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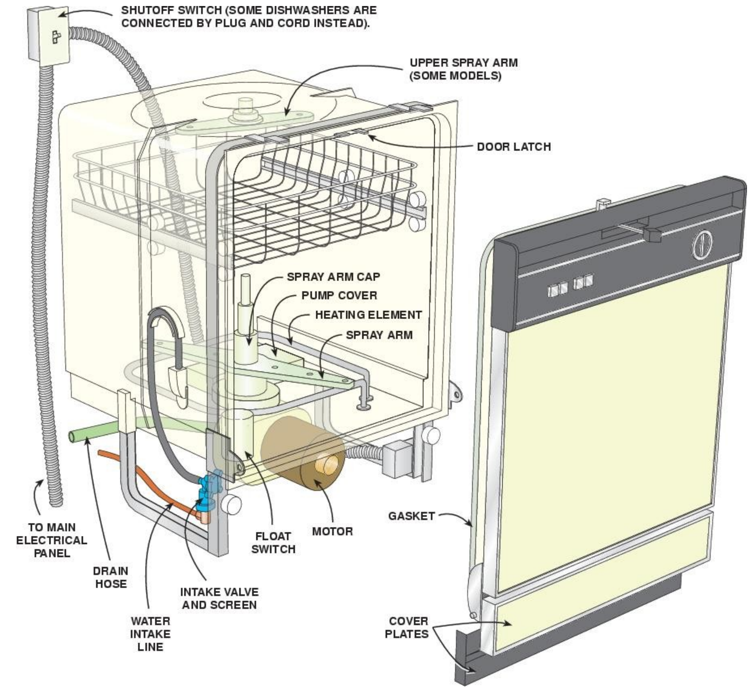

# Appliances in a low-voltage DC house

## Low-power solutions in the kitchen area

*Master of Science Thesis*

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Göteborg, Sweden, 2011

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Cover:
A dishwasher with essential parts marked out in exploded view

[Chalmers Reproservice]
Göteborg, Sweden 2011

# Abstract

In this thesis a system for distributing electricity in a household is investigated. The system is under development in CIT (Chalmers Industriteknik) and distributes electricity as a low voltage DC current. In this way transformers and rectifiers inside devices throughout the house can be avoided which reduces losses in rectifiers, avoid standby power and makes energy efficient LED lights less expensive to install. A low-voltage DC household can also be powered more efficient from solar cells or batteries loaded by local wind turbines. However the proposed system has larger losses in the wires of the home and power is limited in different sections of the house.

The aim of the study is to investigate the wire losses and how much power is required in the kitchen which contains devices that consume much power. It is also the aim of this project to build a prototype version of one kitchen device that has an energy backup or in some other way avoids exceeding the power limitation of the system.

The power consumption in kitchens was investigated with raw data from measurements by the Swedish Energy Agency. A prototype dishwasher was built where peak power consumption is reduced from over 2000W to 80W by avoiding electric heating and replacing all AC components with efficient low voltage DC components. The prototype was tested together with a combined stove-fridge prototype where energy used for cooling is reused for heating by peliter elements and heat is produced for the dishwasher.

The three combined devices was used with a DC power supply at voltages below 50V and with a peak power demand of 500W.

# Acknowledgements

We would like to thank our supervisor Stephan Mangold at CIT for his guidance along the whole project, Yasir Arafat & Mohammad Amin that also made a study on the feasibility of CIT's system which we have constantly cooperated with.

Thanks goes also to Mario Celegrin at Liard Tech for his feedback and help regarding peltier elements and to Torgny Björn and Egil Öfverholm at Swedish Energy Agency for their commitment in supporting researchers that take part of the agency's database on electric power statistics.

We also would like to thank our examiner Lars Almefelt, Chalmers University of Technology for his valuable feedback on the report and the department of Product and Production development for arranging a place to work with the Dishwasher. We would like to specially thank Stefan Lundberg, Assistant Professor, Chalmers University of Technology for his invaluable input and for allowing us to use laboratories in the Electrical power department to conduct experiments.

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# 1 Introduction

## 1.1 Background

On a clients behalf, CIT (Chalmers Industriteknik) is developing a system for low voltage DC electricity in households. The idea of the system is to avoid energy losses in conversion between alternating current 'AC' and direct current 'DC' or high and low voltage. By having electric lines that supports DC, no converter is needed in devices that must run internally on DC (such as TV, DVD, stereo, computers and LED lights). Also, no conversion to AC would be needed for electricity from solar cells or energy stored in batteries from local wind turbines.
Stiftelsen Chalmers Indutriteknik (CIT) is a 80 MSEK annual turnover foundation founded by Chalmers University of Technology in 1984. The foundation has done business with over 1500 customers spreading through 49 countries in 5 continents since its inception. CIT with over 80 employees offer a wide range of service from Research, development, and verification to conducting seminars and workshops and technical audits. CIT covers a wide area of activity, and has experience working in fields like microwave technology, nanomaterials, Fluid dynamics, Energy models and more.[1]

To implement this system all devices in the house must be able to run on DC, therefore a series of master theses have been issued by CIT on converting kitchen devices to run on DC.
A major challenge in this thesis is that the system will only transmit electricity of low voltage. This is because the installation can then be done by the customer him or herself and no transformation to high voltage is needed for electricity from solar cells. However, this limits the power that the devices may use (see Chapter 2.1). It is therefore an objective of this thesis not only to convert a kitchen device to run on DC but most of all find creative solutions to decrease it's power consumption. The proposed idea was to find ways to store the energy during non peak loading (like night) and use it when there is demand for high power.

## 1.2 Objectives

The first objective is to find out if the whole kitchen can run on less than 1500W which a limit set by CIT in their system. The second objective is to find a concept for a kitchen devivce that fits into CIT's system, this means it has be a low voltage DC device that does not consume much power. The third objective is then to build a prototype of this device, the requirements and desired features set up by CIT for this prototype is specified below.

Required Features

- Maximum powerconsumtion 500W
- Only DC componenets
- Powered by < 50V.
- The same functionality as the original device

Desired Features

- The same or better efficiency as original device
- All components operating on the same voltage.
- Maximum powerconsumtion together with other kitchen appliances: 1500W

## 1.3 Distribution of work

The project that has been carried out for CIT consits of two teams where this master thesis is the work of one of the groups. The other group concists of Yasir Arafat and Muhammad Amin, two master thesis students at the division of Electric Power Engineering, Chalmers University. It is important to clarify what has been done by each group since it is a joint cooperation project that have resulted in two different thesis reports. This thesis treats the development of a prototype dishwasher for the low-voltage DC system. The dishwasheer was designed to also work together with a prototype of a combined stove and fridge which is discussed in the other goups thesis. The feasability of the low-voltage DC system has been studied by both groups, this group have studied previous measurements from the Swedish Energy Agency, which is mentioned in this report and the other group have carried out direct measurements on devices which are not used here. The prototype dishwasher have been done by this group and the prototype stove/refigerator unit have been done by the other group. However the devices are made to be able to work together so that a prototype for a minature kitchen could be studied cooperatively. Help have been given in the design of the dishwasher from the other group and help in building the prototype stove/refrigerator unit have been given from this group.

## 1.4 Method

This Master thesis was done both as a literature study and an experimental study. The benefits and losses of a DC system was investigated with data from Swedich Energy Agency on energy consumption in Swedish households. In this way the need of an energy backup system in different appliances was also investigated. Through literature study, benchmarking and estimative calculations the feasibility of storing energy in the devices was investigated and also through experiments was the possibility of certain power reducing concept investigated. These invesigations are forther described in the pre-study: Chapter 2. The final concept was then implemented as a completely low-voltage DC machine and tested in a set up that models the high power consumption devices in a DC kitchen. The workflow of the project os roughly given by Figure 1.

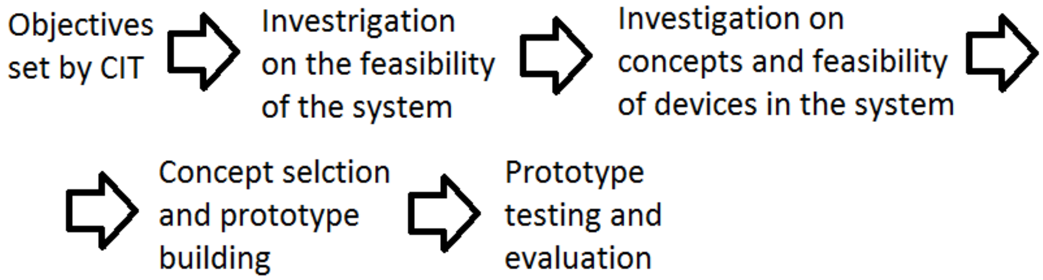

Figure 1: The workflow of the project

### 1.4.1 Statistics from Swedish Energy Agency

The possibility of a kitchen with limited electric power was investigated by statistical analysis. Energmyndigheten made a large survey in 2009 where the end user electricity consumption was measured. The final report of this survey [3] states yearly consumption and the losses in standby power which is a potential for saving energy in CIT's system. However to find the instantaneous power of kitchen devices and how they are used, the raw-data of Swedish Energy Agency investigation had to be consulted. For this study, the power consumption of the kitchen was investigated since this is where the problematic high-power devices of the household (except room heating and clothes-dryer) is. Especially, seven devices with high power consumption in the kitchen were investigated: the stove, oven, dishwasher, fridge, combined 'fridge-freezer', microwave oven and water kettle. The Swedish Energy Agency contributed to this investigation with a large dataset of power measurements from their earlier study. This dataset contained data points of how many Wh (Watt hours) any of the seven devices used at each 10 minute intevall during a whole year in 15 households. From this it was extracted, how often the devices were turned on, how long they were turned on, what power they consumed at most and usually. This was also used to estimate the losses in cables to the kitchen for normal AC houses and for CIT's DC system and also the losses in rectifiers needed in these devices in the AC system. The data points were scanned and analysed by designing scripts that were coded in the Python programming language.

### 1.4.2 Early concepts

The problem formulation of this master thesis is if the problem of electric losses in the cables of a low voltage DC home due to high current (see Chapter 2.1) can be avoided by storing energy in the kitchen devices and in this way lower the peak power demand. This is desired for a low voltage DC house, especially if driven by solar cells where low power is available but over long time.

The methodology for producing and evaluating concepts of low power DC kitchen appliances that either store energy or in some other way have a lower power demand was to look on the way energy is consumed in the devices. Some devices need electric energy that then would be stored electrochemically, but in many devices the power demand would be lowered if they had heat energy or even mechanical energy stored and available directly when used. With this in mind various ways of storing energy either as heat, mechanical or chemical energy were found through literature studies. These ways of storing energy were then evaluated on how they would work in a kitchen device by calculating volumes required and estimating their feasibility Out of these concepts, concepts for storing heat in a dishwasher was found most interesting. This and concepts of storing energy is further described in detail in Chapter 2.5

### 1.4.3 Experimental studies

Experimental studies were performed to measure power demand on kitchen devices. Measurements on kitchen devices and other appliances in the household were done to compare with the data from the Swedish Energy Agency. This was done in collaboration with a master thesis group from the electrical engineering department at Chalmers university, also investigating the feasibility of DC household appliances for CIT [4]. Experiments on average power demand, power demand over time and power consumption of individual components were done on a standard Bosch dishwasher. With this data all the components needed to be replaced in order to convert it to a dishwasher that runs on low voltage DC could be identified. Because of company policy, detailed circuit diagrams could not be obtained and therefore manual tests were required to identify operating voltage, sensor temperature, water flow speed etc. of various components as thermostats, valves, switches and pumps. Carefull consideration has to be taken when designing specifications of DC components that replaces AC components to not decrease overall efficiency but keep operational requirements fulfilled. For example the rotation speed of the main circulation motor in a AC machine is stabilized and determined by the frequency of the incoming AC-current but for a DC-motor the current must either be controlled by expensive motor controllers or carefully dimensioned to meet the force of water pressure to not increase in speed and overheat or shut down due to insufficient momentum. This is further described in Chapter 2.6 and 4.

### 1.4.4 Concept development

The dishwasher was found to be a device with potential for improvements since it uses both mechanical and heat energy and have large space underneath it for modifications and energy storage systems. The heating was found through literature studies to be the major part of power consumption in dishwashers, the concept of heating dishwashers and washing machines with external hot water was also found this way [8]. The power and temperatures needed in a dishwasher were further examined with experiments (see Chapter 2.6.2: ”Working patterns of Dishwasher”) to confirm that concepts regarding heat had the most potential. These results were also used to design a concept where water is heated between the ”hot phases” of the dishwasher program (see Chapter 3.2.3: ”Separate heating tank”). The most promising concepts were then evaluated by experiments where the dishwasher was supplied with heat in different ways. The final concept was selected on basis of how much electric power consumption was reduced and how well it will work compared to the original dishwasher in terms of time needed and temperature reached.

### 1.4.5 Test and Evaluation

The prototype dishwasher was demonstrated together with an experimental low voltage DC stove combined with refrigerator that was developed for this purpose in collaboration with another team of master thesis students [4]. The complete set up comprised a prototype stove, dishwasher and refrigerator - all operating on less than 500W in total. The prototype of combined stove and refrigerator stores energy both as latent heat at 100 °C in a paraffin chemically designed for the purpose and as heat in 60 °C water. Because of this, both a concept of storing energy as latent heat for the dishwasher and circulating hot water through a heat exchanger in the dishwasher could be tested and evaluated experimentally.

# 2 Pre-study

## 2.1 Low voltage DC power compared to 230V AC

AC is by far the most common way of supplying electrical energy, however in some cases DC may be the more favourable. AC is a practical standard since both electricity-generating turbines and electric motors operate with alternating currents. These two ways of generating and consuming energy were common when the standard electric grid was developed and still is to this day. But in the case of a modern household with an independent source of energy the situation is different.

