concept- summarized in Table 1- show that the use of real load control logics can decrease the adverse effects of cycling in the compressor of the HP/ORC system. In addition, the HP2Grid concept enables that the thermal and electrical demand covered by renewable energy reach values up to 33 % ($Ref.500L$ case) and max. 8.4 % ($OccSB + DHW_p500L$ case), respectively. The magnitude of these benefits depends strongly on the thermal mass of the building and volume of the hot water storage. In the case of buildings with passive house characteristics, the improvement in terms of energy efficiency and RES integration are negligible with the new control strategies. However, in poorly insulated houses, controls based on occupation information are more effective in terms of power reduction but not in increasing RES share in the buildings energy consumption or improving energy efficiency. They reduce up to 5 % the power consumed by the HP/ORC unit (% $W_{dem,unit}$) with the RBC methods enhanced with occupancy information, when compared to the Ref.poor case. Finally, in the case of the same house equipped with a sensible water storage tank double as large as the Ref. case, the effects of the different controls are equivalent to the poorly insulated house case in terms of power consumption reduction, only 3 % reduction of $W_{dem,unit}$ is achieved and no RES integration improvement. In contrast, a 5 % improvement on the SPF is reached.

Additionally, it is important to notice that the simple introduction of a larger water storage tank reduced the $W_{dem,unit}$ by 25 %, increased 44 % the SPF, 22 % the share on RES in the electrical consumption, 35 % the share of RES in total energy consumption of the household in comparison with the Ref. case. On the other hand, when comparing Ref. case with Ref. poor case, it can be concluded that better insulation building standards reduce the $W_{dem,unit}$ by 50 % and increase the SPF by 35 %, the share of RES in the electrical demand by 56 % and induce 12 % more RES in thermal demand, than poorly insulated building. In sum, better insulation standards generate 79 % higher RES integration than poorly insulated buildings equipped with the HP2Grid concept.

Table 1: Results for the control comparison

Case	Q_{HP}/Q_{dem} [%]	$W_{dem,unit}$ $[kWh]$	W_{ORC} $[kWh]$	***adc*** [min]	**# cycles**	**SPF**	γ_d	DL_{DHW} [%]	DL_{in} [%]
Ref.	75	1976	3106	19.8	861	2.7	6.7	1.6	0.0
OccSB	76	2061	3112	46.3	377	2.6	6.5	1.0	5.5
DHW_p	75	1976	3106	19.8	862	2.7	6.7	0.8	0.0
$OccSB + DHW_p$	76	2053	3112	46.5	375	2.6	6.5	0.3	5.7
Ref.poor	85	3960	3101	22.2	1544	2	4.3	0.7	0.0
OccSBpoor	84	3776	3105	49.2	661	2	4.4	1.0	10.0
DHW_ppoor	85	3963	3100	22.0	1553	2	4.3	0.3	0.0
$OccSB + DHW_p$poor	84	3759	3102	49.9	651	2	4.4	0.9	10.4
$Ref.500L$	67	1511	3186	37.6	450	3.9	8.2	0.0	0.0
$OccSB + DHW_p 500L$	69	1464	3191	72.5	240	4.1	8.4	0.0	5.2

The dynamic behaviour of the HP/ORC unit components during a typical week (from Sunday to Saturday) controlled by the three different strategies is illustrated through Figures 42 - 46. When comparing the bottom sub-figures of Figure 42 and Figure 43 ($\dot{w}_{HP}$, orange dashed-line), it is clear that when the HP2Grid concept operation is driven by OccSB control the number of on/off cycles reduces from 7 to 2 between hour 0 and hour 60. Still, the results in Table 1 reveals that the power consumption curtailment is not considerable when compared to the Ref. case due to the rebound effect visible on the same sub-plot (43c) at around hour 32. The duty cycle of the HP/ORC unit increases from few minute to over an hour.

On the other hand, the DHW_p control (Figure 44) does not show substantial changes when compared to the Ref. case control. Figure 45 shows the combined effect of the $OccSB + DHW_p$ control, which is comparable with $OccSB$ control (Figure 43) .

