Applying heat pump systems in commercial household products to reduce energy use and environmental impact

How to halve the electricity consumption for a household dishwasher

Peder Bengtsson
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DOCTORAL THESIS

Karlstad University Studies | 2017:10

urn:nbn:se:kau:diva-48132

ISSN 1403-8099


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Distribution:
Karlstad University
Faculty of Health, Science and Technology
Department of Engineering and Chemical Sciences
SE-651 88 Karlstad, Sweden
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Print: Universitetstryckeriet, Karlstad 2017
Abstract

In the household appliance industry, heat pump systems have been used for a long time in refrigerators and freezers to cool food, and the industry has driven the development of small, high-quality, low-price heat pump components. The low price of good quality heat pump components, along with an increased willingness by customers to pay extra for lower electricity consumption and environmental impact, have made it possible to introduce heat pump systems in other household appliances, with the expressed purpose of reducing electricity consumption.

Heat pump tumble dryers have been on the market since 2000 and dominate the market today. A heat pump dishwasher was introduced on the market in 2014 and a heat pump washing machine in 2016. The purpose of adding a heat pump system in these three products was to decrease electricity consumption.

Papers I and II used a methodology where transient simulation models were developed and used to increase knowledge about how to decrease electricity consumption for a tumble dryer (I) and a dishwasher (II) by adding a heat pump system.

Simulations in Paper I showed that a 50% larger compressor in a heat pump tumble dryer decreases the drying time by 14% without using more electricity. This satisfies the consumer requirement for a shorter drying time without increasing energy use.

Papers II, III and V showed that a lower electricity consumption and lower global warming potential together with an energy-efficient drying method, with no humid air going into the kitchen, give a heat pump dishwasher competitive advantages compared to any conventional dishwasher currently on the market. Using simulations, this dissertation concludes that a commercial heat pump dishwasher, using R600a as a refrigerant, will reduce electricity consumption and TEWI by 50% compared to the conventional dishwasher.
Paper IV shows the possibility to use a low cost expansion device as a capillary tube in the heat pump dishwasher without increasing electricity consumption. This result increases the possibility of the heat pump dishwasher becoming more common in the future.

The challenge for the manufacturer is to develop and produce a high-quality heat pump dishwasher with low electricity consumption, predict future willingness to pay for it, and launch it on the market at the right moment with the right promotion in order to succeed.
Sammanfattning

Historiskt har värmepumpar använts i våra hushåll för att kyla och frysa mat. Genom åren har tillverkarna för kylskåp och frysar drivit utvecklingen av små billig och tillförlitliga komponenter till värmepumpssystem. Tillgången av dessa komponenter tillsammans med kundernas efterfrågan av energisnåla och miljövänliga hushållsprodukter gör det intressant att införa värmepumpsteknik i fler hushållsprodukter, nu med syfte att minska elförbrukningen.


I artikel I och II användes en metodik där transenta simuleringsmodeller utvecklats för att öka kunskapen hur man sänker elförbrukningen för en torktumlare (I) och en diskmaskin (II) genom att tillföra ett värmepumpssystem. Simuleringar i artikel I visar att en 50% större kompressor i en värmepumpstorktumlare minskar torktiden med 14% utan att förbruka mer el.

Artiklarna II och III visar att en värmepumpsdiskmaskin förbrukar mindre el och har en mindre påverkan på den globala uppvärmningen jämfört med en traditionell diskmaskin. Simuleringar i denna avhandling visar att en framtida kommersiell värmepumpsdiskmaskin kan minska både elförbrukningen och globala uppvärmningen med 50% om man använder ett naturligt köldmedia som tex R600a. I artikel V introducerades ett nytt energieffektivt torksystem som dessutom har fördelen att inte släppa ut någon fuktig luft ut i köket.

ökar potentialen för värmepumpsdiskmaskinen på den hårt prispressade hushållsmarknaden.

Utmaningen för tillverkaren är att utveckla och tillverka en värmepumpsdiskmaskin med hög kvalitet och låg elförbrukning. Dessutom är det viktigt att kunna förutspå hur mycket kunden är villig att betala för den nya tekniken, och sedan lansera den vid rätt tidpunkt med rätt marknadsföring.
Acknowledgement

First I would like to thank ASKO Appliances AB and the multidisciplinary Industrial Graduate School VIPP - Values Created in Fibre Based Processes and Products - at Karlstad University, with financial support of the Knowledge Foundation, Sweden.

I would like to thank my supervisors, Associate Professor Jonas Berghel and Associate Professor Roger Renström for a fruitful cooperation. Whenever we discuss technical topics, our shared result is always better than what I might have created alone.

I want to thank all the personnel at ASKO Appliances AB for allowing me the space to carry out my experimental work and for their willingness to discuss different technical solutions.

Thanks to Professor Björn Palm and Dr. Samer Sawalha at KTH, Royal Institute of Technology, for helping me and showing me how to perform simulations in energy systems.

Thanks to Professor Trygve Eikevik at NTNU, Norwegian University of Science and Technology, Trondheim, for our cooperation and for my fruitful visits to Trondheim.

Finally, I would like to thank my family who have had patience with me, especially when I was away from home.
List of Publications

This thesis is based on the following Papers, referred to in the text by their Roman numerals.


Paper II Bengtsson, P.; Berghel, J.; Renström, R. A household dishwasher heated by a heat pump system using an energy storage unit with water as the heat source. *International Journal of Refrigeration* 2015, 49, 19–27.


Other related publications listed below are not included in this thesis.


Bengtsson, P.; Berghel, J. Halving the electricity consumption by adding a heat pump system in a household dishwasher. *6th International Symposium*
Oral presentation.
The thesis author’s contributions

Paper I  The planning, development and work with the experimental setup and the simulation model was performed by Peder Bengtsson. The writing was done jointly.

Paper II  The planning was done jointly. The development and work with the experimental setup and the simulation model was performed by Peder Bengtsson. The main part of the writing was by Peder Bengtsson.

Paper III  The planning was done jointly. The development and work with the simulation model and the writing was by Peder Bengtsson.

Paper IV  The planning, development and work with the experimental setup and the simulation was performed by Peder Bengtsson. The evaluation and writing was done jointly.

Paper V  The planning, development and work with the experimental setup was performed by Peder Bengtsson. The evaluation and writing was done jointly.
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1 Introduction

The total environmental impact from housework such as washing and drying clothes and dishware is attributed to the use of energy, water and chemicals. How large this total environmental impact will be depends on many choices the user must make, exemplified in Figure 1 for washing dishware.

Figure 1: Choices a user must make, when washing dishware, which affect the chemical use, water use and electricity consumption finally affecting the total environmental impact.

The first choice for the user is whether the washing of the dishware is to be performed by hand or by a dishwasher (see Figure 1). Studies have shown that a modern household appliance in general uses less energy and water, and fewer chemicals compared with doing the operation by hand in a modern home [1-3]. So the overall advice for achieving a low environmental impact when doing housework such as washing dishware is to use a modern energy-efficient dishwasher [2].

When the consumer has decided to use household appliances such as a dishwasher, the total environmental impact from the use of electricity, water and chemicals is a combination of both the consumer’s dishwashing habits and the effectiveness of the appliances themselves [1,2,4-7] (see Figure 1). Examples of consumer habits which particularly affect the environmental impact of using a dishwasher are programme choice, the use of the dishwasher load capacity and additional pre-treatment by hand [1]. The recommended habits for dishwasher use are
that the machine should be fully loaded and an energy-efficient programme should be used with no additional pre-treatment by hand \[1\].

In my thesis work, only the electricity consumption and the environmental impact attributed to the concept and choice of dishwasher were treated, shown as bolder lines in Figure 1. The effects of chemical and water use on the environmental impact were not treated.

In the past, there was less focus on performance values such as electricity consumption and water use when a customer chose which household appliances to buy \[8,9\]. The customer was simply satisfied that the product worked. Today it is different, as since the 1990s it has been obligatory for household appliance manufacturers in Europe to declare the performance values visibly on the front of the product according to a European standard \[1\]. Visible performance values for the dishwashers are the electricity consumption, water use, sound level, cleanness, dryness and capacity (amount of dishware). These visible performance values make it easy for a customer to compare products in the store when choosing which one to buy. This has forced competition among the manufacturers to have the best performance values on the market \[4,10\]. On internet sales sites and in stores it is now easy for a customer to compare and evaluate these values on a large number of products. Today these values are highly important when the customer chooses which one to buy and when the manufacturer decides what price to put on the product \[4\].

Today’s customers focus on the performance value of low electricity consumption. The fact that this value is visible on the front of a dishwasher has driven the fact that one of the core activities for the manufacturers of household appliances today is to develop, produce and sell products with proven low electricity consumption. Manufacturers are applying a significant amount of resources to develop household appliances such as dishwashers, washing machines and tumble dryers with low electricity consumption. New techniques which reduce electricity consumption are always relevant for the manufacturers to evaluate as they are introduced on the market.
In recent decades the environmental impact from products has been shown to affect customers’ behaviour, and related eco-labels (e.g. EU Ecolabel, Energy Star, Nordic Swan environmental label, carbon footprint labels) are important for many customers when choosing products \[11-19\]. Today, people are aware of environmental aspects such as global warming and many are willing to pay an extra premium for a product if they are convinced that this product is a good environmental choice.

Thus, in today’s market, customers are willing to pay for products with low electricity consumption and low environmental impact. However, few articles are published in the scientific literature that present new techniques for reducing electricity consumption and environmental impact for dishwashers, washing machines and tumble dryers, despite the extensive work by the manufacturers. The latter restrict their sharing of knowledge, and the speed of product development is high. A good concept will quickly be on the market if it is competitive, such that sharing important knowledge in the literature can in that case be disadvantageous for the manufacturer.

Here are two examples of articles about new techniques to reduce electricity consumption for dishwashers which have resulted in new products or new products which have also resulted in published articles. A study on a dishwasher where an additional adsorption cycle was used showed that total electricity consumption was reduced by 25% \[20\]. BSH Home Appliances AB (Bosch) \[21\] used this technique with zeolite as adsorption material mainly to achieve better drying results and decreased electricity consumption. By using this technique, this dishwasher attained the energy label (A++++) and its electricity consumption is 0.83kWh/cycle.

Another concept is to use the heat coming from the wastewater of the dishwasher to heat fresh water entering the dishwasher \[22\]. Calculations and performance tests showed a reduction of 25% in the total electricity consumption. Miele AB (Miele) \[23\] has used this technique and call it ‘EcoTech heat reservoir’ with an energy label of (A+++ –20%) and electricity consumption of 0.67kWh/cycle.
The heat pump system is today a well-known technique and has for decades been used in refrigerators and freezers to create cooling for food and has been used for 15 years in tumble dryers to reduce electricity consumption. For the dishwasher and the washing machine, the heat pump technique has only just been introduced.

The only heat pump washing machine on the market in 2016 was V-Zug Adora SLQ WP [24] which uses R134a as refrigerant. This machine consumes 40% less electricity compared with a conventional variant heated with an electrical element.

The same brand V-Zug was also the first heat pump dishwasher in 2014. This was the only one on the market in 2016 and is called V-Zug Adora SL WP [24] and uses R134a as refrigerant. This dishwasher uses the heat pump system only to heat the dishwasher and consumes 40% less electricity compared with a conventional variant heated with an electrical element.

A new technical solution is described in this dissertation: compared to the heat pump dishwasher from V-Zug AG, the heat pump system in this new concept is used for both heating and drying in the dishwasher. In my work, a new drying system was introduced by which the dishware was dried by circulating humid air against a surface on the water tank, which is full of ice created during the heating step.