Many modern household appliances work internally on DC. For example does an induction stove or a microwave oven need to supply a magnetron with current at the gigahertz range to produce microwaves, this is commonly achieved by first transforming the 50Hz current to a normal DC current inside the machine. Another example is all household electronics such as multimedia units. Because of this, energy can be saved if all transformation is done by one efficient transformer per house rather than several cheaper ones inside every machine. But more importantly, some modern energy sources such as solar panels produce electricity directly in DC, and often at low power. With these things in mind, previous studies have been made on the possibility of a low voltage DC household with less AC/DC converter losses (or DC/DC converters to boost the voltage from low voltage energy sources). Results from [2] state that the lack of household appliances on the market that operates in this mode is a main obstacle for this kind of household.

Another advantage of low power supply for household appliances is the safety when installing the cables. Safety regulations in EU prevents regular house owners to install cables for higher voltage than 50V. With lower voltage, cost of installations could therefore be avoided.

An interesting point with a low voltage DC systems is that it enables the DC technology such as LED-lamps to work without converters which could increase its market potential, it also removes necessity of adapters and devices to charge mobile phones or laptops (which could then be done by a simple cord to the socket).

## 2.2 Losses in rectifiers

AC currents are transformed into DC-currents by rectifiers. These are installed in household machines where DC-current is needed. A rectifier includes a bridge of diodes and a capacitor (see Figure 2). The diodes in the bridge is arranged so that a sinusoidal current is turned into a current with

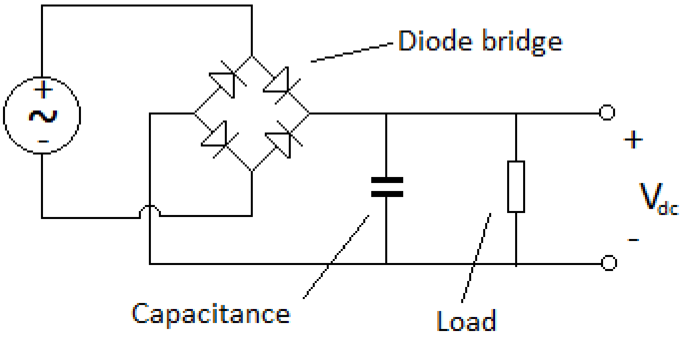

Figure 2: Circuit diagram of rectifier, the diodebridge contains 4 diodes where current flows through 2 of these independent of the direction of incoming current.

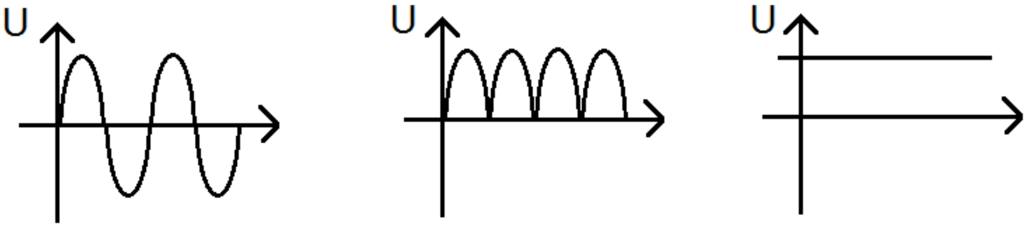

Figure 3: To the left: normal AC current, in the middle: current shape after rectifier-bridge, to the right: smother DC current over the load (appliance) due to the capacitor.

constant positive value (see Figure 3). The current is then smoothed to an almost constant DC current by running through the capacitor. An ideal diode does not have any losses but in reality there is always a small voltage drop due to the diodes in the rectifier. In the bridge rectifier shown in Figure 2, the current always flow trough two of the diodes. A common voltage drop across these diodes is 0.84V and therefore 2*0.84V across the whole rectifier. There are also neglectable losses in the capacitor. The power losses due to rectifiers in machines that operate internally on DC is therefore 2*0.84V multiplied with the current through the machine.

## 2.3 Voltage-drop in DC-cables

A major disadvantage of a low voltage DC household system is that lower voltage gives lower available power if the current is not increased and the current that can be supplied though the cables is limited by the thickness of the cables. This is due to heat losses in the cables, the power lost as heat in a normal 230V cable is according to joules law:

$$P_{heat} = U_{cable} I \tag{1}$$

Where the voltage drop over the cable $U_{cable}$ is given by Ohm's law:

$$U_{cable} = R_{cable} I \tag{2}$$

I is the current needed to support a device with the power $P_{device}$:

$$P_{device} = U_{total} I \tag{3}$$

1,2 and 3 leads to:

$$P_{heat} = R_{cable} \frac{P^2_{device}}{U^2_{total}} \tag{4}$$

In equation 4 we can see that if voltage is changed from the standard 230V to a lower voltage: 50V, the heat losses will increase dramatically. To prevent this, either each device must be limited to a lower power $P_{device}$ or the resistance in the cables $R_{cables}$ must be drastically lowered. $R_{cable}$ can be lowered with thicker cables since resistance is inverse proportional to the area of the conductor. But if $U_{total}$ is lowered a factor 230/50,the area of the cables must increase $(230/50)^2 = 21$ times which is both expensive and inconvenient.

## 2.4 Electric power consumption in Swedish households

In a study by the Swedish Energy Agency [3], four hundred households were examined during a month and some of these for a whole year. The final report of that study, states that in households with families where the owners are 26-64 years old, the maximum power demand during the measured period was on average 5826W if the house has direct electric heating, 4334W if it doesn't and 3139W for apartments. This difference makes low voltage DC systems more suitable for customers without direct electric heating if they don't live in apartments. But how you live also change this number: for couples without children aged 26 to 64, this figure is 5498W with direct electric heating, 4748W without and 2775W in apartments. For couples 64 years and older, the figure is 4977 with direct electric heating, 3582W without and 2494W in apartments. Out of this point of view, a low voltage DC system would be most suitable for couples older than 64 without direct electric heating installed since their power consumption often require less of

Table 1: maximal average power consumption of kitchen devices during 10 minutes

| Device | mean | interval | median | statistical basis |
|---|---|---|---|---|
| Stove | 4110W | 3246-5460W | 3990W | 11 houses |
| Oven | 3186W | 3000-3474W | 3090W | 3 houses |
| Dishwasher | 2082W | 1158-2484W | 2112W | 14 houses |
| Microwave | 882W | 378-1302W | 894W | 14 houses |
| Fridge-Freezer | 180W | 132-288W | 25W | 4 houses |
| Fridge | 132W | 66-366W | 102W | 9 houses |
| Water kettle | 1374W | 624-1944W | 1560W | 3 houses |

the DC cables. The average power consumption is of course even lower in apartments but installing new electric wires or solar cells may be easier and of more interest to people on the countryside.

It is important to note how these values were actually measured to not misinterpret them. In the study for the Swedish Energy Agency, the power of each device was monitored with clamp-on ampere meters for at least a month. The database holds hundreds of thousand data points but with ten minutes between each data point. Each data point is a value of the energy used in a device the last over ten minutes. The power is then given by dividing the Wh measured with these ten minutes, the result is the average power reading during that ten minutes and not the instantaneous reading at the last moment. This result in more accuracy of average power but misses out on short spikes in power consumption between the data points. The values above can therefore be seen as the power consumed during the most intense ten minutes during the monitored time of a household. This may not be the most practical measurement of devices that are used shorter than ten minutes such as water kettles.

In the design of a low voltage DC system it is important to know what machines in what part of the house use more power. Since the aim of this thesis is to investigate power consumption in the kitchen, a small study has been made on seven devices in the kitchen: oven, stove, dishwasher, fridge, combined freezer with freezer, microwave and water kettle . For this thesis, a set of data from 15 households was given by Sweden's Energy Agency from their database. The data set consists of more than 500000 measurements and was analysed with Python scripts. The maximum power values of the seven devices was extracted from these data and can be seen in Table 1.

In Table 1 it can be seen that only the cold-appliances always stay below the power consumption that is allotted for devices in CIT's system: 500W for most appliances and 1500 for stove-oven unit. The dishwasher, microwave and water kettle are devices where the power consumption is set by the machine, the maximum power is often chosen on the microwave. With the stove and oven however the power may vary depending on how the device is used and the maximum reading in Table 1 may be misleading in these cases since the user on average may very well set a power demand under some other limit most of the time.

In Figure 4 the number of hours the stove in a house use power in different intervals are shown. Here it can actually be seen that the vast majority of the time the stove is used, it consumes 1.5 kW. or less.

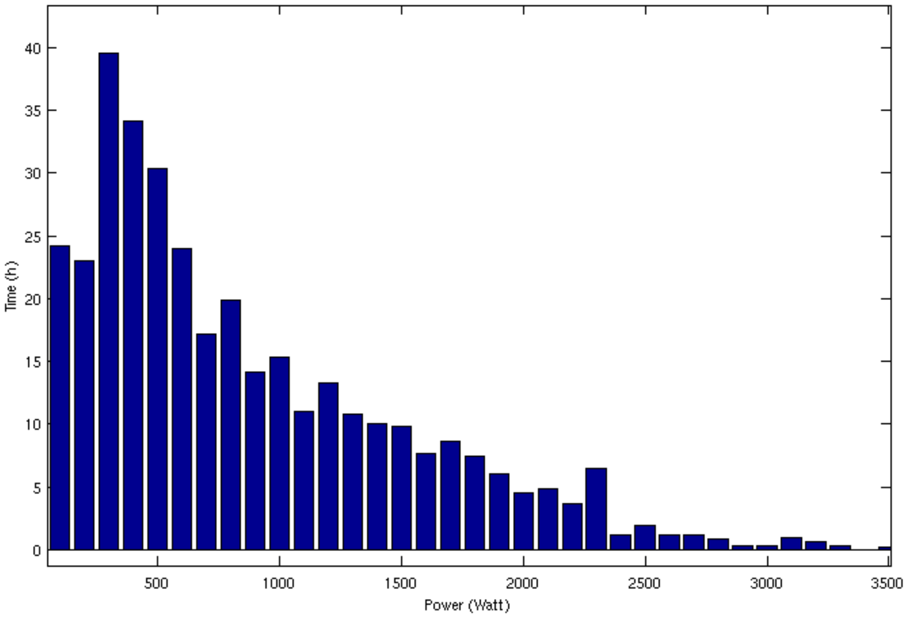

Figure 4: number of hours a stove use different amount of power

The same goes for the oven as can be seen in Figure 5, it is more common that the oven is used at higher power setting than the stove but still most of the time below 1500W.

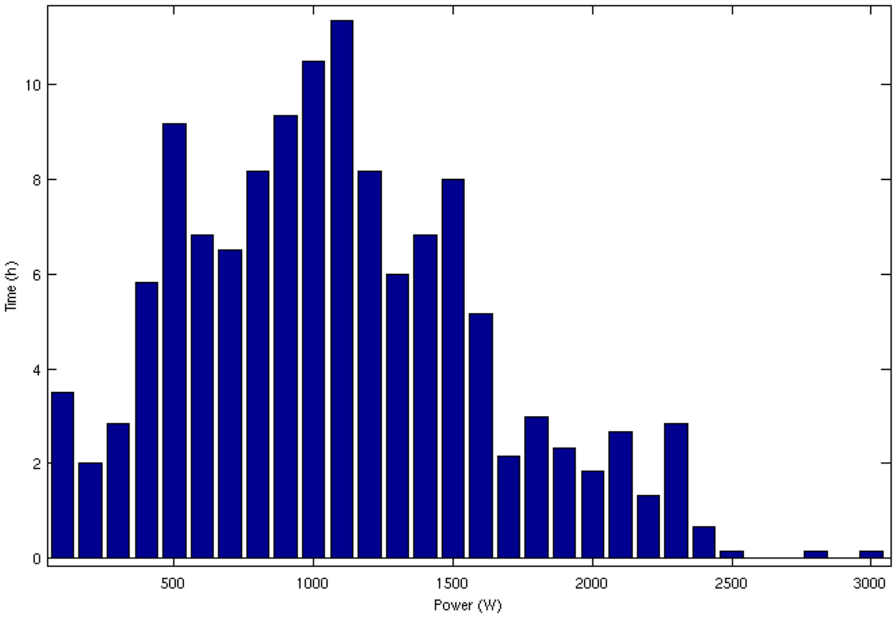

Figure 5: number of hours a oven use different amount of power

This can be compared with the dishwasher in Figure 6 which follows certain programs and therefore most of the time reach a peak power demand, a reduction of this peak power is however not as critical as for the stove since no person attends the dishwasher during the extra time it would need to operate.