Finally, the benefits of the employment of a larger hot water tank storage and the $OccSB + DHW_p$ control are visible in Figure 46. Substantial lower power consumption and increase in the RES share in the electrical self-consumption of the building. Illustrated in Figure 46c by the number of purple line peaks, which represent the power production of the unit in ORC mode.

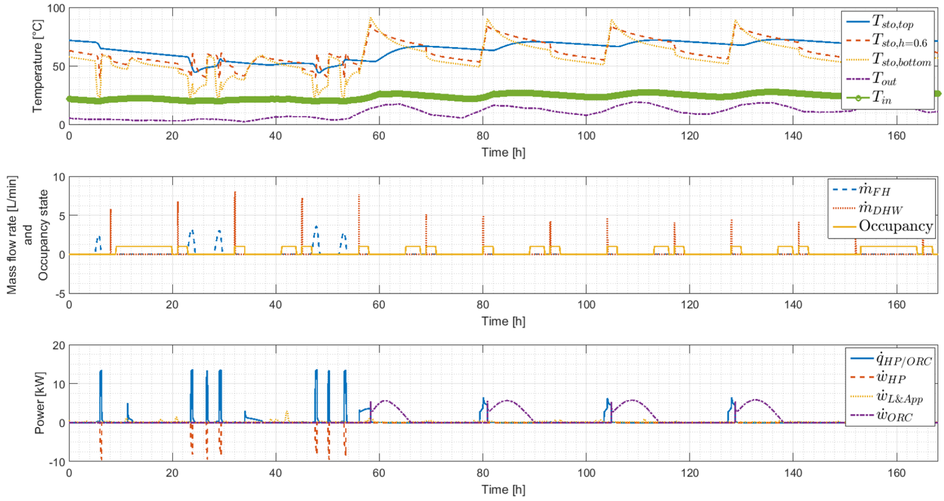

Fig. 42: Ref. case operation variables as function of time during a week in May on a ref. year in Danish climate

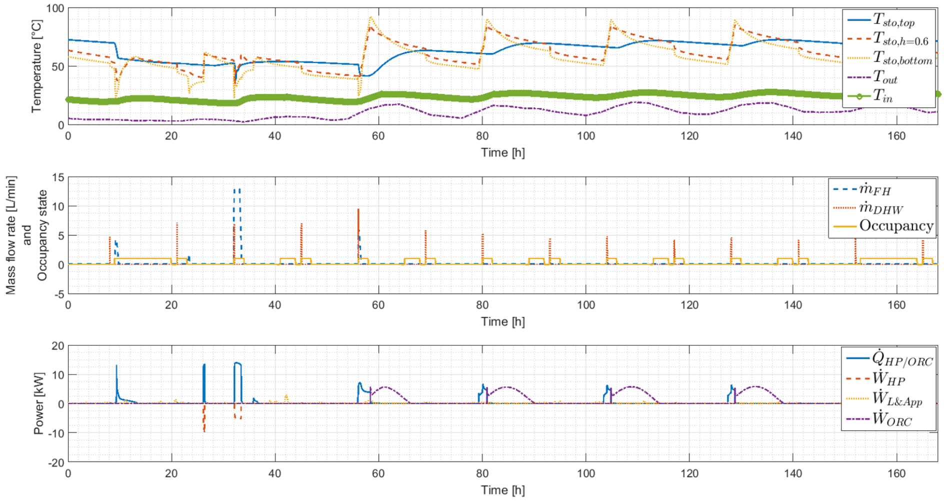

Fig. 43: OccSB case operation variables as function of time during a week in May on a ref. year in Danish climate