When a heat pump system is used in a product, the selection of refrigerant and the total electricity consumption are key aspects of the total environmental impact from the heat pump product. Only a few refrigerants can be considered as environmentally friendly regarding the aspects of ozone depleting potential (ODP) and global warming potential (GWP). Much research has been conducted and is ongoing in the area of introducing and replacing environmentally harmful refrigerants with environmentally friendly alternatives of refrigerants [25-55]. There is significant interest in Europe and elsewhere for the use of hydrocarbons as refrigerants in small-sized heat pump and refrigeration systems (<20kW cooling) [52] because of the low GWP. However, use of hydrocarbons carries a risk of possible explosions and fire. Other possible refrigerants such as ammonia and carbon dioxide, with low
GWP, in a small system are not as common because of the limited supply of components \[56\].

In the household appliance industry today, only the consumption of electricity affects the EU energy labelling system. This labelling system does not take into consideration the choice of the refrigerant, which affects the GWP. In the heat pump industry currently there are examples of using the total equivalent warming impact (TEWI) to rating the products by CO2 equivalent impact, where both the refrigerant emission and the electricity consumption during its lifetime are included \[26,28,57\]. However, in the future, when heat pumps become more common in the industry, a rating system based on the total amount of CO2 equivalent impact, such as TEWI, may be used.

There is a willingness on the part of the end consumer to pay an additional premium for alternative household appliances with low total electricity consumption and low environmental impact. A critical aspect for the manufacturer is whether it is possible to get a matching or greater premium from the whole customer chain compared with the cost of the added heat pump system. In the case of the heat pump dishwasher, the added values are the lower electricity consumption and environmental impact. This economic aspect is crucial for a manufacturer if the introduction of the added heat pump system in a dishwasher is to succeed on the future market.

The selection of the type of expansion device affects the cost of a heat pump dishwasher. Using a less expensive capillary tube instead of a more expensive variable expansion will be preferred with regards to cost. However, in the heat pump system in the dishwasher, the condensing pressure is increasing and the evaporator pressure decreasing when the compressor is on during heating. In these types of transient heat pump cycles, where the pressures are varying, the use of a variable expansion is generally recommended \[58\]. However, it will always be interesting to compare variable expansion devices against a less expensive capillary tube with regards to the electricity consumption in the household appliance industry, where the focus on cost is high.
The washing and drying processes in the dishwasher, washing machine and tumble dryer are transient. When increasing knowledge or comparing performance in terms of electricity consumption for new concepts such as heat pump systems, it is in some cases beneficial to simulate the complete system including the heat pump system by using a theoretical simulation model [27,28,59,71]. In my studies, transient simulation models of a tumble dryer and a dishwasher including a heat pump system were developed and validated. Characteristics of how single components affected the total electricity consumption for the complete tumble drying and dishwashing cycles were studied with these transient simulation models.
1.1 Objective
The five separate articles in this thesis describe research which was carried out with specific aims and methodologies. The overall aim was to increase knowledge of household appliances when adding a heat pump system with the purpose of decreasing the environmental impact and electricity consumption. In the conclusions and discussions of the thesis, industry knowledge was obtained along with the simulation and experimental results. The objectives were to

- increase the knowledge of how an added heat pump system affects the environmental impact and electricity consumption of household appliances, such as tumble dryers and dishwashers, by developing validated transient simulation models.
- introduce and increase the knowledge for a new concept of closed drying system for the heat pump dishwasher.
- use the increased knowledge, show how to halve the electricity consumption in a dishwasher by adding a heat pump system, and introduce a new drying concept, compared with a 2016 on-market conventional dishwasher.
- discuss the market value of a future heat pump dishwasher.
1.2 Development of products and features in the household appliance industry

Washing and drying clothes and dishware has been done by hand for a long time. However, in developed countries washing machines, tumble dryers and dishwashers have become increasingly common. In the past, younger people learned from the older generation how to wash clothes and dishware. At present, much information about what temperature to use, how long to wash something, which detergent to use and how much, mechanical agitation, how to clean spots, etc. has been lost. Instead most of this ‘washing’ knowledge is now built into the electronic unit in washing machines and dishwashers. Developing automatic features with built-in knowledge is currently one of the most important technical areas in the household appliance industry.

1.2.1 Eighteen washing machine manufacturers disappeared from Sweden

ASKO Appliances AB was originally a Swedish company and had acquired 60 years’ experience in developing, manufacturing and selling dishwashers, washing machines and tumble dryers. Today their products are sold in Sweden as ASKO and Cylinda brand, and in the rest of the world they sell under the ASKO brand. The first household product on the market from ASKO Appliances AB was a washing machine, manufactured in 1950. It consisted of a container with a rotating drum into which clothes, water and detergent were put (see Figure 2).
In the 1960s, the company, which would later be known as ASKO Appliances AB, was one of eighteen washing machine manufacturers in Sweden [8,9]. All of them wanted to develop, manufacture and sell washing machines as long as it was profitable. They included brands as Electrolux, Electro Helios, Cylinda, Husqvarna, Värmos, Osby, Selbergs, Crescent, CTC, and others [8,9]. The last manufacturer in Sweden was ASKO Appliances AB, which moved its development and manufacturing to Slovenia in 2013. Some of these companies are still brand names in Sweden, but the machines are manufactured in other countries. Today the household appliance industry is global and is one of the most competitive industries, where the major players have manufacturing units in countries with low costs and can move manufacturing units with relative ease.

The final reason for most of the closures of washing machine manufacturers in Sweden was low profitability, which resulted in closure, bankruptcy or acquisition by other companies. There were four reasons in particular for their economic situation [8,9].

- **Investment in technical features that were wrong, or launched too early or too late.** Some manufacturers invested in technical features that were not well received by customers, which resulted in low sales.

*Figure 2: The first washing machine from the company, which would later be known as ASKO Appliances AB, was made in 1950. Initially the name of the factory and the brand was ‘Junga verkstäder’ [72].*
volumes. Others launched good technical features, but did so too early, when the market was not yet ready.

- **Poor product quality.** Poor product quality with machines breaking down or underperforming led to dissatisfied customers and large after-sales costs. The bad product quality was due to complex technical solutions and poor knowledge of mass production.

- **Small or no sales network.** Small local manufacturers with small local sales organisations found it difficult to increase sales volume by expanding the market.

- **No in-house research and development, copying competitor’s technology.** It is difficult for small companies to have their own development organisation. This is acceptable when the technology is basic. However, as the speed of technical change increased, it was hard for many companies to develop a modern washing machine. Some copied a competitor’s design in every detail, indicating a lack of a development organisation. It is a common belief that by copying, one can only obtain 90% of the product’s characteristics and performance [8]. In many cases this turned out to be true. The copied products always had inferior performance and quality compared to the original.

Generally, it was a combination of these reasons that led to low profitability.

The manufacturers’ ability to survive was rigorously tested when the whole washing machine industry made technological leaps. The manufacturers needed to adopt these new technologies if they wished to continue to sell washing machines on the market. There were three main areas in which manufacturers experienced problems keeping up with technology development [8,9].

- **Heating the water in the washing machine with an electrical element.** In the first washing machines, users had to add the hot water themselves; it was not possible to heat the water in the machine. Introducing an electrical element into the machine to heat the water was a challenge for manufacturers who had a history of purely mechanical manufacturing. A combination of the wrong technical
solutions, lack of development competence, and quality problems meant that some companies ceased to exist.

- **Washing and centrifugation in the same machine.** There was no integrated centrifugation in old washing machines. To spin the washing, you had to have a separate centrifugation machine. Integrating centrifugation required that the mechanical structure be totally redesigned. This huge technological leap generates large vibrations and requires a high-speed electrical drive system. Manufacturers came up with different technical solutions for the drive system and for handling the vibration. Some solutions were not adequate and resulted in poor function and product quality. This technological leap was difficult for manufacturers without well-functioning research and development knowledge.

- **Fully automatic machine with automatic wash programmes.** An automatic wash programme means that the user only needs to start the machine, and then the washing machine will automatically handle all the washing steps such as prewash, wash, rinse, and centrifugation. Developing and manufacturing the first electromechanical generation of automatic washers required electrical competence. Developing and manufacturing the second generation of fully electronic machines required electronic competence. Automatic wash programmes generated a new field of knowledge in research and development. With these automatic programmes, it was possible to design and optimise wash and rinse performance while also keeping electricity and water use as low as possible. Today the development of automatic programmes is one of the core businesses of washing machine manufacturers. Significant resources are invested in research and development in this area.

This evolution of developments for the washing machine occurred similarly for dishwashers and tumble dryers. For both, the introduction of fully automatic machines with automatic wash and dry programmes was a big technical leap. Other technical leaps for the tumble dryer occurred when the condenser tumble dryer and the heat pump tumble dryer appeared on the market. For dishwashers, other technical leaps were less obvious, as development progress occurred in small steps.
1.2.2 Timing for a manufacturer to invest in a new product feature

Abel [73] claimed that the timing of market entry for a feature is one of the most critical decisions manufacturers have to make. Hidding et al. [74] found that it is generally best to enter the market closer to the inflection point in the S-curve where market growth increases rapidly.

The fact that the market value of product features is time-dependent and varies over time makes it a risky decision to start a large project to develop features for the future. As previously mentioned, some washing manufacturers disappeared from the market because of bad economics caused by launching new features too early or too late. The value of features could be totally different for the 1980s, 1990s and 2000s compared to today and changes can occur very quickly. Examples of features of a washing machine for which the market value has changed over time include: ‘cleaning results’, maximum spin speed (rpm) and maximum washing load.

For example, in the first washing machine from ASKO Appliances AB (Figure 2) the cleaning results were an important sales feature compared with washing by hand. In the 1970s, the cleaning result became a natural feature and in the 1980s was taken for granted in a washing machine. Not until the 2000s did the cleaning results appear in another form as sales features such as automatic programmes for specific textiles and unique programmes to wash clothes quickly.

In the 1960s, the ability to spin the clothes was an important sales feature for a washing machine. Users appreciated it because the clothes dried much faster after being spun in the washing machine. From the 1980s to the 2000s, manufacturers competed to have the machine with the highest spin speed. In the late 2000s, this changed as the market became convinced that a spin speed of around 1600 rpm was sufficient. All the manufacturers already had machines at that spin level, so the economic value of this feature rapidly decreased.

Historically, the focus on the economic value of a high maximum washing load was quite high. From the 1980s until the 2000s (when the focus was on spin speed), the maximum washing load had less economic
value. Today the maximum washing load has become one of the most important values for a washing machine, and is in some cases used to rate different washing machines against each other.

A new feature always involves investigation of any new economic aspects regarding the feature and an estimation of when is the best economic timing to enter the market with the feature. In studies discussing the benefits of when to introduce new technical features on the market \cite{73-80}, three groups are common \cite{78,79,81}: first movers, second movers and followers.

*The first mover.* The first on the market with a new technical feature is the pioneer. By starting earliest, first movers have more time than later entrants to accumulate and master technical knowledge \cite{75}. However, information on how the market reacts is unknown in the beginning. Early stage quality problems can occur, and it is more difficult to lead than to follow the market \cite{49}. A strong research and development department and a deep pocket (large-scale marketing for a long period of time) are keys to success as a first mover. In the business world, being a first mover is usually associated with innovation and good performance \cite{79}.

*The second mover (early follower).* In many situations it may not make much sense to try to be the first mover. In environments where a first-mover advantage is likely to occur after years of losses, and then be short-lived, it could be better to wait until the market is ready. The second mover is able to use much technical and marketing information from the first mover.