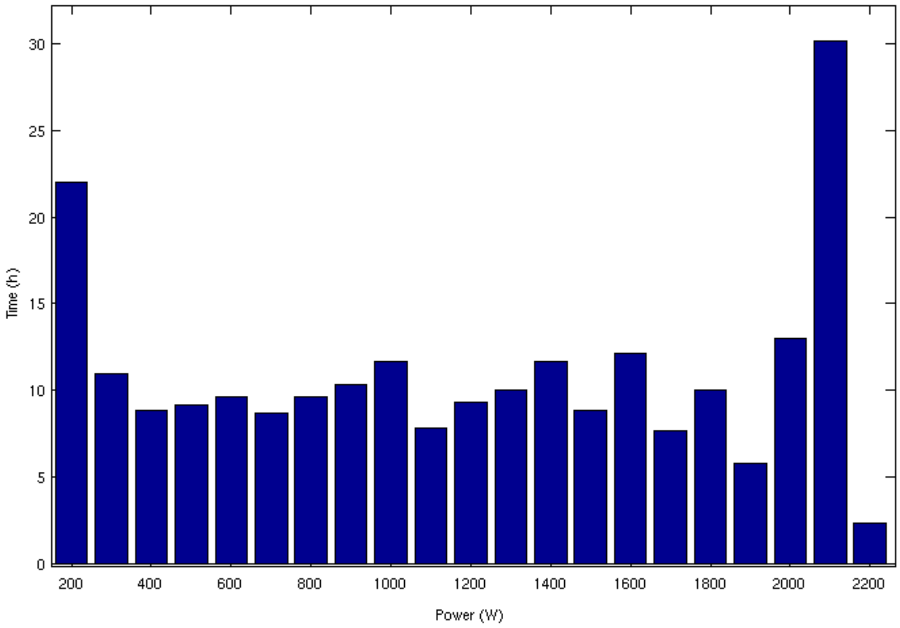

Figure 6: number of hours a dishwasher use different amount of power

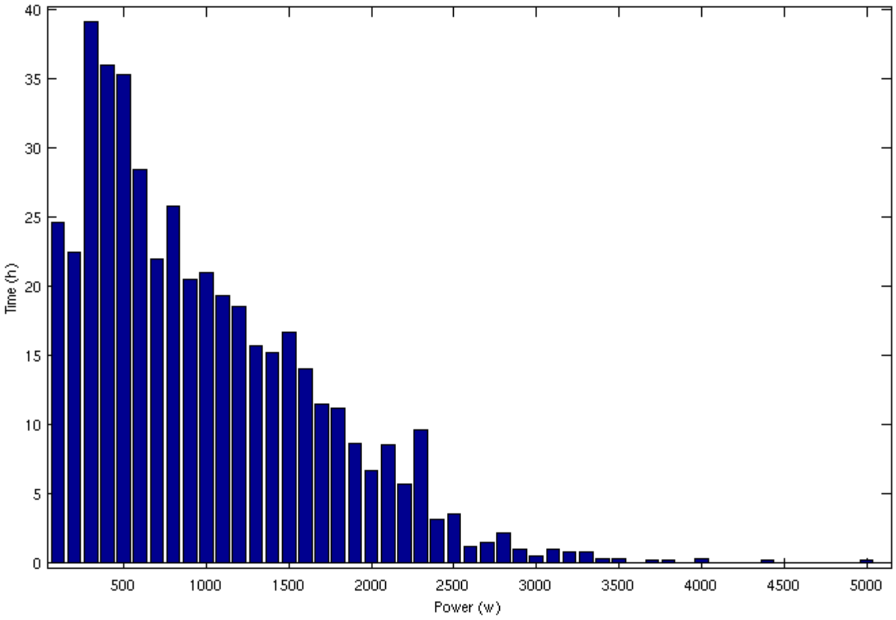

Figure 7: number of hours a stove and/or oven in a kitchen use different amount of power

When it comes to the total limitation of 1.5 kW in the kitchen it can be seen in Figure 7 that if both oven and stove are allowed to sometimes operate on the same time, power consumption may rise extremely much higher than 1.5kW (one explanation for the high mean maximum power of the stove may be that some devices labelled stove in the data provided is actually combined stove-oven units). It is also more common that 1.5 kWh exceeded rather than not in this case (this would not be the case if the two data were uncorrelated, one of the two devices are more prone to be used at times the other one is used). This speaks for putting energy storage system in one of the devices since people then slightly prefer to use them at the same time rather than at some other random moment or for some reason wants to use them at different times. However it is interesting to know more exactly how often different devices are used at the same time.

Table 2: Probability that if device at row A is on, device at column B will be on within 10min

| | Dishwasher | Stove | Water kettle | Fridge-Freezer | Fridge | Microwave | Oven |
|---|---|---|---|---|---|---|---|
| Dishwasher | 100% | 8,7% | 2,3% | 74,6% | 40,7% | 2,6% | 2,8% |
| Stove | 7,5% | 100% | 7,8% | 76,9% | 47,0% | 6,9% | 11,4% |
| Water kettle | 1,6% | 11,9% | 100% | 66,5% | 36,7% | 7,5% | - |
| Fridge-Freezer | 7,3% | 6% | 3,0% | 100% | 22,6% | 4,2% | - |
| Fridge | 5,8% | 6,2% | 3,4% | 66,6% | 100% | 3,9% | 2,7% |
| Microwave | 5,4% | 15,2% | 5,7% | 71,2% | 39,6% | 100% | 4,9% |
| Oven | 8,9% | 22,7% | - | - | 70,0% | 7,3% | 100% |

It can be seen in Table 2 where the probability of one device being on at the same time as another, that two devices may very well be turned on at the same time.

Also, to calculate how much electricity that is lost due to AC-DC rectifiers in a standard house and how much is lost in a low voltage DC-house due to voltage drop in the cables, it is necessary to estimate how often the different devices are used. The number of times the different devices were used in a year in the 15 test houses can be seen in Table 3. Table 4 shows the longest time a device is turned on during the year and Table 5 shows the average time it was used each time it was turned on. When analysing the data, the machines were defined as turned on at a certain data point if the measured consumption was more than 1Wh. Since each data point represents the average power value during ten minutes, each reading holds an uncertainty in how long the device was turned on. For a single 10 min. data point the device is considered to be turned on 5 min. (the correct value (0 to 10) may then be ±5min.). For two succseeding data points where the device used >1Wu it is considered to be turned on 10 min. (the correct value (0 to 20) may then be ±10min.) in the same manner, three succeeding data points it is considered to be turned on 20 min. (the correct value (10 to 30) may then be ±10min.) and so on. Because of these uncertainties, the devices that most probably is turned on less than 5 min. (like the water boiler) may have a lower real value than shown although it is an average over long time.

Table 3: Number of times kitchen devices are turned on during a year

| House | Dishwasher | Stove | Water kettle | Fridge-Freezer | Fridge | Microwave | Oven |
|---|---|---|---|---|---|---|---|
| 1 | 228 | | | | 9186 | 780 | 145 |
| 2 | 126 | 706 | | | 13312 | 647 | |
| 3 | 406 | 1030 | | | 5338 | 361 | |
| 4 | 256 | 477 | 1065 | | 8626 | 400 | |
| 5 | 705 | 520 | | 2980 | | 502 | |
| 6 | | 1497 | 726 | 7713 | | 2953 | |
| 7 | 121 | | | | | 347 | 80 |
| 8 | 21 | 326 | | | | 62 | |
| 9 | 274 | 631 | | | 11778 | 380 | |
| 10 | 233 | 558 | | | 6810 | 988 | |
| 11 | 162 | 1535 | | | 7474 | 709 | |
| 12 | 406 | | | 10805 | 6 | 511 | |
| 13 | 602 | 576 | | | | 1344 | 125 |
| 14 | 56 | 160 | 337 | 2961 | 1389 | 9 | |
| Average | 277 | 729 | 710 | 6115 | 7102 | 714 | 117 |

Table 4: Longest time kitchen devices are turned on during a year (in minutes)
*Abnormal values discarded in average

| House | Dishwasher | Stove | Water kettle | Fridge-Freezer | Fridge | Microwave | Oven |
|---|---|---|---|---|---|---|---|
| 1 | 180 | | | | 400 | 70 | 90 |
| 2 | 90 | 260 | | | 210 | 350 | |
| 3 | 130 | 150 | | | 130 | 50 | |
| 4 | 150 | 170 | 70 | | 100 | 70 | |
| 5 | 1440* | 200 | | 1430* | | 30 | |
| 6 | | 290 | 60 | 390 | | 120 | |
| 7 | 110 | | | | | 50 | 280 |
| 8 | 100 | 560 | | | | 40 | |
| 9 | 150 | 220 | | | 80 | 70 | |
| 10 | 140 | 370 | | | 610 | 60 | |
| 11 | 130 | 290 | | | 130 | 80 | |
| 12 | 100 | | | 550 | 10 | 120 | |
| 13 | 160 | 260 | | | | 60 | 240 |
| 14 | 60 | 120 | 40 | 170 | 500 | 20 | |
| Average | 115 | 263 | 56 | 278 | 241 | 85 | 203 |

Table 5: Average time (min) kitchen devices are turned on each time they are used

| House | Dishwasher | Stove | Water kettle | Fridge-Freezer | Fridge | Microwave | Oven |
|---|---|---|---|---|---|---|---|
| 1 | 75 | | | | 17 | 9 | 20 |
| 2 | 29 | 24 | | | 8 | 11 | |
| 3 | 85 | 24 | | | 19 | 9 | |
| 4 | 77 | 24 | 11 | | 10 | 10 | |
| 5 | 125 | 33 | | 156 | | 6 | |
| 6 | | 26 | 11 | 30 | | 12 | |
| 7 | 93 | | | | | 8 | 47 |
| 8 | 80 | 32 | | | | 8 | |
| 9 | 104 | 34 | | | 8 | 9 | |
| 10 | 81 | 35 | | | 33 | 8 | |
| 11 | 102 | 25 | | | 11 | 15 | |
| 12 | 21 | | | 17 | 5 | 9 | |
| 13 | 69 | 27 | | | | 9 | 78 |
| 14 | 34 | 23 | 9 | 35 | 55 | 7 | |
| Average | 75 | 28 | 11 | 60 | 18 | 9 | 48 |

To estimate the power lost as heat in the wires to the devices, the resistance was assumed to be that of a 20m long wire with a standard cross-section of 1.5mm$^2$. With the resistivity of copper, the total resistance R was found to be 0.227Ω. The inductance of the wire is given by the formula $L = 0.5 + ln(\frac{d}{r})$ [5] where the radius of the wire r and the distance between phase and neutral wires d can be set to 0.5 and 1 mm respectively. In this case the inductance L is $0.417\mu H/m$. The total loss in the wire due to resistive and inductive losses was calculated with:

$$P_{loss} = U_{cable} * I = \sqrt{(I * R)^2 + (I * \omega * L)^2} * I. \tag{5}$$

Here the average current I was calculated for each 10 min. data point ($I = P/U = P/230$). The angular frequency was set to $\omega = 2\pi * (50Hz)$ The total loss for the devices were given by multiplying by the time of each time step: 10 min. and the sum over the whole year can be seen in Table 6.

Table 6: Annual wire losses (kWh) with 230V AC and 1.5$mm^2$, 20m wires

| House | Dishwasher | Stove | Water kettle | Fridge-Freezer | Fridge | Microwave | Oven |
|---|---|---|---|---|---|---|---|
| 1 | 2,61 | 1,82 | 0 | 0,2 | 0 | 0,03 | 0 |
| 2 | 1,82 | 0 | 0 | 0 | 0,05 | 0,04 | 0 |
| 3 | 0,2 | 0,44 | 0 | 0 | 0,06 | 0,03 | 0 |
| 4 | 4,09 | 0,7 | 0 | 0 | 0,04 | 0,02 | 0 |
| 5 | 0,93 | 0,35 | 0,28 | 0 | 0,02 | 0,03 | 0 |
| 6 | 1,35 | 0,91 | 0 | 0,76 | 0 | 0,02 | 0 |
| 7 | 1,46 | 1,01 | 0,25 | 0,09 | 0 | 0,06 | 0 |
| 8 | 0,96 | 0 | 0 | 0 | 0 | 0,02 | 0,78 |
| 9 | 0,14 | 0,76 | 0 | 0 | 0 | 0 | 0 |
| 10 | 1,65 | 0,83 | 0 | 0 | 0,03 | 0,02 | 0 |
| 11 | 2,18 | 1,08 | 0 | 0 | 0,1 | 0,05 | 0 |
| 12 | 1,16 | 0,98 | 0 | 0 | 0,03 | 0,09 | 0 |
| 13 | 0,73 | 0 | 0 | 0,06 | 0 | 0,02 | 0 |
| 14 | 2,67 | 1,81 | 0 | 0 | 0 | 0,07 | 0,8 |
| 15 | 0,12 | 0,24 | 0,02 | 0,09 | 0,03 | 0 | 0 |
| Average | 1,47 | 0,91 | 0,18 | 0,24 | 0,04 | 0,04 | 0,79 |

The same procedure was used to estimate the losses due to heat if the devices had run on 50V DC. Here however the formula only becomes: $P_{loss} = U_{cable} * I = R * I^2$. As described above the losses becomes to great in standard 1.5mm$^2$ wires when transporting low voltage DC. Therefore an example of a low voltage DC household was assumed to have thicker wires supporting more demanding devices. The length of the wires were assumed to be 20m as in the AC household but the cross-section of the wires were chosen as Table 7 for the different devices. The resulting resistances are in these cases 0.227, 0.136 and 0.0567 $\Omega$ respectively for a cross-section of 1.5, 2.5 and 6 mm$^2$. With these values of resistance a current of $I = P_i/U_{device} = P_i/50V$ at each data point, the resulting loss falls out as seen in Table 8.

The last part to estimate the different losses was the loss in rectifiers for the standard AC system where AC is converted to DC. The DC system is assumed to not include any rectifiers and be power by any source of low voltage DC. The power consumption in rectifiers was calculated by multiplying the instantaneous current of each device with the assumed voltage drop of 2*0.84V in a rectifier (see Chapter 2.2). The total average losses are compared in Table 10.