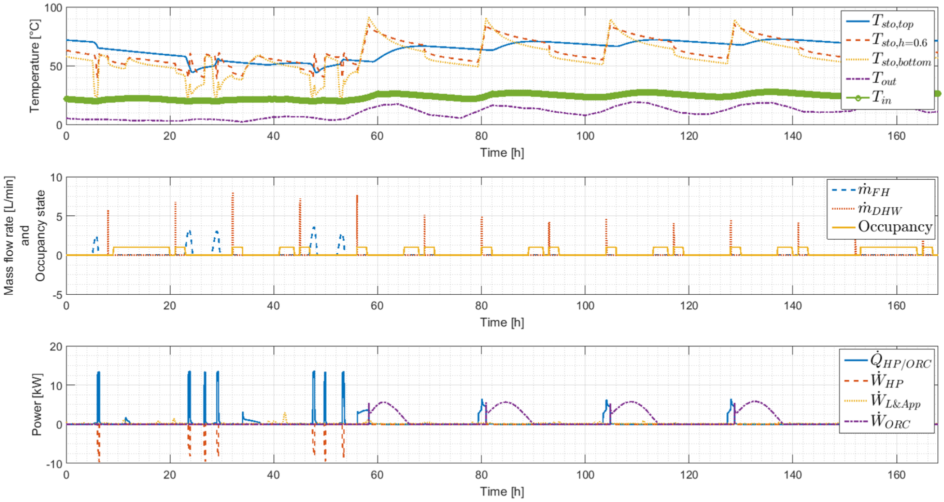

Fig. 44: DHW_p case operation variables as function of time during a week in May on a ref. year in Danish climate

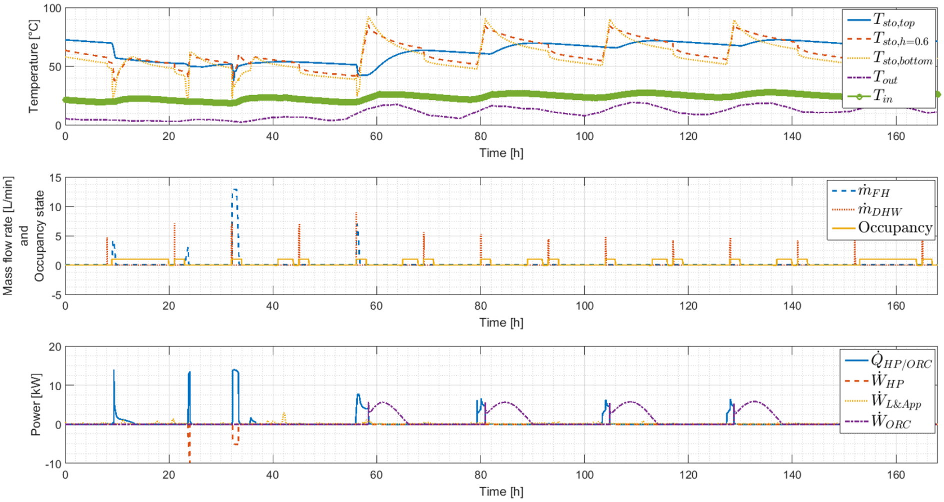

Fig. 45: OccSB+DHW_p case operation variables as function of time during a week in May on a ref. year in Danish climate

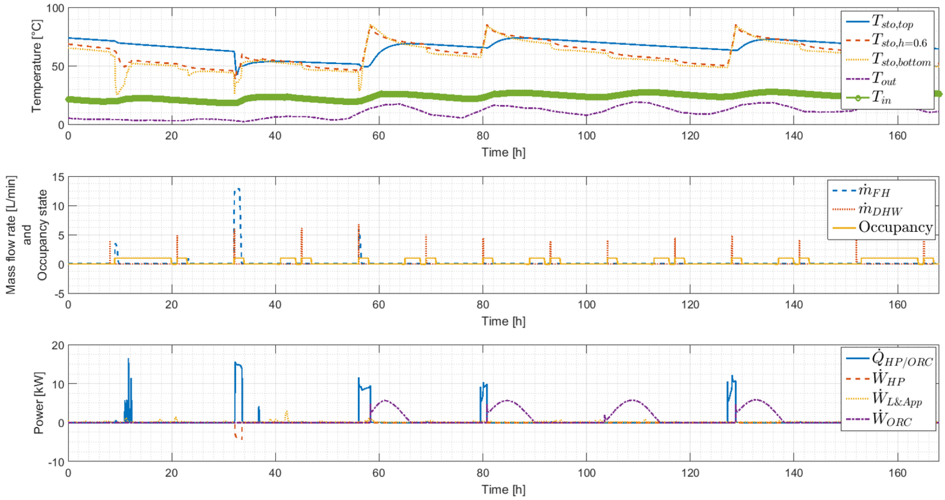

Fig. 46: OccSB+DHW$_p$500L case operation variables as function of time during a week in May on a ref. year in Danish climate