*The follower.* Followers have several advantages. They can focus merely on explaining why their products are better, while early entrants must first explain what their new feature or product is and does \cite{74}. Thus, followers have a lot of information and can avoid some early quality problems. However, they have missed the experience of years on the market (learning-by-doing) \cite{73}. 


1.3 Types of customers for household appliances

There are different types of customers on the market, and it is very important for the manufacturers to identify these customers and understand their requirements. Manufacturers have identified the following three customer types: the end consumer, the consumer institute and magazine, the distribution and the retail chain and the stores for household appliances [72].

End consumer. The first obvious customer is, of course, the end consumer who uses and pays for the product. The product has to meet the end consumers’ requirements and convince them that this is the best product for the service, for example ‘washing and drying clothes or dishes’. It is difficult to define a typical end consumer, although manufacturers spend much time trying to understand how they act when deciding which product to buy.

Consumer behaviour and requirements are different in different countries around the world. Features can provide great value for one group of consumers and no value for another group. The whole customer chain behaves differently depending on which consumer group the household appliances are intended for. Here are some examples of surveys conducted in order to understand how different types of end consumers react to different features and their willingness to pay for them.

Stammer et al. [82] surveyed how different types of end consumers act and look for products in different segments and prices for washing machines. They identified five types, namely: ‘brand-conscious buyers’ (who have high quality expectations and are reluctant to search for low price), ‘discount buyers’ (who aim at simplifying the choice process, targeting discount shops), ‘optimisers’ (who are prepared to invest time and effort for price rewards), ‘high-price shoppers’ (with high quality and brand preferences, for which price has an important signalling role) and ‘price seekers’ (who consider price as the prominent decision criterion).

Ward et al. [15] conducted a survey in the United States and found a willingness to pay an extra $250–$350 for a refrigerator that has been awarded an ENERGY STAR label. The results provided evidence that
respondents’ willingness to pay was motivated by both energy cost savings and environmental benefits.

Willingness to pay for product brands was examined in the United States for products in different categories [83]. The conclusion was that consumers have a stronger preference and higher willingness to pay for brand name products with longer usage, such as electronics products rather than for clothes and food, which have a short life.

Galarraga et al. [16] investigated the willingness of consumers in Spain to pay extra for a dishwasher with a lower electricity consumption. They observed the sales of 318 dishwashers of different brands in different stores. It was found that 15.6% of the final price was actually paid for a reduction in electricity consumption, reflected in the change from an (A) to (A+) on the dishwasher energy label.

In the United States, the value of the Green Power Partnership (which means that the manufacturer uses green power for production) was examined [17]. The conclusion was that consumers would be willing to pay a $53 to $68 premium for a refrigerator produced by a Green Power Partner.

Ha et al. [18] undertook a survey in South Korea of the behavioural intention to purchase energy-efficient products such as air conditioners, TVs, fridges and washing machines. They concluded that existing beliefs about the positive impact of buying an energy-efficient product might persuade green consumers to select that option instead of an alternative with a lower price. The strength of these beliefs increased when energy-saving products were marketed as being innovative as well as energy-efficient.

Harris et al. [19] conducted a survey in New Zealand and Australia to determine whether sustainability is a selling point for dishwasher products. One conclusion was that there is growing consumer concern about the implications of global warming and the currently unsustainable level of exploitation of the earth’s finite resources. This drives increasing consumer support for ‘environmentally friendly’ products and practices, and an increased willingness to pay for them.
Consumer institutes and magazines as Råd och Rön and Choice. This type of customer must be satisfied that the product will turn out well in their tests. Some end consumers read test reports on appliances in magazines before making a purchase, and manufacturers use test results for advertising if they turned out well. Thus, manufacturers work hard to ensure that they get a good rating from the consumer institutes. Assessment criteria such as electricity consumption, usability and noise levels are usually considered in the institute tests.

The distributors, the retail chain and the stores for household appliances. The entire distribution chain from wholesalers to stores consists of customers who have to be motivated to sell the manufacturers’ products. Wholesalers and stores want to make money without having trouble with broken products of poor quality. If a store earns more money by selling a particular brand, or an employee gets some personal benefit, they will, of course, show the product and try to convince the end consumer to buy it. In order to sell many products at a good profit, wholesalers and stores need be treated well so that they are motivated to convince the end consumer to choose household products from that manufacturer.

Manufacturers have to deal with issues such as how much extra money the end consumers are willing to pay, how the magazines will judge a feature, whether wholesalers and stores will promote the new feature instead of others, and whether the manufacturer chooses to be the first mover, second mover or a follower. For some manufacturers, the first-mover advantage is large; for others, the follower advantage is large. However, the odds of succeeding with a new feature depend on how well the manufacturer understands the market and the technology in order to time the introduction. All manufacturers must decide whether it is better to be a first mover, second mover or a follower, to introduce features, improve features or to imitate features [78].
1.4 Electricity consumption for tumble dryers, dishwashers and washing machines

The motivation for manufacturers in Europe to develop tumble dryers, dishwashers and washing machines with low electricity consumption was increased when the EU energy labelling system appeared in the 1990s \(^8\). The labelling system forced manufacturers to measure the electricity consumption in a standardised manner and to display the electricity consumption on the front of the machine in the store. This made it possible for the end consumer to compare the electricity consumption of different machines and thus resulted in competition between manufacturers to have the machine with the lowest electricity consumption.

1.4.1 Tumble dryers

Historically, there has not been any significant reduction in electricity consumption for the two traditional types of tumble dryers, vented and condenser, despite intensive efforts by the manufacturers \(^8\). With these two drying processes, the natural laws when drying water seem to be close to the optimum regarding electricity consumption.

The only major improvement in electricity consumption (compared to dishwashers and washing machines) was when heat pump technology was introduced in a closed cycle dryer (see Table 1, which has used the ASKO Appliances AB tumble dryers as examples).

*Table 1: Development of electricity consumption for ASKO Appliances AB tumble dryers \(^8,72\).*

<table>
<thead>
<tr>
<th></th>
<th>Year 1985</th>
<th>Year 2016</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Vented tumble dryer</strong> (kWh/kg textiles)</td>
<td>0.67</td>
<td>0.59</td>
</tr>
<tr>
<td><strong>Condense tumble dryer</strong> (kWh/kg textiles)</td>
<td>0.73</td>
<td>0.64</td>
</tr>
<tr>
<td><strong>Heat pump tumble dryer</strong> (kWh/kg textiles)</td>
<td>-</td>
<td>0.24</td>
</tr>
</tbody>
</table>
1.4.2 Dishwashers

The purpose of a dishwasher is to wash dishware. To understand the use of energy and how to develop a ‘well-working’ cleaning process, it is important to know the basics of washing.

Four main factors affect the washing results: chemical action, mechanical action, heat and time. To describe how to clean, it is accepted in the industry to use the Sinner’s Circle \[8\] (see Figure 3).

![Sinner’s Circle Dishwasher](image)

*Figure 3: Sinner’s Circle, which illustrates the factors which affect the washing results in a cleaning process such as in a dishwasher \[8\].*

The total area of the Sinner’s Circle defines how clean the result becomes. By combining the four factors, it is possible to reach the same area (cleaning results) with reduced energy use. In a dishwasher, the mechanical treatment affects the cleaning results less when compared with the washing machine where the laundry is rotated in the cylinder. In the dishwasher the pressure of the water jets is low and the chemicals more active compared with the washing machine (see Figure 3).

Historically, the main approach for decreasing the electricity consumption of the dishwasher is to reduce the heat, achieved by lower washing temperature in combination with longer cycle time. That affects the Sinner’s Circle by increasing the time factor and decreasing the heat factor without changing the area (cleaning result) in the Sinner’s Circle.
Table 2 compares the development of water use, electricity consumption and operating time between older and more modern dishwashers from ASKO Appliances AB.

Table 2: Development of operating time, water and electricity consumption for ASKO Appliances AB dishwashers \(^{[8, 72]}\).

<table>
<thead>
<tr>
<th></th>
<th>Year 1977</th>
<th>Year 2003</th>
<th>Year 2016</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Water usage</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(liters/cycle)</td>
<td>60.0</td>
<td>9.9</td>
<td>9.9</td>
</tr>
<tr>
<td><strong>Electricity usage</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(kWh/cycle)</td>
<td>3.70</td>
<td>1.10</td>
<td>0.82</td>
</tr>
<tr>
<td><strong>Total operating time</strong></td>
<td>105</td>
<td>160</td>
<td>200</td>
</tr>
</tbody>
</table>

For the dishwashers there was a reduction in water use together with decreased washing temperatures, which led to lower electricity consumption, when comparing the years 1977, 2003 and 2016 (see Table 2). However, the total operating time was increased to compensate. In the last ten years the decrease in electricity consumption has flattened out because it is difficult to reduce water usage and decrease the washing temperatures any further.

1.4.3 Washing machine

The development of the washing machine was similar to the dishwasher. Table 3 illustrates the development of water use, electricity consumption and operating time between an old and a modern dishwasher from ASKO Appliances AB.

Table 3: Development of operating time, water and electricity consumption for ASKO Appliances AB washing machines \(^{[8, 72]}\).

<table>
<thead>
<tr>
<th></th>
<th>Year 1977</th>
<th>Year 2003</th>
<th>Year 2016</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Water usage</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(liters/kg textiles)</td>
<td>55.0</td>
<td>9.8</td>
<td>9.8</td>
</tr>
<tr>
<td><strong>Electricity usage</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(kWh/kg textiles)</td>
<td>1.06</td>
<td>0.19</td>
<td>0.18</td>
</tr>
<tr>
<td><strong>Total operating time</strong></td>
<td>115</td>
<td>125</td>
<td>200</td>
</tr>
</tbody>
</table>
As for the dishwasher, there was a large improvement in water use and electricity consumption. To compensate to obtain a clean result, the total operating time was increased.

### 1.5 Heat pump system

Refrigeration engineering mainly started to develop in the early 1900s, although the basis in thermodynamics was established somewhat earlier [58]. In the beginning, refrigeration/heat pump systems were used to cool food. Today, a large part of the refrigeration/heat pump system is used to create a good indoor climate. In developed countries, 15%-20% of all electricity consumption is used for driving refrigeration/heat pump equipment, and 40 million air conditioning units are manufactured annually [85].

The purpose of a basic refrigeration/heat pump system is to extract heat $Q_{\text{evap}}$ from a lower temperature source (heat source) and release heat $Q_{\text{cond}}$ to a higher temperature sink (heat sink) as shown in Figure 4. The only difference between a refrigeration system and a heat pump system is that a refrigeration system extracts the useful heat $Q_{\text{evap}}$ at the evaporator, while a heat pump system rejects the useful heat $Q_{\text{cond}}$ at the condenser.

![Figure 4: Schematic of the components and function of a basic heat pump/refrigeration system.](image)

The basic configuration of a heat pump/refrigeration system includes a compressor, expansion device, evaporator, condenser and a refrigerant
which circulates in an closed loop formed by the components, which are connected by tubes, see Figure 4. When the compressor is running, the system will end up with two pressure levels, the high-pressure $p_{\text{cond}}$ in the condenser and the low-pressure $p_{\text{evap}}$ in the evaporator. The characteristics of the refrigerant cause it to condense in the condenser and evaporate in the evaporator. During evaporation to gas at the lower pressure, the refrigerant extracts heat, corresponding to the latent heat of evaporation. During the process at the higher pressure side, the refrigerant rejects heat and condenses back to liquid in the condenser.

1.5.1 Compressor

The purpose of the compressor in a heat pump system is to transfer the vapour from the evaporator to the condenser where the pressure is higher than in the evaporator in the most effective way (see Figure 4). The total performance of a heat pump system is strongly influenced by the compressor capacity, isentropic efficiency and volumetric efficiency. There are different types of compressors on the market; here are some examples of different principles used for compressors today [58].