Table 7: Wire cross-section for appliances in example DC house

| | Dishwasher | Stove | Water kettle | Fridge-Freezer | Fridge | Microwave | Oven |
|---|---|---|---|---|---|---|---|
| Wire size ($mm^2$) | 6 | 6 | 1,5 | 2,5 | 2,5 | 2.5 | 6 |

Table 8: Annual wire losses (kWh) with 50V DC and 1.5 - 6 $mm^2$, 20m wires

| House | Dishwasher | Stove | Water kettle | Fridge-Freezer | Fridge | Microwave | Oven |
|---|---|---|---|---|---|---|---|
| 1 | 19,23 | 9,64 | 0 | 2,53 | 0 | 0,38 | 0 |
| 2 | 9,65 | 0 | 0 | 0 | 0,68 | 0,5 | 0 |
| 3 | 2,94 | 2,33 | 0 | 0 | 0,8 | 0,39 | 0 |
| 4 | 25,14 | 3,7 | 0 | 0 | 0,45 | 0,24 | 0 |
| 5 | 5,98 | 1,84 | 5,83 | 0 | 0,27 | 0,35 | 0 |
| 6 | 9,98 | 4,81 | 0 | 9,61 | 0 | 0,21 | 0 |
| 7 | 11,65 | 5,32 | 5,39 | 1,19 | 0 | 0,79 | 0 |
| 8 | 5,1 | 0 | 0 | 0 | 0 | 0,3 | 4,14 |
| 9 | 1,5 | 4,02 | 0 | 0 | 0 | 0,03 | 0 |
| 10 | 11,96 | 4,41 | 0 | 0 | 0,44 | 0,2 | 0 |
| 11 | 14,51 | 5,74 | 0 | 0 | 1,21 | 0,59 | 0 |
| 12 | 10,26 | 5,19 | 0 | 0 | 0,35 | 1,09 | 0 |
| 13 | 3,88 | 0 | 0 | 0,82 | 0 | 0,19 | 0 |
| 14 | 23,69 | 9,56 | 0 | 0 | 0 | 0,94 | 4,21 |
| 15 | 1,23 | 1,27 | 0,45 | 1,08 | 0,37 | 0,01 | 0 |
| Average | 10,45 | 4,82 | 3,89 | 3,05 | 0,57 | 0,48 | 4,17 |

Table 9: Annual rectifier losses (kWh)

| House | Dishwasher | Stove | Water kettle | Fridge-Freezer | Fridge | Microwave | Oven |
|---|---|---|---|---|---|---|---|
| 1 | 3,06 | 2,31 | 0 | 2,96 | 0 | 0,19 | 0 |
| 2 | 2,06 | 0 | 0 | 0 | 1,51 | 0,24 | 0 |
| 3 | 0,3 | 1,45 | 0 | 0 | 1,53 | 0,2 | 0 |
| 4 | 4,76 | 2,14 | 0 | 0 | 0,97 | 0,11 | 0 |
| 5 | 1,19 | 1,06 | 0,8 | 0 | 0,78 | 0,15 | 0 |
| 6 | 2,85 | 2,08 | 0 | 8,15 | 0 | 0,12 | 0 |
| 7 | 1,34 | 3,4 | 0,63 | 2,14 | 0 | 0,5 | 0 |
| 8 | 1,04 | 0 | 0 | 0 | 0 | 0,11 | 0,72 |
| 9 | 0,16 | 1,15 | 0 | 0 | 0 | 0,01 | 0 |
| 10 | 2,26 | 2,35 | 0 | 0 | 1,03 | 0,11 | 0 |
| 11 | 2,34 | 2,58 | 0 | 0 | 2,16 | 0,27 | 0 |
| 12 | 1,43 | 3,25 | 0 | 0 | 0,85 | 0,37 | 0 |
| 13 | 0,82 | 0 | 0 | 1,69 | 0 | 0,11 | 0 |
| 14 | 2,98 | 2,26 | 0 | 0 | 0 | 0,44 | 1,01 |
| 15 | 0,16 | 0,44 | 0,13 | 1,42 | 0,71 | 0 | 0 |
| Average | 1,78 | 2,04 | 0,52 | 3,27 | 1,19 | 0,23 | 0,87 |

Table 10: AC versus DC

| | 230V AC | 50V DC | difference |
|---|---|---|---|
| Rectifier losses (kWh/year) | 9.9 | 0 | -9.9 |
| Wire losses (kWh/year) | 3,6 | 27.43 | +23.83 |
| Cable cost (sek) | 112 | 288 | 176 |

With the values in Table 10, switching from a AC house to a DC house means that the energy losses in the kitchen due to losses in wires will be 23.83 $kWh/year$ higher assuming that it includes all the seven devices, if most of these devices include a rectifier however, the loss will be 9.9 $kWh/year$ less so there will be an economic loss in the kitchen each year and a slightly higher cost of electric wires of 176kr when installing the wires. However in the rest of the house there are money to be earned since most high-power devices are in the kitchen and there are rectifiers in almost all modern household equipment. The total rectifier losses can roughly be estimated as follows: according to the Swedish Energy Agency's report [3] a Swedish family house without direct electric heating consumes 17173 kWh/year which corresponds to 75 kAh in a 230V system, assuming all of this current passes through a rectifier with a voltage drop of 2*0.84V in some device in the house, it means 75*2*0.84=126kWh could be saved by switching to DC. (46% of the the power consumption is however heating and this device may not include a rectifier since it works as a resistive load). Standby power is another loss that can be avoided by switching to DC. This is because alternating voltage induces a current due to the magnetic field in the coils of a transformer even when no current is running trough the device, according to [10] the total standby power consumption is 272kWh/year if a family own the following devices: Computer, LCD computer display, Playstation, TV-box, LCD TV, stereo, DVD and a microwave oven. Finally there is the possibility to plug in cheap LED diodes directly into the socket in a DC house (in a AC home this is quite expensive since current must be transformer everywhere there was a light bulb) according to the Swedish Energy Agency this will save 517 kWh on average in a family house.

So conclusively it can be said about the economy low voltage DC-households:

- The losses in wires to the kitchen are small, but so are the rectifier losses in the AC system.
- around 517 kWh can be saved with LED's
- around 272 kWh is saved from standby losses
- extra energy savings from enhanced efficiency of solar cells will apply if installed.
- low voltage DC devices are as of today expensive when found (possibly trough trailer or boat suppliers)

## 2.5 Different form of energy storage and their feasibility

The first issue formulated by CIT for this thesis was what possibilities there are to store energy in kitchen devices. In order to answer this question and find a suitable concept for a prototype, interesting ways of storing energy is listed in the sections below. Since kitchen devices often produce heat or mechanical energy, it can be convenient to have energy stored in these ways to be readily available without conversion losses. However some devices like the microwave oven need to operate on pure electric energy.

### 2.5.1 Mechanical Energy

Mechanical energy is used by devices such as dough makers, mixers, food processors and blenders. Some devices like the dishwasher partially uses mechanical energy and partially heat energy. Three possible ways of storing mechanical energy are springs, flywheels and pressurized air:

*Springs:* Springs are a rather primitive technology to store energy. Electric motors in blenders or hand-held kitchen devices have a rotational motion which theoretically could be exchanged with a torsion spring, loaded over a long time when placed in a socket and ready or be used as a cordless device. According to Hooke's law the force $f$ exerted by a spring is

$$f = -kx \tag{6}$$

Where k is the spring constant and x is the extension of the spring. With a torsion spring that rotates this becomes: $\tau = -\kappa\theta$ where $\tau$ is the torque from the spring, $\kappa$ is the springs torsion coefficient and $\theta$ is the angle in radians that the spring has been turned. By integrating this with the angle, the energy that can be stored $U$ is given as:

$$U = \frac{1}{2}\kappa\theta^2 \tag{7}$$

This shows that a problem with storing energy in springs is that the last angle that the spring is turned holds the most energy and loading and unloading the spring at varying force can be a problem. The main problem with springs as a energy storage medium is however the volume it would use. Springs have an energy density of 0.3 kJ per kg [11]. With a steel density of around $8kg/dm^3$ and assuming the torsion steel spring can be constructed to expand minimally when used, then 0.3*8=2.4kJ of energy can be held by a spring inside 1 $dm^3$. This correspond to using a 200W mixer for 12 seconds with a 1 $dm^3$ section of the device making up place for the spring.

*Flywheels:* Flywheels are devices that store kinetic energy in a rotating body. Modern use of flywheels is a high-technological feature and are complicated to implement. However the technology has reached promising energy densities of 500kJ per kg [12]. Although the energy is stored mechanically, flywheels generally accelerate and decelerate by electromagnets to store electric energy. A rare commercial use where flywheels directly exert mechanical energy has been in F1-cars [13]. Because of the friction in the bearings, magnetic bearings are often used in the most efficient flywheels, which would make it quite an engineering feat to implement them at a low cost inside household devices. Except for the cost, to scale flywheels to fit inside a stove for example might be a problem. There is a famous example of flywheels powering buses for several km in the 1940's Swiss "gyrobuss" and there are flywheels commercially available in the size of 500kg [14] but smaller devices seem rare.

*Pressurised air:* Pressurized air has a long history of being used as energy source where it is more available than electricity. On a large scale, compressed air can be used as in the 290 MW Huntorf plant in Germany [15]. It stores energy when electricity prices are low by pressurizing large caverns and then extracting energy with turbines when electricity prices are high. On a small scale, pressurized air is used in carbon fibre bottles to power paint-ball guns. When stored in a strong vessel, air pressure can have a longer life-time than energy stored in a battery and it does not include any of the toxic materials batteries often do. The energy density can also be competitive since it depends on both pressure and volume of the compressed air. It can be derived from the ideal gas law: $PV = nRT$ that the energy $W_{A\to B}$ stored in a vessel when pressurized from pressure $P_A$ to $P_B$ is:

$$W_{A\to B} = PVkn\frac{P_A}{P_B} \tag{8}$$

Where P is the atmospheric pressure and V is the volume of the vessel To evaluate if pressurized air can be used to store energy in kitchen devices a theoretical concept was formulated. In this concept the bottom of the dishwasher is used to contain a compressor, a tank and an air motor turbine. (The dishwasher was assumed to be the device with largest possibilities to house these components) The pressurized air can then be used either in a hydrofor to pump the water that needs to circulate in the dishwasher or in the air motor which rotates a socket on top of the dishwasher where blenders, mixers, dough-makers or other mechanical devices of the kitchen can be used. In Figure 8, Formula 8 is used to plot the theoretical capacity of stored energy in kWh of air pressurized at a certain pressure in bar for different volumes.

In the figure is also plotted what energy is required for the mechanical energy in the dishwasher (approximately 200W for the pump during one hour: 0.2W), for comparison a line is also added in the similar case of a washing-machine (Where an extra 300W motor for rotating the drum is assumed). As can be seen, a 1 l. vessel with air at the very high pressure of 300 bar does contain enough energy for a dishwasher cycle and about 0.3 kWh for other purposes. In case of the washing-machine, this would be just enough for he mechanical energy during a cycle. 300 bar is however complicated and dangerous to achieve. There are small scale compressors commercially available that creates this pressure [16] and there is nothing more complicated needed than an impact wrench to turn the pressure into kinetic energy. However there are big losses associated with converting energy to and from air pressure and generally air-motors are only commercially available that work up to 8 bars pressure [17]. This means that energy for compressing the air more than 8 bars will be wasted in a valve in front of the air motor. In Figure 8 It can be seen that at 8 bars pressure, the energy stored in two standard scuba diving tanks ($0.02m^3$) will barely be enough for the mechanical energy in the dishwasher.

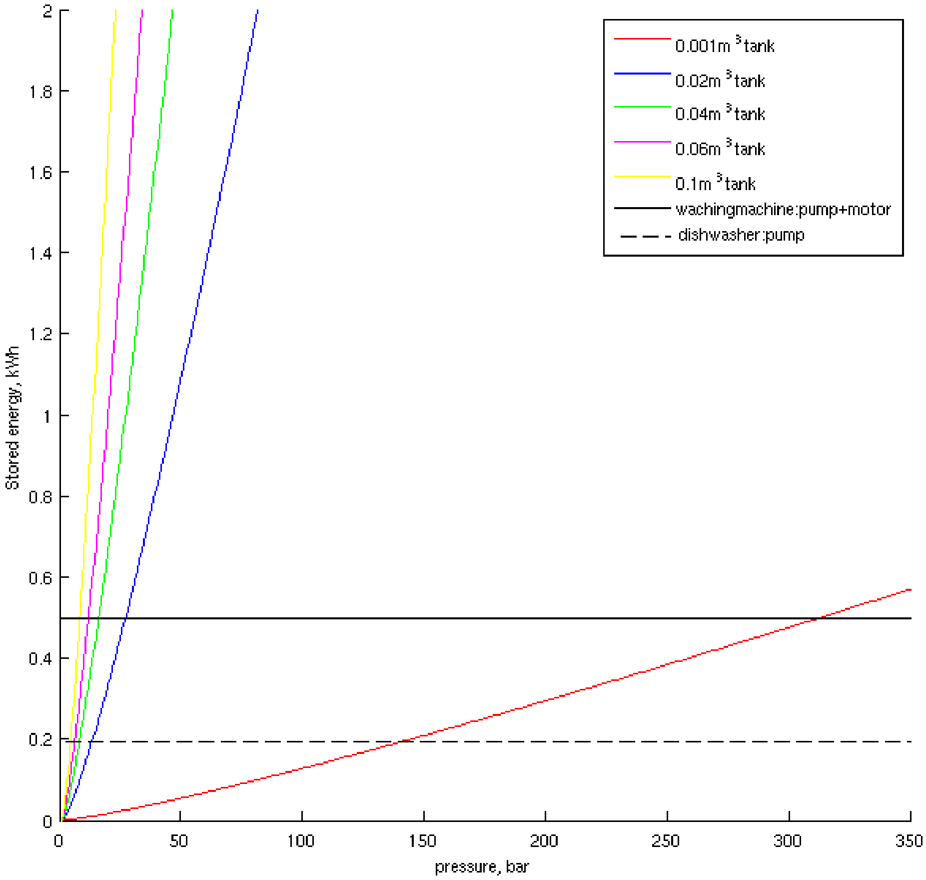

Figure 8: Theoretical capacity of stored energy in kWh of pressurized air stored at certain pressure in bar for different volumes (volumes after pressurization)