Economical feasibility of the concept

Among the different μ- CHP systems, renewable energy based systems have recently gained high level of attention. The increasingly interest is mainly driven by their non-costly energy sources and emission-free nature.

"Solar energy - particularly, photovoltaics (PV) cells - is starting to play a substantial role in the residential electricity generation in some countries, particularly in Europe, while lower prices are opening new markets from Africa and the Middle East to Asia and Latin America. Interest continues to grow in corporate- and community-owned systems, while the number and size of utility-scale systems continued to increase.(...)Module prices stabilised, while production costs continued to fall and solar cell efficiencies increased steadily" [REN21, 2014].

With this trend in mind, a comparison study between the HP/ORC unit and an equivalent well-known cogeneration concept, which consists of a heat pump unit coupled with PV panels is explained in detail in Paper 10 [C.Carmo et al., 2015c]. Its results suggest that the maximum potential of the HP/ORC is reached in southernmost cities, where the optimum location was found in humid subtropical climates, like the one in Torino (Figure 47). Under these climate conditions, the HP/ORC unit maximizes the direct heating supply and at the same time, totally covers the electrical demand. However, these results support the aforementioned findings, which revealed the weak economical feasibility of the HP/ORC unit when compared to equivalent residential μ- CHP systems.

Table 2 summarizes the annual performance results for the Danish climate case and Figure 47 shows a sensitivity analysis of the two system in 5 typical climates in EU28.

Table 2: Results for the HP/ORC vs HP+PV performance comparison in the Danish climate

System	HP/ORC	$HP+PV$
Non-HVAC electrical consumption $[kWh_p]$	1491	
Heat Pump electrical consumption $[kWh_p]$	812	1185
Gross electrical production $[kWh_p]$	2970	6511
Net electrical production $[kWh_p]$	667	3835
Thermal load (SH & DHW) $[kWh_{th}]$	4403	
Thermal energy by Direct Heating $[kWh_{th}]$	1394	0
Running benefits [€]	-78	494
Self-production rate (γ_s) [-]	8.9	9.1
Self-consumption rate (γ_d) [-]	9.2	39

The dynamic simulation results show that the HP/ORC unit is able to lower the electricity power consumption of the HP by 31 % in comparison to a system solution with a HP or HP+PV. In addition, 9.2 % of the amount of electrical energy consumed by the building is produced by the ORC and 32 % of the thermal demand is covered by direct heating. This means that it improves by 63 % the RES integration in the total building's energy demand, when compared to the the HP+PV system solution- from 15 % to 24 %. These values derive from the term γ_d in Table 2, which indicates that 39 % of the total electrical consumption (2676 kWh) is supplied by RES out of a total 7079 kWh energy demand (electrical+thermal) of the building equipped with $HP + PV$ system. While the HP/ORC system provides in total 1606 kWh of energy - both thermal (1394 kWh) and electrical (9.2% of 2303 kWh) - RES based, out of a total energy demand of 6706 kWh. Yet, the RES integration of the HP/ORC system decreases in warmer climates where the heating demand of the buildings is lower or null. In those cases, the HP/ORC system can only provide RES integration for its electrical consumption while the HP+PV system RES integration potential will be similar. Even though the HP does not demand electricity, there is a better match between electrical supply and demand and a higher electrical conversion efficiency in the case of HP+PV.

With respect to energy thermal energy efficiency, the HP+PV system solution is 32 % less efficient than the HP/ORC solution. It uses 1185 kWh of power to deliver 4403kWh, while the HP/ORC uses 812kWh and the rest is supplied by the direct heating from the solar collector.