- Reciprocating, piston-type compressors.
- Rotary compressors (with rotary vanes or rolling pistons).
- Scroll compressors.
- Screw compressors (with one or two rotors).
- Turbo compressors.

All of these variants have different behaviours and are suitable for different applications. In Paper I, a rotary compressor with a rolling piston was used. In Papers II, III, IV and V, reciprocating, piston-type compressors were used. Both of these variants are currently common on the market in small appliances such as fridges, freezers and heat pump tumble dryers.

1.5.2 Expansion device

The purpose of the expansion device (expansion valve) in a heat pump system is first to maintain the pressure differential between the low-pressure side in the evaporator and the high-pressure side in the condenser created by the compressor, see Figure 4. The second purpose is to regulate the refrigerant flow to match the rate of vaporisation in the
evaporator and condensation in the condenser. There are different expansion types on the market and they can be divided into eight basic types [58].

- Hand expansion valve.
- Capillary tube.
- Automatic expansion valve.
- Thermostatic expansion valve.
- Electronic expansion valve.
- Low-pressure float valve.
- High-pressure float valve.
- Constant level regulator.

The first two are non-regulating expansion devices, and the other types adjust the flow based on different signals from the heat pump system. All of these variants have different behaviours and are suitable for different applications. In all the experimental tests in my studies a hand expansion valve or a capillary tube was used and in Paper IV there was a deeper analysis of the performance of a heat pump dishwasher when using a capillary tube. Today, capillary tubes are common on the market in small appliances such as fridges, freezers and heat pump tumble dryers, mainly due to the low price.

1.5.3 Condenser and evaporator

A basic heat pump system comprises the condenser; the heat sink, where heat is released from the heat pump system; and the evaporator, the heat source, where heat is collected to the heat pump system. Both the condenser and the evaporator are heat exchangers where the refrigerant is transformed from vapour to liquid in the condenser and from liquid to vapour in the evaporator in the refrigerant side of the heat exchangers. The other side of the heat exchangers, which are connected to the outside of the heat pump system, are commonly air or liquid exchangers.

Paper I is a study of a heat pump tumble dryer where both the condenser and the evaporator were connected to the circulated process air inside the tumble dryer, see Figure 4. Papers II, III, IV and V are studies of the heat pump dishwasher where both the condenser and the evaporator were
connected to water, see Figure 4. The condenser was connected to the process water inside the dishwasher and the evaporator to the water tank.

### 1.5.4 Refrigerants

One important component in a heat pump/refrigeration system is the refrigerant. There are many alternatives on the market, all of which have different characteristics and have to satisfy a number of requirements, which can be divided into five groups \cite{25,26}.

- **Chemical**: Stable and inert.
- **Health and Safety**: Non-toxic, non-flammable.
- **Environmental**: ODP and GWP.
- **Thermophysical properties**: Critical point and boiling point temperature appropriate for application, moderate liquid molar heat capacity, low liquid viscosity, high liquid thermal conductivity.
- **Miscellaneous**: Soluble with lubricants, high vapour dielectric strength, low freezing point, compatible with common materials, easy leak detection, low cost, readily available.

It is difficult to find a refrigerant that fulfils all of these requirements in each case. The choice of refrigerant is individual and always a compromise. The choice and requirements of refrigerants has varied over time. Figure 6 depicts the progression of refrigerants from their advent through four generations.

---

**First generation** 1830–1930s: Whatever works

**Second generation** 1931–1990s: Safety and durability

**Third generation** 1990–2010s: Ozone protection

**Fourth generation** 2010–: Global warming

<table>
<thead>
<tr>
<th>First generation</th>
<th>Second generation</th>
<th>Third generation</th>
<th>Fourth generation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whatever worked</td>
<td>Safety and durability</td>
<td>Ozone protection</td>
<td>Global warming</td>
</tr>
<tr>
<td>Ethers, CO₂, NH₃, SO₂, HOOCH₂, HCS, H₂O, CCl₄,...</td>
<td>CFCs, HCFCs, HFCs, NH₃, H₂O, HCS, CO₂, ...</td>
<td>HCFCs, HFCs, NH₃, H₂O, HCS, CO₂, ...</td>
<td>Zero ODP, low GWP, high efficiency</td>
</tr>
</tbody>
</table>

*Figure 6: The progression of refrigerants over four generations. The figure is inspired by J.M Calm* \cite{25}.

**First generation, whatever works, 1830–1930s**: The main purpose was to cool down food and so forth, using whatever worked. Natural refrigerants such as carbon dioxide, ammonia and propane dominated.
Second generation, safety and durability, 1931–1990s: The many serious toxic and explosive accidents that occurred with the natural refrigerants pushed the industry to develop safe refrigerants. The new synthetic chlorofluorocarbon (CFC) was introduced as a non-toxic and non-flammable solution.

Third generation, ozone protection, 1990–2010s: Research reports in the late 1970s pointed out that the chlorine from CFC refrigerants was reacting with ozone in the atmosphere. New synthetic refrigerants such as hydrofluorocarbons (HFC) without chlorine were developed and introduced on the market.

Fourth generation, global warming, 2010–: Warnings about global warming appeared during the 1980s and 1990s. Some refrigerants, for instance HFC, have a large GWP. So the fourth generation focusses on using refrigerants with low GWP value.

The fourth generation only began in the 2010s. It is difficult to predict which refrigerants will dominate in the future. However, taxes and regulations force the selection of refrigerants. For example, a new tax was introduced in 2010 in Nordic countries affecting the phase-out of HFC refrigerants. For instance, from 2010 the tax for R134a is 20 Euro/kg in Denmark, 34 Euro/kg in Norway and 28 Euro/kg in Sweden [20]. A new regulation introduced in 2006 forbids refrigerants with GWP>150 in Europe in new car models from 2011, and in all new cars from 2017 [86].

A large field of research in the heat pump sector currently is devoted to investigating and comparing refrigerants with low GWP against refrigerants with high GWP and the consequence of changing to refrigerants with low GWP in different applications. Meanwhile, chemical industries are spending large amounts inventing new synthetic low-GWP refrigerants to sell in the future in order to survive.

1.5.5 Simulation models to evaluate heat pump systems
Both the tumble dryer and the dishwasher processes are transient. A simulation of such a complete transient process including a heat pump system comprises several complex mathematical relationships. In these cases, it is an advantage to use computer programs to evaluate performance such as electricity consumption. There are many examples
in the literature of how to use simulation models to evaluate heat pump drying systems, both transient and steady-state.

Braun et al. \cite{59} analysed two alternative drying systems, an air heat pump (reversed Brayton) tumble drying process, and a conventional closed cycle condenser tumble dryer. Results from the simulation model show that the energy use of an air heat pump (reversed Brayton) tumble drying process is up to 40% lower than the conventional closed-cycle condenser tumble dryer.

Using a simulation model, Novak et al. \cite{28} compared the refrigerants R134a, R290 and R774 in a heat pump tumble dryer. They also converted two heat pump tumble dryers (originally R134a) to R290 and R774 and conducted experiments to compare the experimental and simulation results. The result was that R290 has the lowest TEWI.

Pal and Khan \cite{60} developed a simulation model and proposed calculation steps for the design of different components of a heat pump dryer during the constant drying rate period. The model consists of three submodels: a drying model, a heat pump model and a performance model. Heat and mass balance between the refrigerant and the air circuits in the components was used to obtain a complete simulation model.

A performance analysis using simulation models of five heat pump dryer configurations was carried out by Saensabai and Prasertsan \cite{87}. The models work under steady-state conditions, and the purpose of the analysis was to find the best configuration with the lowest energy use in different ambient temperatures and humidity profiles.

Sarkar et al. \cite{62,63} developed a simulation model of a transcritical CO$_2$ closed cycle heat pump dryer and validated it against experimental results. The model operates under steady-state conditions and has been used to predict the characteristic coefficient of performance (COP) and specific moisture extraction rate (SMER) of a heat pump dryer with different bypass ratios for the drying air in the evaporator.

Wang et al. \cite{64} developed a simulation model in engineering equation solver (EES) of two high-temperature heat pump systems. A performance analysis and comparison between the systems was made.
The results from the model were used to design and build a prototype. EES has also been used for simulations of heat pump systems in the following articles [65,66,68,69,88].

EES is commonly used to simulate heat pump systems. The programme was developed by two professors, Prof William Beckman and Prof Sanford Klein, both of the University of Wisconsin [89]. Their experience in teaching mechanical engineering thermodynamics and heat transfer showed that students were spending too much time looking up property information and solving equations for their homework problems, tasks that did not help the students master the main subject material. Interesting practical problems could not be assigned because of their mathematical complexity. Dr Beckman and Dr Klein designed EES to allow users to concentrate more on design by freeing them from mundane chores. Nowadays EES is one of the dominant programmes in the literature for simulating heat pump systems and has been used in this thesis.

1.5.6 Environmental impact from a heat pump system

There are different approaches to quantify efficiency and how environmentally friendly a heat pump system is [22,26,28,57,62,63,87,90,91]. The most used in the literature are electricity consumption [kWh] and COP [-]. Two other approaches are TEWI [kg CO₂ eq.] and total life cycle energy inventory (LCI) [MJ/unit]. None of these are a complete evaluation of the environmental impact but are used to define and quantify the environmental impact from a product with heat pump systems.

Electricity consumption is very commonly used to rate and compare heat pump systems against each other, or to similar products without heat pumps [89,90].

The COP can be used as a performance value for heat pumps and refrigeration systems [22,62,63]. For a refrigeration system, COP\textsubscript{evap} is used and is defined as the ratio of the useful refrigeration power to the necessary operating energy. For a heat pump system, COP\textsubscript{cond} is used and defined as a ratio of the amount of useful rejected heat power to the necessary operating energy.
The choice of refrigerant in a heat pump system is important and part of the total environmental impact. Different refrigerants affect the environment differently. TEWI is affected by both the refrigerant and the electricity consumption when comparing and rating the environmental impact of a product [26,28,57]. TEWI considers both the direct impact related to refrigerant leakage to the atmosphere and the indirect part impact related to the electricity consumption, and how the electricity is generated. The environmental impact from the electricity generation is strongly dependent on the technology used to produce electricity: higher for coal, oil and gas, and lower for hydroelectric, nuclear, wind and solar.

For small plug-in appliances, using hermetic compressors, the leakage rate and the refrigerant charge are small. Thus the indirect impact dominates and represents up to 95% of the total contribution [28] to the TEWI. For large installations and mobile air conditioning, the direct impact of refrigerant leakage represents a larger contribution to the TEWI.

The LCI quantifies cumulative energy inputs and outputs for all life cycle stages for a product. It calculates the total electricity consumption for the raw material processing, the manufacturing and the use of the product.

Adding a heat pump system also adds a quantity of material. The compressor and the heat exchangers are a considerable part of a dishwasher’s total weight and consist of steel, aluminium and copper, which create an environmental impact during manufacturing and mining. The use of the product, the materials and the manufacturing jointly affect the LCI. However, Boustani et al. [91] in the United States concluded that 88% to 95% of the LCI arises from the use by the end consumer of washing machines, refrigerators and dishwashers. Thus the most effective way to reduce total LCI for these products is to focus on the customer behaviour, how the end consumer uses the product, and to use products with low electricity consumption.