### 2.5.2 Heat energy

*Water medium:* To use water as a medium to store energy in households is not uncommon. The hot water in non-electric radiators help smooth out short peaks in demand of domestic heating and make renewable energy from geothermal heating or solar collectors more available. In the opposite manner, water was used before the electric refrigerators to keep food cold in so called iceboxes with blocks of ice. As a theoretical concept for a modern refrigerator in CIT's system, a normal refrigerator may store energy for cooling in a block of ice. When cooling water below the freezing point, constant energy is needed to lower its temperature but when passing the freezing point, extra energy is needed for each kg transformed into ice. This energy or 'enthalpy of fusion' is 334 kJ/kg and can make sure that the refrigerator stays at 0 °C (the melting point can be altered by adding different substances like salt or glycol to the water) until this energy has been transported as heat leaking through the insulation of the machine. For example, 1kWh of energy in the refrigerator is more than enough to shut it down for an hour. This would require $1kWh = 3600kJ = 3600kJ/334kJ/kg = 10.778kg$. This means that installing 100 kg (a block 1m wide, 1m deep and 1dm high for instance) of ice in the refrigerator would render it without need for electric power until about 10kWh of corresponding energy has leaked out. However this may be a fairly easy solution for the refrigerator in CIT's system, it was deemed as a too small project for the scope of this master thesis and to power the refrigerator is not a big problem in CIT's system. On the other hand the dishwashers uses a lot of their energy for heating water and it happens now and then that the stove and dishwasher both need power at the same time (see Table 2). However the power a dishwasher needs is quite a lot to store in a tank of water, according to [3] an efficient dishwasher use 0.98 kWh during a cycle and most of this is energy for heating. According to [8], a modern dishwasher uses about 0.9 kWh for heating each cycle. Water has a volumetric heat capacity of $4.2J/(cm^3K)$. To calculate how much water is needed to store this heat energy we assume that the water is heated 70 degrees (if room tempered water is heated more, it approaches 100 °C and

may be dangerous to store in a tank). This means that $0.9kWh = 3240kJ = 3240kJ/(70K * 4.2J/(cm^3K) = 11020{,}4cm^3 = 11l$ of water is needed to be stored. If this water is stored in a tank in the dishwasher and heated up before use there will of course be losses during the time it is stored, the dishwasher would need some intelligent mechanism for sensing how loaded the dishwasher is and guess on beforehand when there is little time before being used or it would have to use longer time for a program cycle where all the 11l of water is heated first under a long time to keep the power down and then run the normal program using the already hot water. However, according to [8] the heating in a dishwasher is not done continuously during the whole program but in shorter intervals so the peak power demand can theoretically be lowered by heating continuously and use pre-heated water from a tank when it is needed during the program. This concept is further investigated experimentally in Chapter 2.6 and 3.2.3.
In many households there is already heat energy stored in water available from the radiator system. Some literature suggest that dishwashers and washing machines can use heat from circulating hot water [8], this was also further investigated as a experimental concept, see Chapter 3.2.4.

*Latent heat energy:* As in the example of cooling power being stored in a block of ice, heat can be stored in materials that are molten to a liquid at high temperature. The latent heat of fusion can then be released at a steady temperature of the melting point over as long time as the material solidifies. To find a material suitable for storing energy in a certain application, the material should have a melting point at the operating temperature of the application. In this project, materials was searched for that have a melting point of either a suitable operating temperature of a stove or oven (100 °C to 250 °C) or a dishwasher (60 °C to 100 °C). Quite few materials fit this requirement and also have a high latent heat of fusion-value so that much energy can be stored per molten kg. There are certain types of paraffin developed that may have their melting point specificity designed to a certain value. [18] The amount of paraffin V needed for the 0.9kWh of heat energy W during one cycle of the dishwasher is given by:

$$V = W/(C_p * \rho) \tag{9}$$

RT 100 is a paraffin designed to have a melting point at 100 °C, it has a heat capacity of $124kJ/kg$ and a density $\rho$ of 0.77 which gives V=20.1$l$.
20$l$ is quite a big space to store energy for a dishwasher and there will always

be losses when storing heat in this way. However, a concept for a stove and refrigerator and dishwasher was developed in cooperation with another mater thesis group where 10 l of RT 100 was used in this purpose, here the power demand of the dishwasher was lowered by having hot water ready and energy is saved by having the stove and fridge share energy using the 'peltier effect' (see Chapter 5.1).

### 2.5.3 Electric or Chemical energy

*Fuel cells:* Fuel cells is a technology that is still under development but is already commercially used, most famously in hydrogen powered buses in Iceland [23]. It is a clean and efficient technology that produces electricity directly out of fuels (commonly hydrogen gas) and may operate in reverse, producing electricity from this fuel, which yealds a way for energy storage [19]. To calculate what amount of hydrogen would be needed to store for running any of the greater devices we assume a possible energy density of the stored hydrogen. Researchers have acquired quite good energy densities for hydrogen fuel cells in terms of weight, 450Wh per kg [24]. However at atmospheric pressure, hydrogen has a density of 0.08988 g/L or 11.1 $m^3$ per kg. According to [3], kitchen stoves use on average 281 kWh/year, ovens 174 kWh/year and dishwashers 193 kWh/year in Swedish households. With the figures from Table 3, a stove requires about 0.38kWh each time it is used, ovens 1.49kWh and dishwashers 0.69kWh. In uncompressed hydrogen this would then require 13.2$m^3$ stored for the stove, 36.8$m^3$ for the oven or 15.7$m^3$ for the dishwasher. This is a low estimate of the hydrogen needed since the energy density of 450Wh/kg is at good conditions, we assume the machines aren't used for longer time than on average (the oven for example is turned on normally 48 min. according to Table 5 but as long as 203 min. once in a year according to Table 4). So no matter how much space of the devices that are dedicated to store energy, it must be compressed thousands of times to be stored in the range of several $dm^3$. Fuel cells can produce hydrogen under pressure [19] and still work so no compressor is needed but the pressures needed here are too dangerous and not practical.

*Batteries:* This is the most common way of storing electric energy at the scale of household devices. However batteries either loose storage capacity over time or need maintenance when recharged several times. In addition, batteries include rare metals and/or toxic materials which would increase the environmental impact of CIT's system if batteries were to be used. The battery charge that is needed to back up one cycle of a kitchen device can be estimated as follows: for the stove, 0.38kWh is used on average, with 12-volt batteries, this requires 31Ah, for the oven this number is 124Ah and for the dishwasher it is 58Ah. These Ampere-hours can easily be supplied by one car battery [20] or several smaller 12-volt batteries in series if the system runs on higher voltage. In conclusion, batteries would solve any problem with power limitation in CIT's system but would require maintenance of the user and is a less environmentally friendly solution, also this was deemed as a too easy solution for the scope of this project.

*Super capacitors:* In the microwave oven, power is regulated by supplying power to the magnetron in short bursts of different lengths (see Figure 9). A concept was therefore formulated for a microwave oven where the power demand is lowered by a s.c. super capacitor in which charge is built up between the burst and supply extra power to the magnetron when needed.

In this way, the peak power demand could be lowered to the actual power that is used on average in the machine. Capacitors do not suffer from lowered capacity after each charge and discharge as batteries and since they have much longer lifetime the environmental impact is less. Supercapacitors are capacitors made to hold great charge of many farads but still they self discharge at a higher rate than batteries. Supercapacitors that use organic electrolytes have the highest self-discharge rate of 50% in 30 to 40 days [21], in commercial devices it can be mentioned as an example that superconductor-powered screwdrivers has according to manufacturers a self-discharge rate of 85% in three months[22]. This makes superconductors suitable to store energy for short periods of time as in between the short bursts of power in the microwave oven.

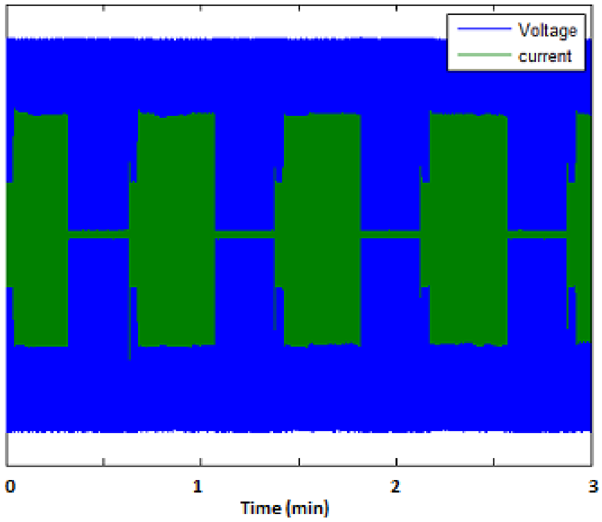

Figure 9: Measured voltage and current over time (min) in microwave oven, voltage is a constantly alternating 50hz 230V rms voltage, current appears in burst 56% of the time. 'Power' set to 450W when measured

*Sodium acetate:* Heat can be stored chemically in materials that have a variable melting point. For temperatures needed in stoves and ovens, there are no materials of this sort but for dishwashers which may operate in 60 °C there is sodium acetate ($NaC_2H_3O_2$) which has a melting point of 58 °C [29]. The phenomena that can be used here for heat energy storage is that when solid sodium acetate is heated to above 58 °C and completely molten, the temperature may be lowered all the way to room temperature but the material experience so called 'super cooling' and is still in liquid phase. Only when stirred or when a small nucleus of crystals is forced to form by vibration, the material starts to solidify. Since the solidification is an exothermic reaction, the heat energy used to melt the whole volume is stored and is rejected as heat during the crystallisation, the most common commercial application for this is so called heating pads and the density of the energy that may be stored in this way is 264 to $289kJ/kg$ [29]. With this in mind, a concept was formed where the heater in the dishwasher is replaced by a tube immersed in a volume of sodium acetate. The volume of sodium acetate can after the last time dishing was done, slowly be heated up at low power during a longer period of time until it reaches above 58 °C. At this stage the volume is left as it is in liquid phase until the dishwasher is started again and heating is needed. At this point the circulating water moves through the tube and exchanges heat with the sodium acetate, then a crystallisation is started by a small servo or

actuator so that the heat of fusion in the sodium acetate is released to the water. The volume needed for the 0.69kWh of heating in the dishwasher can then be estimated to about 0.69kWh=2484kJ=(2484kJ)/(270kJ/kg)=9.2kg. With a density of 1.45kg/l only 6.3l of sodium acetate need to be fitted into the volume replacing the heater for this solution to work.
This was deemed a very interesting concept and a low cost solution but the chemical reactions needed, exchange of heat and the risk of nucleation before use makes it a less reliable mechanism to use for heating.

## 2.6 Experimental and observational studies

### 2.6.1 How dishwashers work

The inner workings of a dishwasher may not be the most mysterious of things, however it can be good to go over the details for the sake of clarity. A dishwasher takes in 3 to 5$l$ of water at a time, it circulates this for several minutes each time and at some intervals heat the water while circulating. In terms of performance and energy cost, it could just as well take in and flush out hot tap water all the time but for the sake of sustainability and good marketing most dishwasher brands try to keep the water consumption to a minimum. The rotating spray arms inside the dishwasher are almost always driven by the pressure of the water and not by motors. This means the main things that need electricity is a pump and a heater. As examined in next Chapter, the heating consumes most of the energy.

### 2.6.2 Working patterns of Dishwasher

Figure 10 shows measurements on an Electrolux dishwasher running at the “65 °C” mode. The power was measured as the root-mean-square value at the standard 230V AC wall socket. The temperature was measured with a thermo-element wire with its sensitive point placed at the bottom of the dishwasher case, hooked up to a multimeter outside its door lid.

As can be seen, dishwashers consumes over 2kW at times, these are the parts of the dishwasher programs where the water is heated as can be seen in the rising temperature value during the same time, during the ”heating phases”. The total energy consumption during the cycle is 0.865 kWh. Before and in between the heating phases the dishwasher only needs power for pumps and electronics, therefore the consumed power during these phases is only 160W maximum.

To decrease the power demand, a concept was developed in this project for a prototype dishwasher where the water is heated also in between the

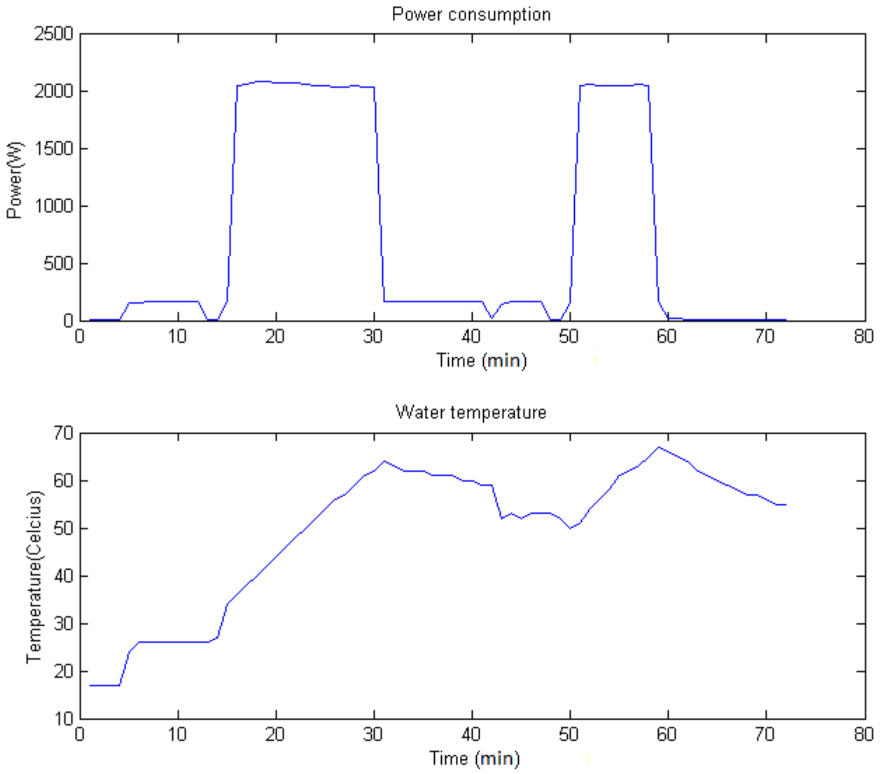

Figure 10: Power consumption and temperature inside dishwasher

heating phases. As Figure 10 shows, there is lot of time between the heating phases where water could be heated elsewhere and thereby lower the over-all power. Another concept is to simply take in hot water to lower the power needed during the heating phases, the effect of using hot tap water instead of cold can be seen in Figure 15 and 12. In Figure 15 it can be seen that hot inlet water clearly decreases the time where power is needed for the heater. However Figure 12 shows that even though hot tap water is 50°C (about 46°C in this case due to long flush-time) the inner temperature of the dishwasher only starts at max 35°C.