In sum, these results verify that the HP/ORC system could only become competitive with mature renewable energy based μ- CHP alternatives in the case of a large heat demand of the building and/or restriction on buying

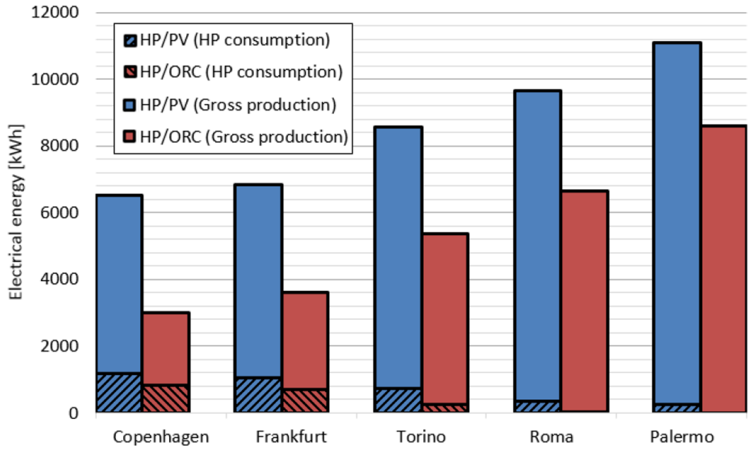

Fig. 47: Annual HP/ORC vs HP+PV performance comparison results in 5 typical climates in Europe

electricity from the grid. More generally, this means that buildings with a high heat demand, everything else being constant, are profitable for the reversible unit. For instance, the HP/ORC system employed in building with different end-uses than single-family dwellings, like office building, hospital, prison, stadium, etc.

3 Conclusions

This chapter summarises the results and findings afore stated. It starts with the answers to the research questions. Subsequently, perspectives of the findings are presented. Finally, suggestions for further research are given.

3.1 Conclusions on the research questions

This study aimed at contributing to the modelling and development of a novel dual-mode heat pump concept, called *HP2Grid*, from an integrated system level approach and at determining the main benefits in terms of renewable energy integration and improve domestic thermal energy conversion efficiency. A descriptive research method was adopted to explain how domestic heat pump units operate under real-life conditions. Following, a simulation model of the new heat pump concept was developed. This model was used to predict the annual operation and estimate the benefits of the HP2Grid concept. Subsequently, part of aforementioned empirical based knowledge was used to define realistic boundary conditions under which the HP2Grid should be developed.

The motivation for this research and its state-of-the-art are given in Chapter 1. Chapter 2 summarizes the main contributions of this work, which insights gained can be summarized by answering the following research questions:

- **Research question 1:** *How much can the single family dwellings' consumption contribute to the future energy system renewable energy integration without compromising comfort needs?*

Up to 80 % of the residential energy demand is used for space heating and cooling and domestic hot water preparation. To cover this end-use demand, heat pump units can be employed. In this work, it is shown that their power load to deliver heating - mainly driven by building characteristics and external load conditions - should not represent a burden to a Danish energy system with a high-share of wind power most hours of the year (between 70-80 %). The resemblance between domestic heat pump installations power demand profiles with the wind power availability indicates that **between 56-64 % of the total residential energy demand can be easily converted to renewable energy sources (RES)** by installing heat pumps even without smart control and without household comfort levels deprivation.

Furthermore, it is found that 50 % of the hours in the year when heat pumps could represent a stress for the power grid occur in periods where active citizens are not at home (8AM to 7PM) and, out of this, 30 % have a maximum duration of 3 hours, which indicates that the flexibility embedded in the buildings' thermal storage mass and hot water storage tanks - which varies from 2 hours to 22 hours depending on the outdoor temperatures - could be activated with active control implementation to provide ancillary services to balance the power system. Still, it is found that the flexibility expected from domestic heat pump installations can be constrained by household characteristics, like the existence of young and small children in houses. In this case, everyday practices and social contexts should be taken into account, when exploiting demand side management methods through the use of heat pumps.

In addition, domestic heat pumps show to be energy efficient with measured seasonal performance factors ranging from 2.4 to 3.5.