It is obvious that the companies that manufacture and sell products including heat pump systems have a vested interest in high ratings for their own products, independent of the rating system. For the manufacturer it is important to have something to show the end
consumer that their product is one of the best on the market, whether ‘best’ means lowest electricity consumption, highest COP value, lowest environmental impact or some other indication value.
2 Adding a heat pump system to household appliances

For decades heat pump systems have been used in our homes in refrigerators and in freezers with the purpose of keeping food cool \(^{[92]}\). In recent decades, focus on electricity consumption in combination with the reduced cost of heat pump components allow the manufacturers to apply heat pump systems in other household appliances, now with the purpose of decreasing the electricity consumption.

2.1 Heat pump tumble dryer

The first mover to introduce a heat pump tumble dryer was Allgemeine Elektrizitäts-Gesellschaft (AEG). It was introduced on the market in 2000 and was expensive. The purpose of using a heat pump in a tumble dryer is to reduce the electricity consumption. Today heat pump tumble dryers have a competitive price and dominate the market. Figure 7 shows the system design of a variant of a closed cycle heat pump tumble dryer treated in Paper I.

The heat pump system in a tumble dryer improved the energy label from B to A+++, in the EU-energy labelling system. In practical terms, 2.66kWh/cycle (64% reduction) less electricity (see Table 1) is needed to dry 7.0kg of textiles for a heat pump tumble dryer compared with a traditional variant. On the 2016 market almost all manufacturers of heat
pump tumble dryers have removed the sub-cooler from the heat pump system, see Figure 7. The reason was mainly cost reduction and that the saving in energy was small when adding a sub-cooler.

2.2 Heat pump dishwasher
A basic dishwashing cycle in a conventional dishwasher operates similarly for all brands on the market today, see Figure 8.

![Diagram of dishwasher operating cycle](image)

Figure 8: Temperature inside a conventional dishwasher including dishware and washing water and its four operation steps. Just over three litres of fresh water enter and are drained three times, in total about ten litres for a total dishwashing cycle.

The cycle consists of four operation steps: prewashing, washing, rinsing and drying. In the beginning of the prewashing, fresh water enters the dishwasher. The two changes of water in the rinsing cause a temperature drop of 3-8°C. At the end of the rinsing step the process water is pumped out.

Most of the electricity consumption takes place in the two heating periods in the washing step and the rinsing step. The heating in the washing step is needed for cleaning in the washing process with the detergent. The heating in the rinsing step is needed to have warm dishware during the drying in the drying step.
Adding a heat pump system has only been implemented in one dishwasher on the market. The first mover was the V-Zug Adora SL WP \cite{24}, which appeared on the market in 2014 with the energy label (A+++–40\%) in the EU-energy labelling system and an electricity consumption of 0.48kWh/cycle. By comparison with tumble dryers, the heat pump systems have just been introduced to dishwashers.

The purpose of applying a heat pump system to a dishwasher in my work was to decrease the electricity consumption and to introduce a new closed drying system. To achieve that, a water tank, heat pump system, and fan and duct system were added to a conventional dishwasher (see Figure 9 and Figure 12).

![Diagram of heat pump dishwasher](image)

**Figure 9**: Schematic of the function of a heat pump dishwasher. On left is the heating process and on the right is the drying process.

During the two heating processes in Figure 8 the dishwasher is heated by the heat pump system which transfers heat from the water tank to the dishwasher see Figure 9. When the dishwasher enters the drying step, the dishware in the dishwasher is warm and the water tank is cold with a
large portion of ice. During the drying, the warm humid air is transported from the dishwasher against a surface of the water tank using a fan and duct system (see Figure 9). On the cold surface, water from the humid air is condensed and drained to the bottom of the dishwasher.

2.3 Summary of Paper I
The methodology in Figure 10 was used in Papers I and II and includes both an experimental setup and a transient simulation model. The inputs from the experimental setup and knowledge from 2010 were used to define the transient simulation model. Experimental results were used to validate the transient simulation model.

![Figure 10: Schematic of the methodology of using a transient simulation model in Papers I and II for evaluation of a heat pump tumble dryer and a heat pump dishwasher.](image)

The aim of Paper I was to develop a methodology, shown in Figure 10, to use a physical transient simulation model to increase knowledge of the heat pump tumble dryer. The experimental setup was a 2010 on-market heat pump tumble dryer (see Figure 11). The transient simulation model was validated against this experimental setup with good similarity and was then used to examine how the size of the compressor (cylinder volume of the compressor) and the condenser (total heat transfer) affect the total electricity consumption and drying time.
The refrigerant was R134a, a HFC refrigerant. The simulations show that an increase of 50% in the cylinder volume of the compressor decreases the drying time by 14% without consuming more electricity.

In the future, to reduce the drying time with maintained low electricity consumption, this result will probably be implemented in heat pump tumble dryers on the market. Today, most heat pump tumble dryers use about 1000W of electricity power and have the same drying time as the traditional condense and vented variants. In most homes in Europe, the maximum permitted electrical power is 2300W, which makes it possible to use an additional 1300W to reduce the drying time.

2.4 Summary of Paper II
The heating system in a heat pump dishwasher consists of an added heat pump system and a water tank (see Figure 9 and Figure 12). The water tank is the heat source and the dishwasher is the heat sink.
Figure 12: Schematic of the simulation model and the function of the heating in a heat pump dishwasher showing the water tank, heat pump system, and heat transfers.

Paper II is a concept study with the aim of increasing knowledge about the heating system and quantifying the possible savings in electricity consumption for a heat pump dishwasher. The same methodology, shown in Figure 10, which was used in Paper I was also used in Paper II. The experimental setup here was handmade and based on a conventional dishwasher from 2010. The water tank and the heat pump components were added to this dishwasher by hand.

A physical transient simulation model of a heat pump dishwasher was developed. The simulation model was validated against the experimental setup with good similarity.

A simulation study of the compressor cylinder volume and the compressor operating time was performed with the validated simulation model. R134a, an HFC refrigerant, was used.
Figure 13: Schematics of the heating and cooling operations in the dishwasher cabinet and the water tank unit in the transient simulation model. Temperatures of the dishwasher and the water tank are illustrated.

The schematics of the simulations is shown in Figure 13 when the compressor or electrical heater is operating, when the dishwasher is heated or cooled, and when the water in the tank cools, freezes, or melts. The compressor operating time was varied from 20 min to 60 min in the washing cycle. After the compressor was turned off, the electrical element operated until 55°C was reached. The total operating time for the washing was 80 min. In the rinse step, the compressor was on until the same amount of ice was created in the water tank as in the washing step, followed by the electrical element until 55°C was reached. The results in Paper II showed a reduction of total electricity consumption of 24% compared to a conventional dishwasher.

2.5 Summary of Paper III

In Paper III, the choice of refrigerant was examined to find an environmentally friendly alternative for the heat pump dishwasher instead of R134a. The simulation model developed and validated in Paper II was used, except for the definition of the compressor and the condenser where modifications were made in order to treat different refrigerants in a comparative way. Simulations were performed to determine the lowest total electricity consumption for the refrigerants R134a, R290 and R600a.
with different cylinder volumes of the compressor. The results showed similar electricity consumption for the three refrigerants, but at different cylinder volumes of the compressor.

TEWI was calculated in three regions, Sweden, Europe (OECD), and Europe (Non-OECD), with different CO$_2$ eq. emissions from electricity generation, for three sizes of households: small, medium-sized, and large. The conclusion and the recommendation in Paper III, to reduce the total global warming impact of dishwashers, was to concentrate on replacing all conventional dishwashers with heat pump dishwashers, with the condition of using a low-GWP refrigerant such as R290 or R600a.

### 2.6 Summary of Paper IV

In Paper IV, the expansion device in a heat pump dishwasher was studied to investigate the possibility of using a less expensive capillary tube instead of an expensive variable variant. The heating process in a heat pump dishwasher is transient, where the temperature of the dishwasher increases and the temperature of the water tank decreases (see Figure 14).

![Figure 14: Simulated capillary tube length (left) and condensing, evaporating and dishwasher temperatures (right) during heating of the heat pump dishwasher.](image-url)
Normally a variable expansion device is used in such applications. In the household appliance industry, as the focus on cost is high it is relevant to evaluate a less expensive simple component such as a single capillary.

Three methods of calculating the length of the capillary tube were used to estimate the length of the capillary tube (see Figure 14). Because the transient process was calculated length shorter in the beginning and longer at the end when the pressures changed, a difference was also noted between the calculated results comparing the three methods. However, these calculations together with initial experimental tests were used to determine five lengths for evaluation.

In an experimental setup, the electricity consumption was measured using these five lengths of a 0.9mm capillary tube with four different masses of refrigerant. Alternatives when switching capillary tube lengths during the heating was also evaluated. A Secop XV7.2KX compressor with a cylinder volume of 7.2 cm$^3$, with R600a as refrigerant, was used.

![Figure 15: Experimental compressor electricity consumption when heating the heat pump dishwasher from 22°C to 40°C with different combinations of refrigerant mass and configurations of the capillary tube.](image)
The results in Figure 15 show that using a single capillary tube throughout the transient heating period yields similar electricity consumption to a variable expansion device, which occurs here by switching the capillary tube between two or three different lengths during the heating period.

The results in Paper IV showed the possibility of using a less expensive single capillary tube as a fixed expansion device in the transient heating period without increasing the electricity consumption compared to a variable expansion device. The possibility of using a capillary tube can be crucial, regarding cost, when designing a future physical heat pump dishwasher.

2.7 Summary of Paper V

Current dishwashers use various methods to dry dishware. These methods may be open or closed, dynamic (with a fan) or static (without a fan). If there is no fan, the air flow around the dishware is due to natural convection (Figure 16).

![Figure 16: Five current methods for drying dishware in a dishwasher: a) static open; b) static closed; c) dynamic open; d) dynamic closed; e) dynamic closed adsorption drying with zeolite. The thin black arrows represent condensed water in b and d.](image-url)
The drying system in a heat pump dishwasher consists of an added fan and air duct system (see Figure 9). When the drying step begins, the temperature of the dishware is high, and the water tank is cold with a large portion of ice. Paper V is a concept study where this new closed drying system was evaluated and compared to an existing open drying system, c in figure 16. Experimental results showed that this new closed drying method was more energy-effective compared with the existing open drying method because it reached the same drying performance with less accumulated energy at the start of the drying step, represented by a lower drying start temperature of about 2 °C.

In Figure 17, the experimental drying results from Paper V were shown as crosses where the drying performance was just above the drying rating (A) according to EN50242. For each cross, the drying start conditions, drying start temperature (y-axis) and the amount of ice in the water tank when the drying step starts (x-axis) were shown. In all these experimental tests the air flow was 8 m$^3$/h and the drying time was 75 min.

![Figure 17: The crosses represent drying start conditions with drying performance, which represent drying rate (A) according to EN50242 from Paper V with a drying time of 75 min and an airflow of 8 m$^3$/h.](image)
The grey area above the crosses in Figure 17 is here added to show the drying step start conditions which result in dryer dishware ‘Dry result’, comparing drying rate (A) in drying performance, and conditions below the crosses produce wetter dishware ‘Wet result’.
3 Performance of a future commercial heat pump dishwasher

All conclusions in Papers II–V were made from simulations or experimental results from hand-built prototypes based on household appliances manufactured in 2010. During my research from 2011 to 2016, there was progression in the development in the household appliance industry regarding electricity consumption. A future manufactured heat pump dishwasher will be different in comparison with this hand-built prototype, attributed to the differences between the hand-built experimental setup and supposed future physical heat pump dishwashers based on year 2016 knowledge.

So, to achieve a fair estimation of the performance in electricity consumption for an expected future heat pump dishwasher, an evaluation with the transient simulation model, needed to be performed with updated input parameters, based on a dishwasher manufactured in 2016.