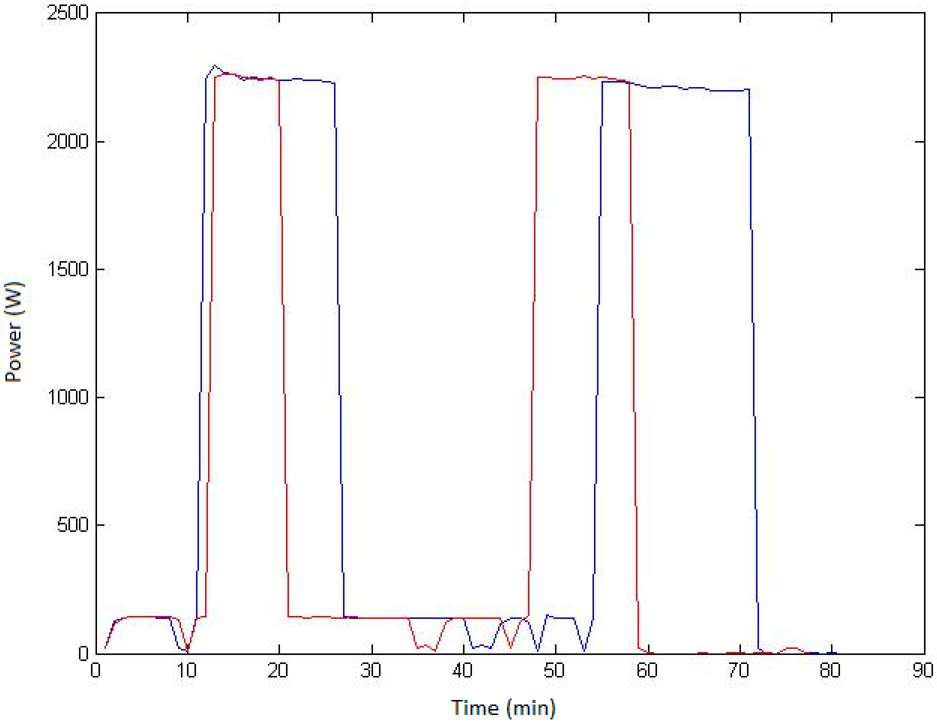

Figure 11: Measured power consumption in Watt over time in minutes of a dishwasher, blue curve at 21°C inlet water and red curve at 46°C

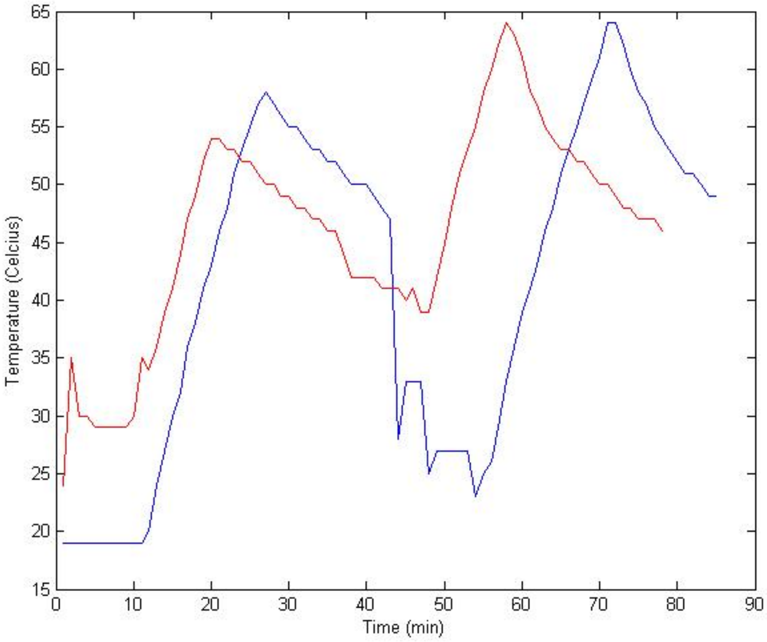

Figure 12: Measured temperature over time inside dishwasher, blue curve at 21°C inlet water and red curve at 46°C

# 3 Concept Development

## 3.1 Concept generation and selection

### 3.1.1 Benchmarking

During the early stages of the project benchmarking was carried out as a basis for generation of concept solutions. In addition to household appliances sector, car industry and other industries which deal with energy conservation and alternate energy consumption were studied.

The automotive sector trying to cut on fuel consumptions and emissions and has been working hard on energy conservation and storage and transformations. Also most of the automobiles use low voltage DC in their electrical system therefore it was a good industry to study.

"Compressed air cars" or "Air cars" are compressed air powered cars. Unlike an internal combustion engine, compressed air at pressures close to 300 bars from external tanks are allowed to expand in a motor and this expansion is converted to work in rotating the wheels of the car. Automobiles use flywheel rotating at high speeds to store mechanical energy as well (Chapter 2.5.1,' Mechanical Energy').

In large cities like Goteborg in Sweden, most of the houses and other buildings are heated by hot water which is pumped from a central district water heating. Excess of heat energy produced by industries are used to heat the water in large volumes which is then pumped to various households [25].

The sodium acetate hand warmers are an example of how energy could be stored in form of latent heat to be used at any time [26]. There has been research to use phase change material (latent heat mediums) in the automotive industry to warm the car engines by absorbing and storing the exhaust and waste heat produced during the engine run [27].

### 3.1.2 High level concept generation

The first level of concepts was generated by brainstorming around the ideas of best practices that came out during the benchmarking. The ideas were arranged in a matrix which is a slight modification of a morphological matrix. As shown in Table 11 the necessary functions of a dishwasher are listed in the first column and the corresponding solutions of how to achieve it in this project are presented in the corresponding rows. The solutions are further classified into solutions that use energy storage in their principle and those that do not have energy storage.

Table 11: Morphological matrix of concepts involved, the number of combinations was reduced to the different foms of heating combined with one solution each from the rest of the functions (green boxes). These combined solutions was then further investiated.

| Functions | Solutions | | | | | | |
|---|---|---|---|---|---|---|---|
| | Solutions with energy storage | | | Without energy storage | | | |
| Water circulation | Stored energy in spring | Stored energy in flywheel | Stored energy in internal compressed air system | Stored energy in external compressed air system | A Low voltage DC motor directly coupled | Low voltage DC motor connected by belt drive | Using Ac /Dc converter on existing system |
| Water draining | | | | | Low voltage Dc motor coupled to existing pump | New Low voltage Dc pump | Using AC/Dc converter |
| Water inlet | | | | | Use a Dc solenoid valve | | Use AC/Dc converter |
| Water heating | Sensible heat energy storage ,(Separate heating tank) | Latent heat energy storage, extraction of heat from other sources | Hot water from district water heating | Hot water recirculated to maintain water temperature. | Low voltage Dc Heater | Use of Peltier element as heating elements | AC/DC converter |
| Timing and control | | | | | Timing and control | Computer controlled digital switches | |

### 3.1.3 Narrowing down concepts

The solutions of the different functions are distinct and will therefore lead to a large number of unique concepts (7x3x2x7x2= 588). So it was decided to eliminate the solutions from the morphological matrix to reduce the number of concepts to be to compared.
During meetings with the project manager Stephan Mangold of CIT it was concluded that AC/DC converters are to be avoided, it was further reflected that since energy storage systems always take up space, separate energy storage systems for low energy capacities can be avoided as well.
The first round of elimination removes all the solutions which were based on energy storage, except in-case of heating which consumed a lot of power (see Chapter 2.6.2: ”Working patterns of Dishwasher”).
On discussion with Stefan Lundberg, Assistant Professor, Chalmers University of Technology, who has lots of experience working with electrical machines, it was realized that direct coupling of a new motor with a different dimension to the existing pump will require high precision machining which will increase the cost. For this reason, a new pump was chosen for draining and a new DC motor to be coupled by a toothed belt drive to the existing circulation pump.
The storage of heat in latent heat storage system and heating with peltier element was investigated externally as a separate thesis [4]. The findings including the dishwasher of this project are discussed in Chapter 5.1 “Combination with experimental stove and fridge”.
The remaining concepts are discussed in the next chapter.

## 3.2 Prototype Concepts

The following ideas (and combinations of them) were considered to decrease the power consumption of the prototype:

### 3.2.1 Hot tap water

A common way to save energy in dishwashers is to let in hot tap water instead of cold. According to [9] Swedish tap water should be at least 50°C (this is to stop bacteria growth in piping) but maximum 60° (high risk of scalding).

Results can be seen in Chapter 2.6.2, Figure 15 from a series of experiments where power and water temperature is measured when using hot tap water compared to cold. Measurements were done with a Bosch machine set on the standard ”60°C mode” and it was concluded that the 2000W heating element only had to be turned on 20 min. instead of 33 min. This gives an

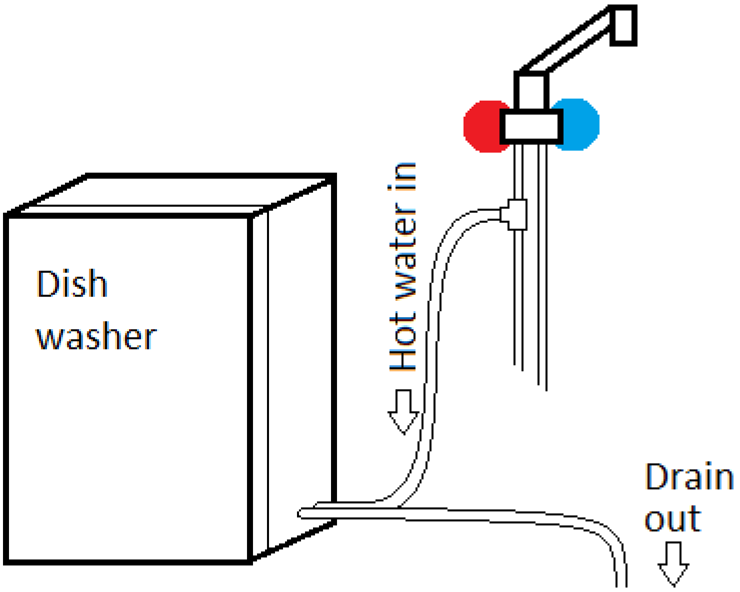

Figure 13: Concept 1: simply use hot water instead of cold

energy saving of 2.64MJ or 0.73 kWh, which is 58% of the total 4.55MJ used during the normal cycle of the dishwasher. This result is approximately the same if 55°C mode is used. As described in [8], it can be seen from these results that hot inlet tap water can not make up for all heating in the dishwasher. This is because a lot of energy is used to heat up the metal case and inside parts of the dishwasher. The water that enters the machine almost instantly cools down from 46°C to 35°C while heating the room tempered inside of the dishwasher to the same temperature. It can also be seen from the slope at 30 min. that the temperature of the water drops with about 0.5 degrees per minute, this corresponds to a 140W continuous heat loss in the 4 litres of water. This also shows that some extra heating source is necessary if the temperature should be maintained inside.

### 3.2.2 Low voltage heater

One way of lowering the power demand is to simply allow the dishwasher to heat the water during longer time. This can be done by lowering the voltage since the heater works as an electric resistance. However the heater's resistance needs to fit the voltage level to produce the right amount of heat:

Joule's law: $P = UI$ and Ohm's law: $U = RI$ give the following relation:

$$P = \frac{U^2}{R} \tag{10}$$

In the case of CIT's system the dishwasher is supplied with a power $P = 500W$ at a voltage $U = 50V$. If all the power is used for heating, the resistance R should then be 5Ω which is 5.3 times lower than a regular 2000W heater for 230V at 26.5Ω.

### 3.2.3 Separate heating tank

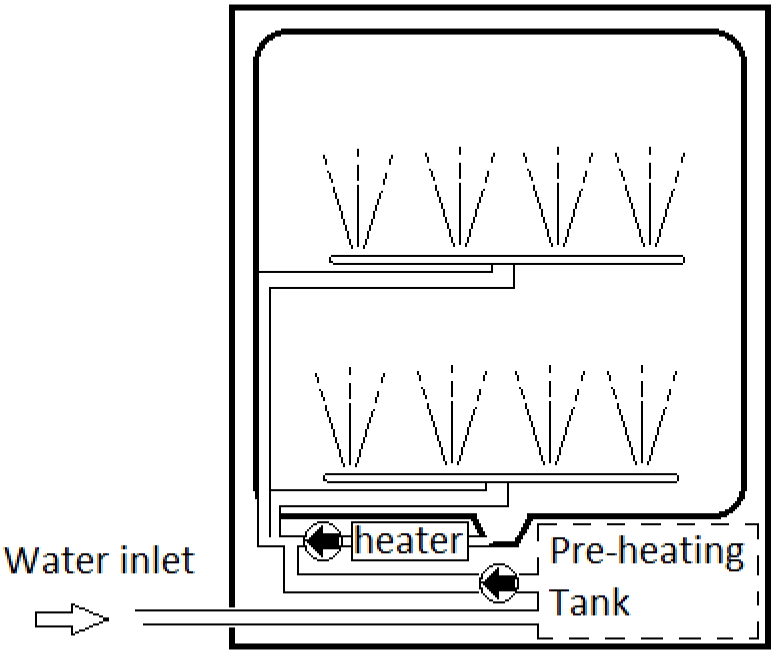

Figure 14: Concept 3: Separate tank for pre-heating water during cold phases

Most dishwashers have programs where the water is heated at some intervals and then replaced by cold water and then again replaced by new water that is heated. This is something manufactures decide based on when particles are to be removed, how the detergent dissolves and how fast the dishes dry up afterwards. Because of this there are periods where the dishwasher only consumes power for circulation pump like at minute 30 in graph 12. By installing a separate water tank at the water inlet, some water could start heating up for the next "phase". This could even out the power consumption. For example, in the Bosch, 1000W could be used all the time instead of 2000W at half the time.