- **Research question 2:** *Which low capacity power generator(LCPG) should be implemented and developed? Why? And How?*

On the basis of the encouraging results with respect to domestic heat pump performance, under real-life conditions, to further support the integration of RES and increase the energy efficiency in household energy demand, this work argues that **heat pumps should be coupled with solar thermal**

collectors and modified to use extra solar energy to cover the electrical demand of the house. In this work, a ground source heat pump (HP) coupled with a thermal solar collector modified to enable reversing the heat pump cycle and produce power in Organic Rankine cycle (ORC) mode is studied. This novel energy supply system is known as reversible HP/ORC unit and is referred in this work as *HP2Grid* concept. It is found that this modification can improve their thermal efficiency up to 32 % and increase the RES share by 63 % when compared to the heat pump unit alone.

However, the benefits of this synergy are only competitive with mature technologies (HP+PV, Photovoltaic thermal panels, etc.) in the case of buildings with large heat demands and/or in case of restriction of buying or selling electricity from/to the grid. The hybrid solution HP coupled with PV has a larger electrical output and shows a better match between domestic electricity demand and supply in comparison with the HP/ORC unit. Still, the HP/ORC unit also permits thermal demand flexibility and this allows this novel concept to be competitive in buildings with large thermal demand and/or in markets where the electricity feed-back is not possible or does not offer pay-back conditions. On the other hand, when compared to photovoltaic thermal (PV/T) energy solutions, which present similar electric to power ratio but higher user-friendliness, the HP2Grid can be undervalued because the PV/T principle is easier to understand. Yet, it is important to remember that, while PV/T is solely supplied by solar energy, the HP2Grid can further increase RES integration if integrated in a national grid with high-share of wind power.

- **Research question 3:** *How to optimize the interaction between HP2Grid system components for energy efficiency, especially considering thermal storage? And is that, also, the best control strategy for smart grid integration?*

It is found that in a single-family house, the HP2Grid overall system performance is enhanced when coupled with a **large hot water storage tank** (500 L) as well as better **house insulation standards**. The first reaches up to 44 % improvement in seasonal performance efficiency (SPF) and 35 % increase in the share of RES in the total energy consumption, when compared to a system installed in a similar house but with a 250 L hot water tank. While, the benefits with better insulation are 35 % improvement in terms of SPF and up to 79 % higher RES integration than in poorly insulated buildings. In terms of hot water storage configuration- based on empirical results of traditional heat pump installations [C.Carmo et al., 2015a] - hot water reservoir **used exclusively for domestic hot water preparation is recommended** to increase the system efficiency when compared to buffer tanks for both space heating and domestic hot water.

The answer to the second part of this research question -concerned with control strategies to generate smart grid integration - is studied by maximizing the solar energy integration. In this way, the solar fraction is maximized and the HP2Grid is more flexible from the power grid perspective. The control strategies used are rule base control and consider real load conditions enabled by occupancy information. It is discovered that, if implemented in passive buildings, the gain with these control strategies is negligible in terms of power consumption reduction, SPF improvement or RES integration increase, except if the system is equipped with a large hot water storage tank (500L), then a 5 % improvement in terms of SPF can be achieved. Still, if employed in poorly insulated houses the power consumed by the unit for heating can be reduced up to 5 % with the implementation of these control strategies. However, the use of such control strategies has shown to reduce the adverse effects of cycling in the compressor of the HP/ORC unit. With the control strategies used, the number of on/off cycles in a year is reduced by half.

- **Research question 4:** *What are the estimated benefits and costs of the HP2Grid concept at local and national level?*

  This question has been studied using dynamic simulations. A model of the HP2Grid concept integrated in a passive single-family house in Denmark was run under the power market conditions and for comparison a sensitive study of the influence of climate 4 other European locations was performed. Under Danish climate and current market conditions the HP2Grid concept **annual running costs are around 120€.** It is further shown in this work that, in different climates but under the same condition market, the running costs of the HP2Grid concept can be smaller than the benefits of selling electricity to the grid and, thus the house-owner could obtain a revenue of up to 1048€ by selling electricity produced to the grid. However, it should be bared in mind that in climates where the HP2Grid concept provide such benefits there is no need to install a HP/ORC unit as a solar thermal collector could cover the thermal demand. In addition, if combined with PV panels to cover the electricity demand of the building, they would provide larger benefits both economical and of demand cover factor.