In this section, I selected five design cases of a heat pump dishwasher to be evaluated with the transient simulation model from Paper III, using updated input parameters from a dishwasher manufactured in 2016. The selection of these five cases came from my experience during my research, as examples chosen with the aim of showing the potential of a future heat pump dishwasher to provide the customers with two values. These values were, namely, a dishwashing cycle with low electricity consumption and a dishwashing cycle with short operating time. On the market, today and in the future, customers will be willing to pay for a dishwasher including these two values.

For all five cases the total operation time, the electricity consumption and the TEWI were calculated.
3.1 Method
In the method, the approach of using the five different cases and the updating of the input to the 2016 conditions were described.

3.1.1 The five cases
The five cases were selected as examples of improvements which in my opinion are possible to implement in a manufactured dishwasher to reach a 40% reduction, (the heat pump –40% case) and a 50% reduction (the heat pump –50% case) of electricity consumption compared with a conventional dishwasher (the electrical element case).

A competitive dishwasher on the market must have an alternative dishwashing cycle with a short total operating time. As an example of a short dishwashing cycle, the short operating time case was also evaluated for the heat pump dishwasher. The five cases are:

*Electrical element.* The dishwasher is heated only with the electrical element as with a conventional dishwasher.

*Heat pump.* The dishwasher is heated with both the heat pump system and electrical element as it is described in Paper II.

*Heat pump –40%.* The dishwasher is heated with both the heat pump system and electrical element as it is described in Paper II. Changes compared to the heat pump case:

- Using better insulation with 0.035W/(m°C) for the inner insulation instead of 0.05W/(m°C), as shown in Figure 12.

*Heat pump –50%.* The dishwasher is heated with both the heat pump system and electrical element as it is described in Paper II. Changes compared to the heat pump case:

- Using vacuum insulation with 0.0035W/(m°C) for the inner insulation instead of 0.05W/(m°C), as shown in Figure 12.
- 10% lower heat loss from the dishwasher out to the environment, as shown in Figure 12.
- 0.205dm³ more available volume for the water tank and the inner insulation, representing 1mm wider space, as shown in Figure 12.
• 10% better volumetric and isentropic efficiency for the compressor.
• 1°C lower max temperature in the washing step, as shown in Figure 13.

Short operating time. The dishwasher is heated by both the electrical element and the heat pump system at the same time to achieve a fast heating in the washing and rinsing steps. The temperatures and operating times were taken from a current quick cycle in a conventional dishwasher. Changes compared to the heat pump case:
• The washing step operates here for 39 min.
• The max washing temperature was 60°C.

3.1.2 2016 parameter inputs
The changes which are attributed to the evolution which has occurred in the dishwasher industry from the year 2010 to 2016 are defined in Table 4.

Table 4: The updated inputs which are attributed to the development of the dishwashers on the market from year 2010 to 2016.

<table>
<thead>
<tr>
<th></th>
<th>2010 inputs</th>
<th>2016 inputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation time of the washing step (min)</td>
<td>80</td>
<td>103</td>
</tr>
<tr>
<td>Max temperature in the washing step (°C)</td>
<td>55</td>
<td>49</td>
</tr>
<tr>
<td>Water use in the rinse step (dm³)</td>
<td>3.0</td>
<td>2.4</td>
</tr>
<tr>
<td>Electrical consumption of the water circulation pump</td>
<td>76W - none of this power was dedicated to heating the process water in the simulations.</td>
<td>60W - half of this power was dedicated to heating the process water in the simulations.</td>
</tr>
</tbody>
</table>

The operation time of the washing step has been increased from 80 min to 103 min and the maximum temperature in the washing step has been decreased from 55°C to 49°C. The amount of water in the rinse step has been decreased from 3.0dm³ to 2.4dm³. The power of the water pump was decreased from 76W to 60W. In the simulations in Papers II and III, no part of this power was used to heat the dishwasher. In the simulations
in this study with 2016 inputs, 50% of this power was assumed to heat the dishwasher and 50% was assumed to be losses.

There were differences attributed to the unique design of the hand-built experimental setup used in Papers II and III comparing a future physical heat pump dishwasher based on year 2016 knowledge. The changes which are attributed to the hand-built experimental setup are defined in Table 5.

Table 5: The updated inputs which are attributed to the differences between the hand-built experimental setup and supposed future physical heat pump dishwashers based on year 2016 knowledge.

<table>
<thead>
<tr>
<th></th>
<th>2010 inputs</th>
<th>2016 inputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Available total volume for the water tank and inner insulation (dm³)</td>
<td>7.0</td>
<td>2.7</td>
</tr>
<tr>
<td>Heat loss from the dishwasher to the surrounding</td>
<td>Heat loss based on measurements from a freestanding dishwasher</td>
<td>Heat loss based on measurements from a dishwasher placed under a hood of wood</td>
</tr>
<tr>
<td>Compressor</td>
<td>Initial compressor R134a, 5.1cm³</td>
<td>New compressor R600a, 10.3cm³</td>
</tr>
<tr>
<td></td>
<td>28% better isentropic efficiency and compressor motor compared with the initial compressor</td>
<td></td>
</tr>
</tbody>
</table>

The available total volume of water and inner insulation in the water tank in the experimental setup was 7 litres and is assumed to be 2.7 litres in the 2016 inputs to fit in a future physical heat pump dishwasher.

The energy losses $Q_{loss}$ from the dishwasher to the surrounding was in the transient simulation models in Papers II and III defined from measurements on the experimental setup standing free with no extra insulation. The dishwasher was heated and then cooled in those surrounding conditions. In a performance test, according to the European standard for dishwashers, a wooden hood, which acts as extra insulation, should be used. In the 2016 inputs the energy losses $Q_{loss}$ occurred from measurements when the dishwasher cools down where an extra wooden hood was used as extra insulation.
The definition of the compressor with 2010 inputs used in Papers II and III was based on measurements from an experimental setup with a compressor using R134a as refrigerant. Performance tests of other compressors have been carried out with similar capacity but with lower electricity consumption. The 2016 inputs were based on measurements of a better compressor using R600a as a refrigerant. Both the isentropic efficiency and the correction coefficient, \( C_{\text{compressor}} \), shown in Paper II, are defined from measurements from this better compressor to be 28% better compared with the compressor used in the experimental setup in 2010.

### 3.1.3 Simulation approach

The overall method is defined in Figure 18. The two boxes in the upper part of Figure 18 define the method used for the simulations of the heat pump dishwasher in Papers II and III, see Figure 10.

![Figure 18: Schematic of the methodology of using a transient simulation model in section 3.](image)

The method for the simulations of the five cases is defined in the boxes in the lower part of Figure 18. The same transient simulation model used in Paper III was used here. Parameter inputs based on knowledge from 2016, called 2016 inputs, were used in the simulations with the transient simulation model for the five cases. The simulations of the washing and
rinsing steps for the five cases were performed as in Papers II and III with the 2016 inputs showed in Tables 4 and 5. The compressor operating time was 60min as in Paper III.

The definition of the needed drying start condition to reach drying rating (A) according to EN50242, after the drying step with the new closed drying method, was based on experimental results from Paper V, with 75min drying time and 8m³/h airflow. In the electrical element case, an open type drying method, shown in Paper V, was used with a needed drying start temperature of 48°C. In the other cases, a closed type drying method, shown in Paper V, was used where water condenses on the cold surface of the water tank. When the rinse step of the dishwasher was complete, the drying step was entered with a certain amount of ice. By using this amount of ice, a needed drying start temperature was collected in Figure 17 to achieve a drying performance just above the drying rating (A) according to EN50242.

For all cases, total operating time, total electricity consumption per cycle and lifetime, and TEWI were calculated. The calculations of TEWI were performed using the same method as in Paper III. Refrigerant R600a was used and the number of dishwashing cycles was 280 per year for 15 years; and the CO2 eq. emissions from electricity generation was 0.4534 kg CO₂ eq./kWh, from Paper III for Europe (OECD) used. The amount of R600a was 0.078kg with a leakage of 3% a year.

3.2 Results
The results are based on the transient simulations of the five cases presented in section 3.1. In all the simulations the behaviour of the dishwasher was similar to that described in Papers II and III. In the electrical element case, an open drying method was used with no water tank with a drying start temperature of 48°C.

In the short operating time case, the closed drying method was used. The operation time for the heat pump system was short, which resulted in a low amount of ice in the water tank. However, it was enough to achieve a drying performance just above the drying rating (A) according to EN50242 with the new closed drying method by using a drying start temperature of 54°C (see Figure. 17). In the other cases, the closed
drying method was used and there was enough ice in the water tank to use a drying start temperature of 46°C (see Figure 17).

The electricity consumption, operating time and TEWI from the simulation model is shown in Table 6 for the five cases.

Table 6: Total electricity consumption, operating time and TEWI from the simulations where the 2016 inputs were used for the five cases.

<table>
<thead>
<tr>
<th></th>
<th>Electricity consumption (kWh/cycle)</th>
<th>Total operating time (min/cycle)</th>
<th>Electricity consumption (kWh/lifetime)</th>
<th>TEWI (kg CO₂eq./lifetime)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical element</td>
<td>0.89</td>
<td>202</td>
<td>3740</td>
<td>1690</td>
</tr>
<tr>
<td>Heat pump</td>
<td>0.55</td>
<td>237</td>
<td>2310</td>
<td>1040</td>
</tr>
<tr>
<td>Heat pump -40%</td>
<td>0.53</td>
<td>225</td>
<td>2230</td>
<td>990</td>
</tr>
<tr>
<td>Heat pump -50%</td>
<td>0.44</td>
<td>207</td>
<td>1850</td>
<td>830</td>
</tr>
<tr>
<td>Short operating time</td>
<td>0.87</td>
<td>114</td>
<td>3650</td>
<td>1650</td>
</tr>
</tbody>
</table>

The results in Table 6 show that the electricity consumption in the electrical element case was 0.89kWh/cycle. The heat pump dishwasher with the new drying method in the heat pump case consumed 38% less electricity compared with the conventional dishwasher in the electrical element case.

The improvement of inner insulation in the heat pump –40% case reduced the electricity consumption even more. This single improvement achieved the purpose of reaching a 40% reduction of electricity consumption compared with the conventional dishwasher in the electrical element case.

By using a combination of improvements in the heat pump –50% case, the reduction of the electricity consumption was larger. The electricity consumption with these improvements was 0.44kWh/cycle compared with the conventional dishwasher in the electrical element case, which consumed 0.89kWh/cycle. This was a reduction of 51%.
By using both the heat pump system and the electrical element for heating in the short operating time case, it was possible to reduce the total operating time for a heat pump dishwasher by 88min (44%) to 114min. This is a large reduction of the operating time compared with the other cases. The total electricity consumption was 0.87kWh/cycle, which was lower compared with 0.89kWh/cycle for the electrical element case.

The lower electricity consumption and the use of a refrigerant in the heat pump system affect the electricity consumption and the TEWI during the lifetime of a dishwasher. Table 6 shows that the total saving in electricity consumption was 1510kWh/lifetime by changing a conventional dishwasher in the electrical element case to a heat pump dishwasher in the heat pump –40% case. To change a conventional dishwasher as in the electrical element case to a heat pump dishwasher in the heat pump – 50% case, using 50% lower electricity consumption results in a lifetime electricity consumption saving of 1890kWh/lifetime.

The environmental impact, here defined as the TEWI, was lower when using the heat pump system. Due to using R600a as a refrigerant which has a low GWP, the TEWI was mainly affected indirectly, in relation to the electricity consumption from the appliance. So, a 50% reduction in electricity consumption will in this heat pump dishwasher reduce the TEWI by 50%.
4 Discussion

The development of new products that have low electricity consumption and environmental impact is an ongoing process in the household appliance industry. There is much competition among the manufacturers to have the best product with the lowest electricity consumption and environmental impact on the market. One approach to achieving that for a tumble dryer, dishwasher and washing machine is to add a heat pump system. When evaluating the potential of a new concept, such as an added heat pump system, it is important to have as much knowledge as possible about the likely reductions of electricity consumption and environmental impact in an early stage of the development – preferably long before manufacturing begins.