### 3.2.4 Circulated hot water

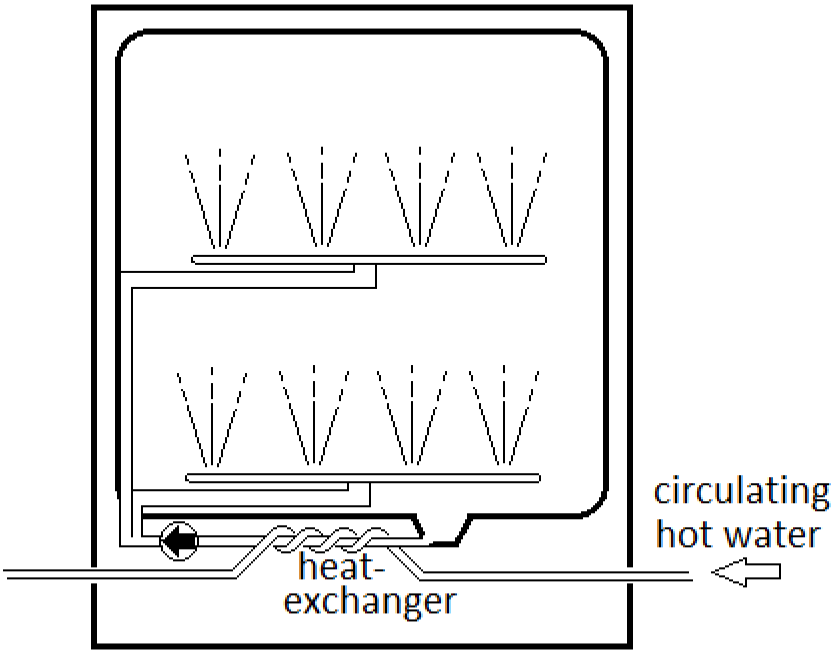

Figure 15: Concept 4: Heat is transferred trough a heat exchanger instead of electric element.

One concept for heating that is investigated in [8] replaces the electric heating of water in a dishwasher and washing machine by heat from the hot water circulated for heating in the rest of the house. According to [8], if the dishwasher water and external water of 70°C is led trough a heat exchanger, all electric heating of the dishwasher can be avoided. Without the heating element, a normal dishwasher does not need more than 170W for the remaining operations (about about 140W for the pump motor, 19W for drain pump and 11W for inlet valve).

It can be argued that this method does not avoid the problematics in a low voltage DC house but simply moves them from the dishwasher to wherever the water is heated. However in a low voltage DC house the major problem is to conduct much electricity over short time through the low voltage wires and this is not crucial if the water is heated over long time in a domestic water heater. Further arguments could be that the water can be heated without electricity in solar collectors or by geothermal heat.

## 3.3 Concept selection

When choosing a concept for the final prototype it was prioritized that its power consumption should be lower than the original dishwasher and also that the performance should not be decreased. The performance in the different concept was estimated in terms of how close to the original 55 to 65 degrees inside the dishwasher can be reached and how much longer time this would take.

When experimenting with the starting temperature of washing water, it became clear that only taking in very hot water, the room tempered dishwasher still needs to heat the water further with electricity to reach the temperature in usual programs. However hot inlet water from the tap is a quick way to reduce the power needed.

To change the heating element inside the dishwasher is an obvious way the power consumption can be regulated but it will naturally take longer time to reach desired temperatures with a low power heater.

In the concept of having a separate heating tank, the water could theoretically enter the dishwasher preheated at such high temperature that both water, dishwasher-case and dishes stabilizes at the highest desired temperature in a program. This would however require much longer time in the pre-heating tank than the time in between the phases where the washing water normally is heated. In the best way to implement this concept the power used is therefore reduced to half with a low voltage heater and the spare time in between the heating phases (which make up about half the program time) is then used to pre-heat water.

The concept of leading hot water from another source through the dishwasher is of course unfair to compare with other concepts since it requires another infrastructure of the home. However in the home where this dishwasher is targeted to be installed, the owner may have an interest in renewable sources such as solar collectors or geothermal heat, and since new low voltage DC cables preferably are installed inside the walls, plumbing could possibly also be done to connect the dishwasher to the radiator system. When comparing the four concepts in Table 12 on equal grounds, the circulated hot water concept stands out since it makes power for electric heating unnecessary without

Table 12: Concept comparison

| Concept | max temp | Extra time needed | Power consumtion |
|---|---|---|---|
| hot tap-water | 30-40 °C, Not as high as max water temperature in the tap-water (60 °C). Generally 10 to 20 degrees lower | none | 58% of normal power |
| Low voltage heater | only limited by time | relative to the amount of power: half the power - double the time | lower than normal, depending on the extra time needed |
| Separate heating tank | only limited by time | none | minimum 50% of normal power, losses will occur due to leakage of heat. |
| circulated hot water | Depends in the source of hot water. | none, depends on temperature in accumulation tank | no electric power necessary for heating |

reducing the maximum temperature in a program or the time needed. (According to [8] ”All electricity for heating can be replaced by water [circulating trough the heat exchanger] having normal boiler temperature of 70°C ...”) The effect is not so great if the water delivered to the dishwasher does not hold high enough temperature but it was still chosen as the final concept since it could be evaluated together with another prototype machine for the low voltage DC project where hot water is available at low power.

The final concept is summarized in figure 16

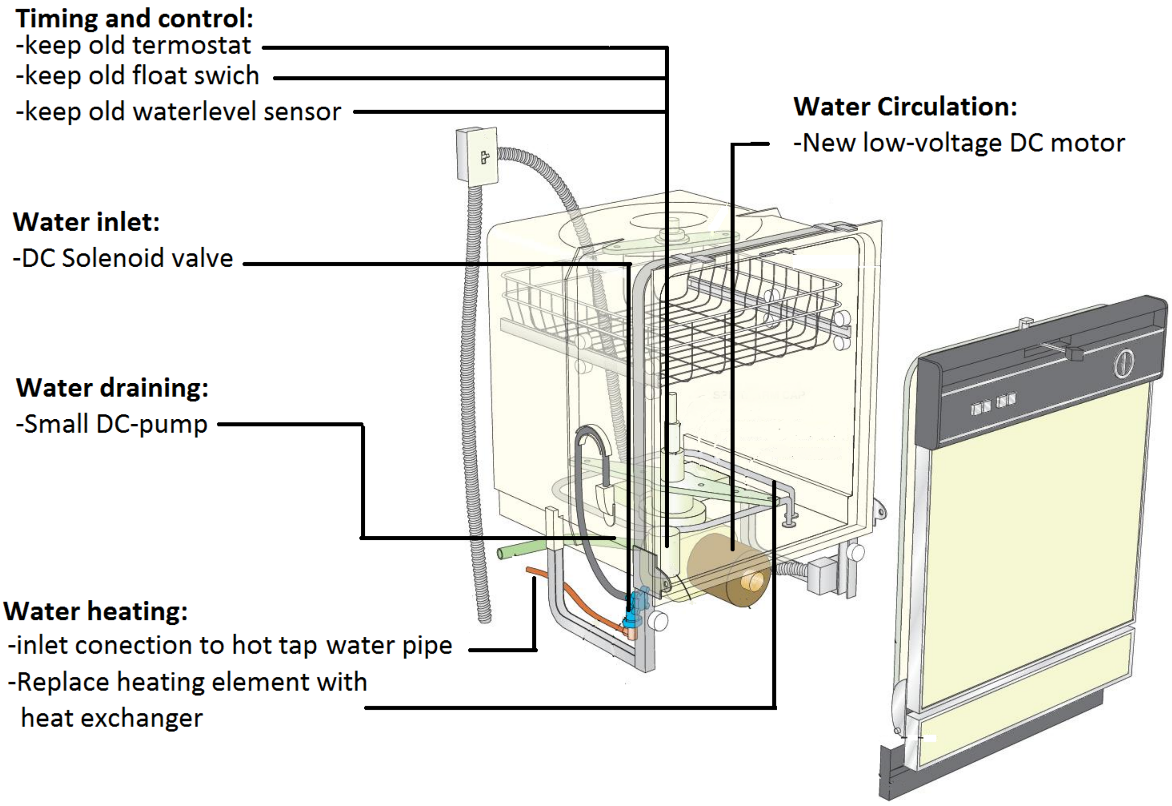

Figure 16: Parts to be replaced in the final concept where all components run on low voltage DC and heating is done by hot water at the inlet in combination with circulating hot water in a heat exchanger

# 4 Prototype Construction

The original dishwasher operated only on AC. Therefore suitable replacements for inlet valve, heater, drain pump and the motor for circulation pump were found in DC by measuring original power used and calculating what torque was needed for the motor.

## 4.1 Components

In addition to a small DC drain pump and electronic parts to reconnect thermostats, pressure sensors float switches with valves and motor, the main parts that needed to be modified were the main pump motor and the heater.

### 4.1.1 Replacing the heater with heat exchanger

The heater in the prototype dishwasher is replaced by a heat exchanger which heat up the washing water as described in Chapter 3.2.4.

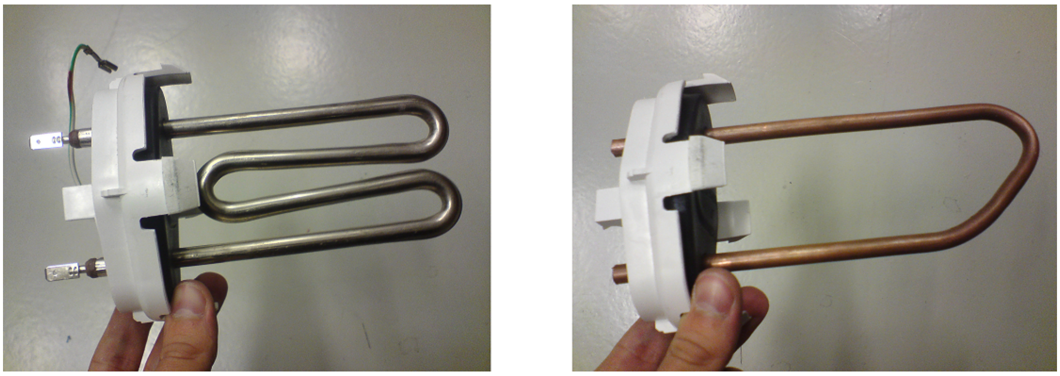

Figure 17: To the left: original 2000W 230V heater, to the right: the copper tube working as heat exchanger in the prototype

The principle is simply that hot water for heating elements (radiators) in the house enters and exit the machine through a tube, the tube heats up and in turn heats the water circulating in the dishwasher. The tube is made of copper to conduct heat and is so long that the water inside release enough heat during the time it passes through. The calculations below show that the dish washing water can be heated up just as fast with a heat exchanger as an heater:

The law of heat conduction states:

$$\frac{\Delta Q}{\Delta t} = -kA\frac{\Delta T}{\Delta x} \tag{11}$$

The heat exchanger was replaced by a $30cm$ long copper tube, the diameter of the tube is $8mm$ to fit the holes from the heating element. This gives it an area $A = 75.36cm^2$ and its thickness is $\Delta x = 1mm$. Copper has a thermal conductivity of $k = 401$ W/mK. Equation 11 then shows that the temperature difference $\Delta T$ between the in and outside of the copper tube only needs to be 0,66 degrees to give a heat transfer $\frac{\Delta Q}{\Delta t}$ of $2000W$. This is however only possible if enough amount of energy is transported to the heat exchanger.
The prototype dishwasher was equipped with a 18W DC pump to transport hot water to the dishwasher. It is specified to pump 6l/min. If an average temperature difference of 20°C in the heat exchanger is assumed and with a heat capacity of 4200 $J/dm^3K$ in water, this means up to 504000 J/min or 8400W of power is available from the hot water.

### 4.1.2 Finding the right DC Motor

The obvious choice of motors for appliances in a normal kitchens is a 230V AC motor since 230V at 50Hz is the standard way power is transferred through sockets. The rotation speed for these motors is then 50Hz times a factor given by the number of poles in the motor. In a DC household there is no 50Hz standard speed and the rotation speed of a DC motor always depends on what application it is used for. Therefore the following calculations needs to be done to find out what DC motor fits a dishwasher.