  In terms of national benefits, the answer was partly introduced in the answers to the previous *research questions 1* and *2*. Households represent around 27 % of the total final energy consumption in Denmark, of which 48 % are detached single-family houses. Thus, if heat pump installations are extensively employed in detached residential buildings, the main national benefit are in terms of RES integration. Domestic heat pumps will enable the use of wind power. Additionally, if upgraded to HP2Grid concept, these benefits can be extended by an improvement up to 32 % on the energy conversion efficiency of these systems and an increase of 63 % RES integration by using solar energy to cover the final building energy demand for electricity, space heating and domestic hot water preparation. Also, the integration of solar energy enables more flexibility of the household demand, with the potential to reduce the grid stress in case of no wind power supply and solar energy availability.

Exactly how much the HP2Grid is able to support the Danish energy system with 50 % wind power, in terms of flexible power is considered ambitious to predict. First, at individual unit level, the flexibility potential of HP2Grid concept, depends on the heat pump capacity installed and the heat demand of the building, which ultimately are driven by end-users and/or installers preferences. Additionally, these predictions are expected to be less realistic when stable framework conditions of energy systems can no longer be assumed, as it has happened in the recent years with successive energy policy changes.

3.2 Perspectives

The overall conclusion it that the HP2Grid concept can contribute significantly to the transition from fossil-fuel to renewable energy based energy system. If it becomes widely implemented in the residential sector, cogeneration technologies, like the HP2Grid concept can make a fundamental turn in the future energy systems. The domestic demand sector becomes also a production sector, shifting the sector from consumers to prosumers, i.e. consumers some times and producers in others. Yet, the actual employment of the HP2Grid and the realization of its benefits at local and national level depends on private and/or corporative economic perspectives backed by the implementation of financial, regulative and policy incentives. For instance, apart from the mechanisms aforementioned, the author believes that the introduction of a heat market - where the energy in form of heat can be exchanged between different buildings - in the national energy systems market could be a key tile to pave the way to 100 % fossil-free energy systems.

3.3 Future work

To conclude, the author would like to share ideas for future work based on challenges encountered:

- The study of associations in building, household characteristics and space heating load profiles in residential buildings equipped with heat pumps was limited to the available data. Yet, it could be interesting to consider more household variables like everyday practices, age and social status as well as increase the time resolution to further understand the differences in the temporarily of space heating profiles.

- The study of influence of different tank volumes, different sizes of spiral internal heat exchangers and tanks operating on a large range of different flows, as it can happen in different building installations, could be extended. The hot water tank model validation in this work only covers one volume, one size and position of heat exchangers and a set of 5 different operation conditions. In case of mismatch, new discretization methods or new mixing parameter values should be implemented based on the model and experimental results of the test rig designed for this work.

- The annual simulations of the HP2Grid concept performed in this work only considered one demand profile representative of residential buildings in one country. It is thus suggested to simulate annual performance of the system in different building types - with different lighting and appliances and domestic hot water profiles- that might turn the reversible HP/ORC unit more competitive. In addition, the amount of "green" power integrated from the grid into the building demand thanks to the HP2Grid concept should also be taken into account. In other words, it could interesting to determine if the power consumed from the grid by a residential building equipped with HP2Grid concept is produced by large scale RES based power generators in the grid when determining the amount of RES integration with this new concept. Finally, it could be also interesting to develop a simple control strategy to the HP2Grid model which considers weather forecasts to improve both RES integration and the potential of the concept to deliver ancillary services.

- With the improvement of insulation standards in buildings cooling loads gain significance in buildings energy demand to such a degree that it essential to take them into account to study new energy supply concepts. The current application of the system simulation model is limited to heating demand loads, cooling loads should also be considered for more realistic results.

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