Using a simulation model, with feedback validations as a tool to increase knowledge when making decisions during the development of products, is common both in the industry and academically. The reliability of the knowledge gained from simulation results depends on the validation and how well the studied parameters in the model imitate the physical behaviour of the physical product.

The heat pump processes in both the tumble dryer and the dishwasher are transient and of batch type. To imitate the behaviour in a faithful way, from the start to the end of the process, the simulation model must be transient, as in my studies (see Papers I, II and III). For all the simulation studies, in the Papers and in the five cases in section 3, the response of the total electricity consumption was studied when different parameters were changed in the transient simulation model. All of these studied parameters were defined physically in the simulation models to represent the behaviour in a physical product.

This approach, that the simulation model is transient, validated and that the studied parameters were defined physically, strengthened the reliability of the trends and results from the simulations. This approach was used effectively in this study to increase knowledge about expected future electricity consumption and environmental impact for a heat pump dishwasher and can be recommended for use in other similar applications.
4.1 Heat pump tumble dryer
The first mover on the market to introduce a heat pump system for a tumble dryer was AEG in 2000. Today, the heat pump tumble dryer dominates the European market for tumble dryers. Changing from a conventional to a heat pump tumble dryer decreases electricity consumption from 0.64kWh/kg textiles to 0.24kWh/kg textiles (see Table 1).

Results in Paper I showed the possibility of reducing the operating time with low electricity consumption retained by using a larger compressor in a heat pump tumble dryer. The electrical power for heat pump tumble dryers on the market is approximately 1000W, with the same drying time as traditional tumble dryers. The total available power in many European countries is 2300W, which leaves an additional 1300W available to support a larger cylinder volume for the compressor in the heat pump system. Tumble dryer manufacturers could thus in the future develop a heat pump tumble dryer that has shorter drying times without increasing the electricity consumption.

However, there could be problems with a larger compressor, as it could increase the compressor temperature to such an extent that it is too high for the lubricant in the heat pump system. A larger compressor could also decrease the evaporator temperature, risking ice growing on the evaporator surfaces. For the largest compressor in Paper I, the evaporator temperature was about 0°C during the constant drying period and –20°C at the start. The icing risk can be avoided with larger total heat transfer of the condenser and the evaporator, together with increased airflow.

Because of the limited space inside a tumble dryer cabinet, it may be difficult to put in larger components. This is a general limitation, and a major challenge for all manufacturers when developing products such as tumble dryers, dishwashers and washing machines.

4.2 Heat pump dishwasher
The first mover on the market for the heat pump dishwasher was V-Zug Adora SL WP [24] in 2014. In 2016, there was still only one heat pump dishwasher on the market. The electricity consumption in that heat pump
dishwasher was reduced by 40% compared with a conventional variant heated with an electrical element. This dishwasher appeared on the market at the same time as my study of the heat pump dishwasher in Paper II was published, therefore Paper II was not influenced by V-Zug Adora SL WP [24]. The approach of using a transient simulation model as used in Paper I works well to increase knowledge of the heat pump tumble dryer, and the same approach was used both in Paper II and III and in this dissertation to increase knowledge of the heat pump dishwasher.

Other studies where a simulation model was validated against an experimental setup have stated that discrepancies of less than 10%–20% of the performance results between experimental and simulation results show good agreement [62,63,70,87]. The transient simulation models in Papers I, II and III were developed and validated with a difference between the measurements and the simulation of less than 5.4%. The same transient simulation model used in Paper III was used in this dissertation. The simulated total electricity consumption with the 2016 inputs, for a conventional dishwasher in the electrical element case was 0.89kWh/cycle (see Table 6), comparing 0.82kWh/cycle for a measured conventional dishwasher from 2016. This is a difference of about 8%. To find out exactly in which physical definition the simulation model differs is difficult. The reason for the different result is probably a combination of many factors. However, it is relevant to assume that percentage changes from parameter variations for the transient simulation model will be similar to those of a physical heat pump dishwasher.

In Paper II, the reduction of the electricity consumption was 24% compared with 40% for V-Zug Adora SL WP [24]. The reasons for the different results originated in a hand-built experimental setup based on a dishwasher manufactured in 2010. The difference in inputs from years 2010 to 2016 and the fact that the experimental setup was hand-built, changes the conditions for the simulation in this dissertation (see Table 4 and 5). With the 2016 inputs used in section 3, the reduction of electricity was 38% for the heat pump case, which is similar to the 40% reduction of electricity consumption for V-Zug Adora SL WP [24].
In section 3 in the heat pump –40% case, using a better inner insulation, the decrease in electricity consumption was 40% compared with a conventional dishwasher in the electrical element case (see Table 6). Thus, in a small context, the achievement of a 40% reduction in electricity consumption would be possible to implement in a future physical heat pump dishwasher. This is also the electricity consumption of the first mover V-Zug AG (A+++–40%) [24]. In the example of decreasing the electricity consumption from the heat pump case to the heat pump –50% case, five parameters were improved (see Table 6). There ought to be other numbers, and combinations of the improved parameters which could achieve a 50% reduction in electricity consumption could be different. However, achieving a 50% reduction in electricity consumption for a future physical heat pump dishwasher will be challenging but possible.

Simulations in the heat pump, heat pump –40% and heat pump –50% cases showed that the total operating time for a heat pump dishwasher will be longer compared to the electrical element case. However, it is possible to achieve a dishwashing programme in the heat pump dishwasher, as shown in the short operating time case, with a total operation time shortened by 88min (44%) with the same electricity consumption compared with the conventional dishwasher in the electrical element case. In the short operating time case both the heat pump system and the electrical element were operated at the same time. This is possible if the total electrical power does not exceed 2300W during the heating with both the electrical element and the compressor.

In the shorter dishwashing programme in the short operating time case, the drying start temperature was increased to 54°C to achieve the drying rate (A) using the new closed drying method. This temperature was selected from the experimental results from Paper V, as shown in Figure 17 in section 3. The amount of ice was 0.24kg in the water tank when the drying step started. This means that all ice in the short operating time case will melt in the beginning of the drying step, followed by an increased temperature of the water tank at the end of the drying step.

To implement the next dishwashing cycle with the same electricity consumption, all the ice had to melt, and the water in the tank had to
return to the ambient air temperature. When the rinsing step was finished and the drying step started, there was ice in the water tank. During the drying step, the heat from the dishwasher melted the ice in the water tank. The conditions of the water tank during the drying step were studied in Paper V, and when there was a drying step of 75min, such as in section 3, all the ice melted. This makes it possible to do sequential cycles with the same performance.

One challenge in this concept study was the space limitation. This makes it important to consider the space-consuming components such as the compressor, water tank and the insulations in order to further reduce total electricity use. However, the geometry and components used in the simulations with the five cases in section 3 are possible to use in a future physically manufactured heat pump dishwasher. Also, it is possible to implement all the modifications regarding the space limitations in the five cases in a future physical heat pump dishwasher. This possibility of using physical geometries increases the value of the results both for the industry and the academic.

At the manufacturer’s, the evolution of the decrease in electricity consumption for a dishwasher has forced electricity consumption to a low level. Today, this level is so low that the other aspects in Figure 1 also need to be treated in order to lower the total environmental impact of washing dishware in a household situation. This dissertation only treated the environmental impact attributed to the electricity consumption from the dishwasher. Both the habits of the end consumer when using the appliances and the effectiveness of the appliances affect the total environmental impact when washing household dishware [1,2,4-7] (see Figure 1). To obtain an overall perspective of the total environmental impact, the other factors in Figure 1 need to be included. However, the results in Paper III showed that, if the dishware were chosen to be cleaned by a dishwasher, it was preferable to use a heat pump dishwasher with a low-GWP refrigerant, compared with a conventional dishwasher in order for the environmental impact to be as low as possible.
4.3 Introduction of heat pumps to products in the household industry

It is difficult to predict what the next technical leap will be to decrease electricity consumption and the environmental impact of tumble dryers, dishwashers and washing machines. The research and the development teams at all the manufacturers are working hard to develop the next generation of environmentally friendly household appliances, and the willingness of customers to pay for environmentally friendly products will force the competition by the manufacturers to supply such products to the market. This competition has pushed the development of energy-efficient products and forced the introduction of added heat pump systems in household products. In Table 7 are examples of three household products where heat pump systems have been introduced.

Table 7: Year of introduction and the 2016 situation of heat pump systems in a tumble dryer (left), dishwasher (middle) and washing machine (right).

<table>
<thead>
<tr>
<th>Heat pump introduced to the product on the market (first mover)</th>
<th>Tumble dryer</th>
<th>Dishwasher</th>
<th>Washing machine</th>
</tr>
</thead>
<tbody>
<tr>
<td>AEG year 2000</td>
<td>V-ZUG year 2014</td>
<td>V-ZUG year 2016</td>
<td></td>
</tr>
<tr>
<td>Heat pump products on the market 2016</td>
<td>Dominate the market</td>
<td>Only V-ZUG</td>
<td>Only V-ZUG</td>
</tr>
</tbody>
</table>

The heat pump tumble dryer has been on the market since 2000 and is dominating the market today. The first mover for both the heat pump dishwasher and the heat pump washing machine on the market was V-Zug AG (see Table 7). The other manufacturers must choose whether they want to be the second mover or a follower, or to not adopt this technology at all [78,79,81].

One important prediction the manufacturers must deal with is whether the heat pump dishwasher and the heat pump washing machine will become the state-of-the-art solution and dominate the market in the future, as with the heat pump tumble dryer. This prediction of the future market is crucial when the manufacturer takes the decision to start or not to start a large development project such as a new heat pump dishwasher or a heat pump washing machine.
Starting a development project to introduce a heat pump system, for example, in a dishwasher, to the market is a large technical and economic risk. The history of the Swedish household industry, exemplified here (in section 1.3.1) by the washing machine manufacturers, shows how important it is to adopt and develop the right product features, with good quality, and introduce them at the right time [8,9]. History has shown that it is always a significant risk for manufacturers to add new features. Therefore, the manufacturers are always restrictive and careful when launching new product features.

4.3.1 Heat pump tumble dryer

The heat pump tumble dryer was dominating the market in 2016. It is not clear what affects the end consumer the most when choosing a more expensive heat pump tumble dryer compared with a less expensive conventional dryer: the decreased electricity consumption, the change in the EU-energy labelling system, the decrease in the electricity bill or the reduced environmental impact. With a fully loaded tumble dryer with about 7kg textiles, the total electricity consumption for a conventional tumble dryer will be 4.48kWh/cycle compared with a fully loaded heat pump tumble dryer which will be 1.68kWh/cycle. This reduction of 2.80kWh/cycle is perhaps the explanation why the heat pump tumble dryer was dominating the market in 2016. This reduction is large when compared with the dishwasher where the reduction is 0.41kWh/cycle for a fully loaded heat pump dishwasher.

One important factor for the successful introduction of the heat pump tumble dryer is that the reduction of electricity consumption can save money due to a reduced electricity bill. This saving can be significant, and the payoff time can be short despite the higher price for a heat pump tumble dryer. The whole customer chain, including all stores, was informed about the possible low payoff time to convince the end consumer to buy a heat pump tumble dryer rather than a less expensive conventional tumble dryer. The low payoff time and promotions for the whole customer chain were the main success factors involved in making the heat pump tumble dryer one of the state-of-the-art tumbler dryers in 2016.
Another important factor was the improvement of the energy label from B for a conventional dryer to A+++ for a heat pump tumble dryer according to the European standard. This energy label is visible on the front of the tumble dryer and is currently a common way to communicate the electrical consumption for all kinds of products on the market. The difference of the ratings on the energy label between the conventional and the heat pump tumble dryer was one success factor for the heat pump tumble dryer on the market.

Results in Paper I showed a possibility of decreasing the operating time without changing the electricity consumption by using a larger compressor. In the professional market there is a lower focus on purchase price compared with the household market. A heat pump tumble dryer with a larger compressor will be more expensive, but will be attractive to this professional market such as textile laundering services and laundry rooms in apartment buildings where drying time is critical.

**4.3.2 Heat pump dishwasher**

There was still only one heat pump dishwasher on the market in year 2016. Is there going to be any second mover? The concept of the heat pump dishwasher presented in this thesis work has added market values compared with the conventional variant which will attract customers on the market.

- Saving money with a lower electricity bill.
- Better energy rating in the European labelling system.
- Lower electricity consumption.
- Lower environmental impact.
- Short dishwashing programme with the energy label of A+++.
- Closed drying system with no humid air out to the kitchen.

Which of the improved values are the most important for the customer and what the customer is willing to pay for in the future depend on the individual. The first four values are attributed to electricity consumption. These values will attract customers who in all their purchases are looking for and are willing to pay for the product with the lowest electricity consumption. These customers will be comparing the electricity consumption and the energy rating between different dishwashers and
will always have the heat pump dishwasher as a relevant alternative to buy.

From the customer’s perspective, it is in some case important to buy a household product that decreases the total electricity bill for the household [16]. Saving money by choosing the right product is important for these end users, for example, when buying products such as lighting fixtures, cars, heating and cooling equipment. For heat pump dishwashers, the money saved due to the lower electricity consumption is lower compared to heat pump tumble dryers. Changing from a conventional to a heat pump dishwasher, the electricity usage decreases by about 126kWh per year if the number of washes is 280 per year. Here the extra premium to pay for the heat pump variant compared with a conventional variant, together with the energy saving and the price for electricity, affects the total money saved by the customer. For the customer it is difficult to correctly evaluate the money saved by choosing a heat pump dishwasher. Here the promotion from the manufacturer, together with the communication between the customer and the store for household appliances, is important. In general, it is in the interest of customers to save money by reducing the electricity consumption when the price for electricity is high with a forecast of higher prices in the future. Probably it is the European energy labelling system and the decrease in environmental impact more than the particular money saved due to decreased electricity consumption that should be promoted for a heat pump dishwasher.

In a heat pump dishwasher, it is possible to develop a dishwashing programme with a short operating time with an energy rating of A+++. This is the same energy rating A+++ as the dishwashing programme in a conventional dishwasher which has the best energy rating. This dishwashing programme shortens the total dishwashing time by 88min (44%), compared with the dishwashing programme in the conventional dishwasher with the energy rating A++. This alternative short dishwashing programme with an energy rating of A+++ will have a market value that may and should be promoted if the aim is to push the heat pump dishwasher to be the state-of-the-art dishwasher in the future.
Surveys show that a large group of end consumers are willing to pay extra for a low-impact environmental products \cite{15,17-19}. These surveys outline that environmental awareness is high and will probably increase in the future for a very large number of people. According to the results in Paper III, a heat pump dishwasher, using a refrigerant with low GWP, will always be a better alternative with regards to the total environmental impact compared with a conventional dishwasher. This provides a high market value which can be used when marketing a heat pump dishwasher.

In the heat pump dishwasher, the drying system is closed so that no humid air is vented out to the kitchen. This is a benefit in many modern kitchens where the dishwasher is built-in to the kitchen interior. In these built-in kitchens an open drying system could damage the kitchen interior with water when the warm humid air condenses as it hits cold interior surfaces. The closed drying system in the heat pump dishwasher together with the zeolite drying system \cite{21} are energy-effective closed drying systems that has the potential to dominate the future market for closed drying systems in dishwashers.

From the manufacturer’s perspective, project lead time for a large technical feature such as the added heat pump system is two to five years from project start to delivery to end consumer, and involves large financial and development investments. Starting such a large project is a risk for a manufacturer. If the whole customer chain does not perceive the value of the feature, it could be difficult for the manufacturer to survive. A large manufacturer might be able to withstand the economic loss, but for a smaller manufacturer it could be a catastrophe leading to huge losses and their disappearance from the market. As previously mentioned in section 1.2.1., this was one of the reasons why some washing machine manufacturers have disappeared from the Swedish market \cite{8,9}.

When a manufacturer has decided to develop and manufacture a new product such as a heat pump dishwasher, the timing for introducing it on the market is important for success. The risk of failure is higher for the first mover, but so is the opportunity for large profits. For a small manufacturer, with a less well-known brand, it could be more beneficial
to minimise the risk, be a follower, and join the market when the market is ready for them. For a follower, the best timing to introduce a feature is generally when the market is closer to the inflection point in the S-curve where market growth increases rapidly, just before it becomes the state-of-the-art solution. Usually followers enter the market too late and miss the best period for large profits. However, if the feature becomes the state-of-the-art solution, manufacturers are forced to procure it if they want to be on the market in the future.

For a new feature to be considered a state-of-the-art solution on the market, with large sales volumes, depends on which company is launching it. If a large well-known manufacturer introduces a new feature together with a large-scale promotion campaign, and alongside a well-known brand, the whole customer chain will adopt the feature. Then the feature will soon be the state-of-the-art solution that other manufacturers must add to their products if they want to continue to compete on the market.

If a smaller manufacturer introduces the feature alone, the situation will be different. The motive for the manufacturer could be to promote a small-scale niche product for one type of end consumer. In this case, the manufacturer has no advantages if the feature becomes a state-of-the-art solution with large volumes on the market. If the volumes are small, the feature can be exclusive and the manufacturer can then set a high price. In that case, the worst that can happen is that the feature becomes the state-of-the-art solution and sells large volumes, which results in a lower price.

There will be added components and manufacturing costs for a heat pump dishwasher compared with a conventional dishwasher. How high this cost will be is specific to each manufacturer and its design solution. The fact that it is possible to use a capillary tube, as shown in Paper IV, is important regarding the extra added cost for the heat system. There is a significant difference in cost when comparing a variable expansion device and a capillary tube. This possibility of using a less expensive capillary tube can be the crucial factor regarding the decision for a manufacturer to start to develop a heat pump dishwasher.
In this study, no simulations or experimental setups have been performed on a washing machine with an added heat pump system. However, applying the same approach as for the dishwasher, the following reasoning can be assumed for a heat pump washing machine.

The electricity consumption for a conventional washing machine is 0.18 kWh/kg textiles (see Table 3). In a fully loaded washing machine with about 7 kg textiles, the total electricity consumption will be larger for a washing machine: 1.26 kWh/cycle compared with a fully loaded dishwasher 0.82 kWh/cycle. The washing temperatures for washing clothes are similar to those for washing dishware. This means that an assumed added heat pump system will work at similar conditions for the washing machine compared with the heat pump dishwasher if a water tank is used as the heat source. Corresponding to these assumptions, the electricity consumption should, with the attributed environmental impact for a heat pump washing machine, be reduced by about 40%–50% compared to a conventional washing machine.

The condenser and evaporator temperatures in a heat pump washing machine will be similar to those for a heat pump dishwasher; which allows the use of a less expensive capillary tube, shown in Paper IV as an expansion device. Thus the possibility to succeed with a heat pump washing machine in the future will be even better compared with the heat pump dishwasher.
5 Conclusions
This thesis work was an evaluation of an existing dishwasher on the market with an added heat pump system. The conclusion was that there are three environmental advantages for a heat pump dishwasher compared with a conventional dishwasher.

- By adding a heat pump system, it is possible to halve the electricity consumption from A+++ for a 2016 on-market existing conventional dishwasher to A+++–50% for a heat pump dishwasher.
- By using the heat pump system and the electrical element for heating at the same time in a heat pump dishwasher, the operation time can be decreased by 88min (44%), with an electricity consumption of label A+++, compared with a 2016 on-market existing conventional dishwasher.
- The environmental impact from a heat pump dishwasher will be lower compared with a conventional dishwasher in all normal conditions if a low-GWP refrigerant such as R290 or R600a is used.

A new drying method was introduced where the humid air from the dishwasher circulates against the cold water tank in a closed air duct system. Experimental tests showed that this new drying method has benefits compared with an existing on-market open drying method.

- No humid air is vented out to the kitchen.
- The new drying method achieves the same drying performance with less accumulated energy at the start of the drying step, represented by a 2°C lower drying start temperature, compared with an on-market existing conventional venting drying system.
6 Future research

Much work is required to develop a commercial heat pump dishwasher. I would like to point to some areas where more knowledge is needed. The two most important future technical working areas that remain when developing a future physically manufactured well-performing heat pump dishwasher are these.

- Practical tests in Paper V have shown that the drying method introduced in this thesis works efficiently. However, the design of the prototype used in Paper V was based on early stage assumptions and is not optimal. A combined experimental and simulation study should be performed to increase knowledge of which parameters to consider and how much they affect the drying performance.
- The validated transient simulation model with the 2016 inputs used in this study have much ‘built-in’ knowledge which should be used in future work. Further parameter studies with this transient simulation model could increase knowledge of improvements and could advise a future design of a heat pump dishwasher in an effective way.

Other working areas regarding the heat pump dishwasher.

- Detailed studies of the condenser and the evaporator should be performed with regards to the aspect of the geometry and the total heat transfer. Also, studies of the location of the condenser in the system and the location of the water tank, including the evaporator inside the dishwashing cabinet, should be considered.
- It would be interesting to study how to combine the heat pump system with other systems such as using the heat coming from the wastewater of the dishwasher to heat fresh inlet water or using an additional adsorption cycle during the drying process [16]. It could be difficult to implement all of these together because of the limited space inside the cabinet, and together they will probably not provide the decrease in the total electrical consumption as they do individually.
Applying a heat pump system in other household products.

- In 2016, there was one washing machine with a heat pump system on the market. This heat pump washing machine showed that it was possible to use a water tank as a heat source, similar to the heat pump dishwasher presented in this study. Quantifying how large the reduction of electricity consumption can be requires further work. The presented methodology in this study using a validated transient simulation model can be used to effectively quantify the potential decreased electricity consumption and environmental impact for a washing machine with an added heat pump system.

- A general study should be performed to evaluate if there are more products in a modern household where the electricity consumption and the environmental impact can be decreased by adding a heat pump system.
7 References

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Applying heat pump systems in commercial household products to reduce energy use and environmental impact

The competition in the household appliances industry is strong. Manufacturers are continuously trying to develop, produce and sell product functions and features with good profit. To continually develop new features that the customer chain is willing to pay for is a key factor for a manufacturer to survive.

In this study has a heat pump system been added as a new feature to a dishwasher. The first heat pump dishwasher was introduced on the market in 2014 and the heat pump system was only used to heat the dishwasher. Comparing that first heat pump dishwasher was a new closed drying method introduced in this study where no humid air evacuates to the kitchen. Experiments and simulations showed that a dishwasher with an added heat pump system can decrease the total electricity consumption by 50% when cleaning and drying the dishware comparing to an on market conventional dishwasher.

The willingness from the customer chain to pay extra for this heat pump dishwasher is because of the decreases in electricity consumption and the fact that no humid air evacuates to the kitchen. This willingness makes the heat pump dishwasher to a variant which have possibility to succeed on the future market.