In the original dishwasher for the prototype of this project, the main pump motor was measured to rotate at 2800 rpm and using a power of 140W. The appropriate torque for a pump motor rotating at this speed was calculated using the formula:

$$P = 2\pi\omega\tau \tag{12}$$

Where the power P = 140W and the rotation speed is 2800 revolutions per minute (or $2800 \cdot 2\pi/60 = 293$ radians per second), this gives a torque $\tau$ of 0.48 Nm. The most appropriate motor for a low voltage DC dishwasher would be a DC motor that exert this torque at the same speed. To simulate such a motor, a more standardized DC-motor was used with a gearbox. The new motor is efficient at a lower torque and has peak performance at the higher speed of 4000 rpm. To ensure that the pump work at the same speed and torque, the reduction in the gearbox was calculated using the following approximations:

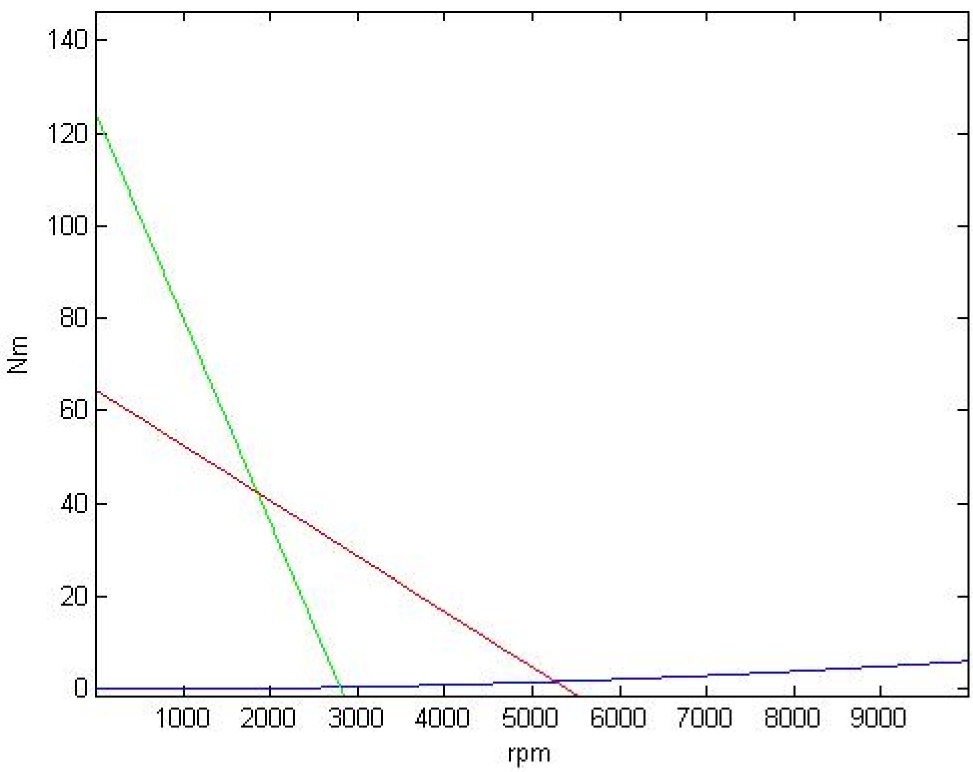

Figure 18: The torque in Nm depending on rotation speed in rpm, the blue curve represents the torque needed to run the pump at certain speed, red and green line shows what torque the new DC motor has at certain speed, red without a gearbox and green with a gearbox that makes it intersect the pump's curve at 2800 rpm

The torque $\tau_1$ needed to pump the water is assumed to increase quadraticly with speed:

$$\tau_1 = k_1 \cdot (2\pi\omega)^2 \tag{13}$$

Where $\omega$ is the rotation speed. The measured values of $\tau_1 = 0.48Nm$ when $\omega = 293s^{-1}$ is then used to estimate the constant $k_1$ to $k_1 = 0.48/(293^2) = 5.59 \cdot 10^{-6}Nm/s^2$. The torque of the pump can then be plotted as a function of rotation speed as seen in Figure 18.

On the other hand can the torque $\tau_2$ from the DC-motor be calculated as follows:

$$\tau_2 = k_2 I \tag{14}$$

Where I is the current through the motor and the constant $k_2$ is given by the following equation:

$$V = IR + k_2 \omega_2 \tag{15}$$

Here, $R$ is the motors internal resistance: $63m\Omega$ and $\omega_2$ is its rotation speed at voltage $V$ over the motor. The motors optimal values is rated $V = 36V$,$I = 8A$ and $\omega_2 = 4000rpm$ which give the a value of $k_2 = 84.8mV/s$. This value can be inserted in equation 14 to give the torque of the DC motor at different speeds. This is plotted as the red line in Figure 18 and here it can be seen that the motor has a higher torque than is needed for the pump at speeds lower than 5300 rpm where the red and blue lines intersect. Therefore a gearbox was constructed, the effect of introducing a gearbox in above equation with reduction $k_g$ is that $k_2$ is reduced $k_g$ times. With $k_g = 0.68$ the torque of the motor follows the red line which intersects the torque of the pump at 2800 rpm which was the original speed of the pump. $k_g = 0.68$ corresponds to a reduction of 28:19, therefore a gearbox with this reduction was built between the new motor and the pump shaft inside the old motor-housing, see Figure 19.

Aluminium sheets proved to be a convenient material to work with. Aluminium is easy to cut and drill to desired shapes with little effort and experience. A hacksaw and a drilling machine were enough to cut and shape the sheets for mounting the new motor to the pump. The pulley wheels which came with no drill holes required a hole in the centre to be mounted on the 8 mm shafts of the motor and the pumps. It was not possible to centre the drill hole with a vertical drilling machine. Therefore the wheel had to be mounted on a lathe and drilled to a size lower than required and the hole was finished by broaching.

### 4.1.3 Computer control, valves and draining

Even though the prototype was not completely controlled by computers it was demonstrated with manual switching that computer control is possible. The water level sensor and the thermostat in the original dishwasher worked by physically closing and opening circuits; it did not matter if the supply was AC or DC for low current voltage situations. Therefore the sensors which existed in the original washing machine were retained for input purposes

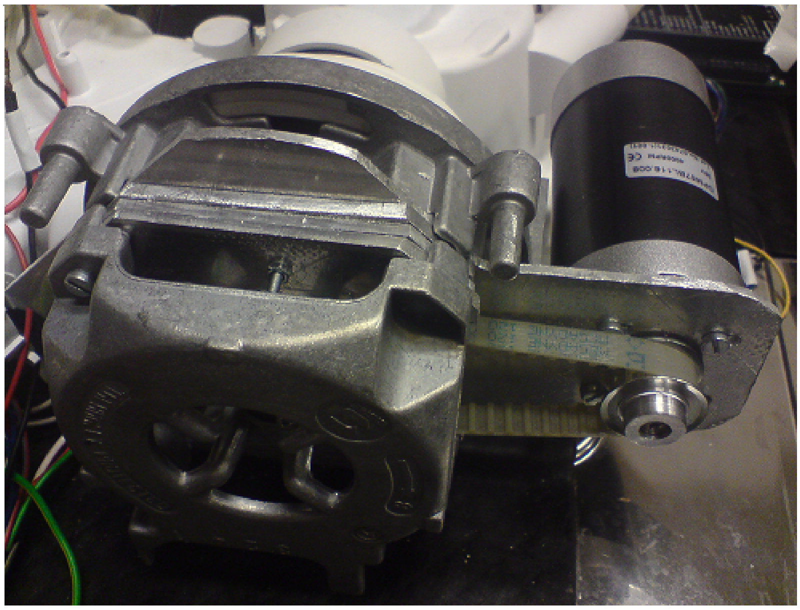

Figure 19: The gearbox, connects the pump-shaft inside the old motor-housing to the left with the new DC motor to the right with a reduction of 28:19

for the system indicating temperature and water level (demonstrated with LED's).

Solid state relay circuits (transistors) could be used to control switching based on output signals, the various functions of the dishwasher like, the pump and the inlet valve and draining. A flyback diode needs to be used as the circuit includes inductive loads. The computer control could more

dynamically control the various functions of the dishwasher unlike the original dishwasher which completely based wash cycles on time and temperature alone.

A low voltage DC 2/2 way solenoid control valve was used to control the inlet of water to the dishwasher. The inlet valve consumed an insignificant power of 11W for the time water was inlet this was the same power required for the inlet valve in the original dishwasher. It was noted that the inlet valve did not function smoothly at temperatures over 80 degrees and needed to be cooled down to operate at normal again. The low voltage DC drain pump which was used in replacement to the original drain pump also consumed 18W and pumped water at 6.6 litres per minute.

# 5 Tests and Evaluation of the prototype

The new heating system of the machine was tested by measuring temperature of the water inside the dishwasher and the temperature of the water circulating through the heat exchanger. The circulated water was simply held at a constant temperature to simulate water from either geothermal heating, district heating, solar thermal collectors or any water heater for radiator systems. The measured temperatures can be viewed in Figure 20. As can be seen the temperature raises although no electric power is supplied, the water is pumped through the heat exchanging copper-tube at a rate of $6l$ per minute.

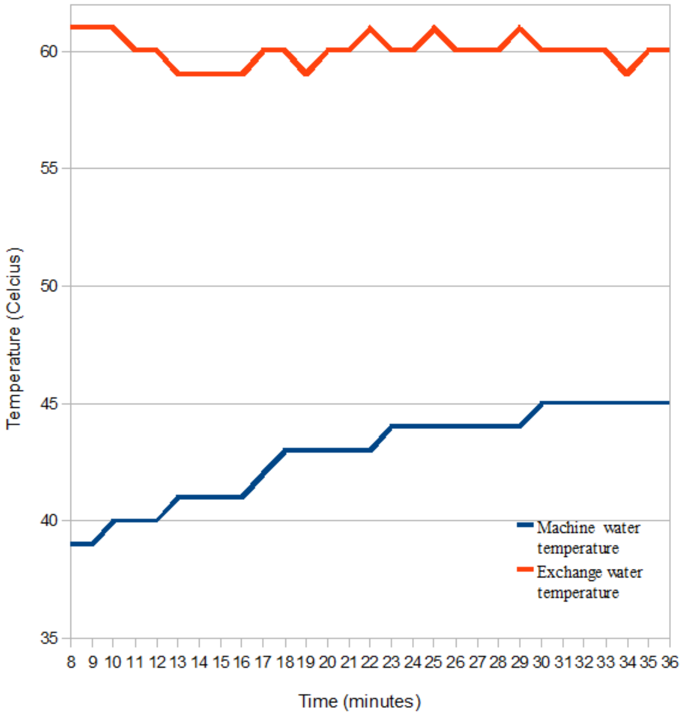

Figure 20: Water temperature inside the final prototype when supplying exchange water at a constant temperature of 60 °C

The remaining electric parts of the dishwasher, inlet valve, drain pump and circulation pump motor required a maximum of 80W to take in water, circulate it and drain it. Although this was much lower than the original 140W used by the AC motor, the water pressure was controlled to be the same as originally by test-dishing some dishes.

## 5.1 Combination with experimental stove and fridge

The prototype dishwasher was also tested together with another prototype kitchen appliance developed in cooperation with a second master thesis [4] on the same low voltage DC system. This device store heat as latent energy in paraffin using peltier elements to combine cooling of a small fridge with heating of a stove. This set-up of prototype stove-fridge-dishwasher was made to simulate a small prototype kitchen for the low voltage DC house. The following section will explain how this device and the dishwasher were constructed to simulate a very low-power, less than 50V DC unit which handles the major functions needed in a kitchen.

### 5.1.1 Peltier elements

Instead of a freon heat pump or similar which is normally used in fridges, peltier elements were used in this prototype device. A peltier element is a simple solid state device (often in shape of a plate), that provide heat at one side of the plate by extracting heat from the other when applied with a voltage. The thermoelectric effect that makes this possible can in a rough way be described like this: An electric current is led through a series of differently doped semiconducting blocks. The way these small blocks are arranged and the way the current flows trough them is so that electrons move from p-type semiconductor to an n-type semiconductor at one side of the plate and in the opposite way on the other side of the plate. This have the effect that electrons have to absorb phonons (heat) at one side of the plate in order to reach a higher energy level required in the p-type material and the effect is the opposite on the other side of the plate [30]. In these experiments, two sets of four peltier elements were used, each constructed to use 12V and thereby $4 * 12 = 48V$ required for each set, just under the 50V limit required for CIT's system.

### 5.1.2 Paraffin, ”RT100”

In an experiment, heat was generated over long time and accumulated in a medium to be used as a stove, thereby lowering the power needed when using the stove. The chosen medium was a paraffin with the product name RT100. This paraffin is composed to have a melting point at 100 °C. With a melting point at 100 degrees, the whole energy needed to melt the 10 kg used in the

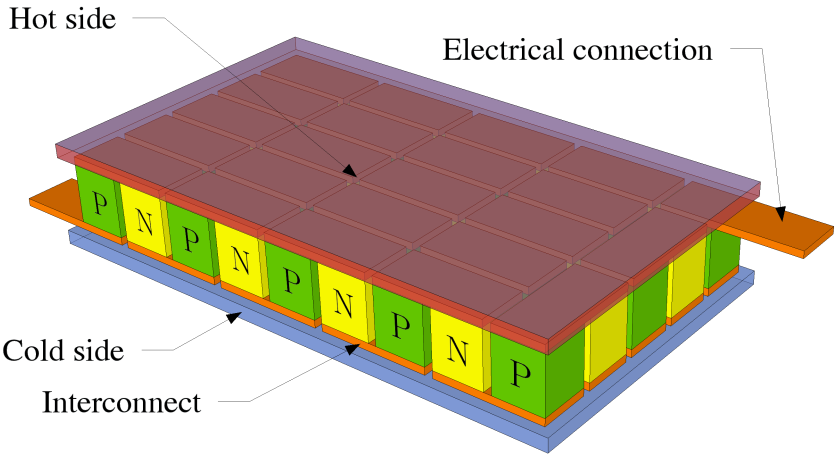

Figure 21: Peltier element schematics (picture from [28])

experiment can be extracted without letting the temperature drop. This is called latent heat storage and the paraffin was chosen because it can store 124 kJ of energy per kg that is molten. The paraffin was kept in a thermally insulated box, inside yet another box made of aluminium to easily spread the heat from the heat source in the bottom and to easily be absorbed by a heat sink on top under a lid of the insulation.

### 5.1.3 Experiment set-up

The two sets of peltier elements were placed inside the wall of one cell-plastic box each. The first was placed with the cold side onto a heat sink and a fan inside the box to create a cooler. The second was placed with the hot side onto the bottom of the aluminium box containing the paraffin inside the other styrofoam box. Each peltier element has the ability to pump heat from one side to another that is 50 degrees hotter. The two set of peltier elements were connected with a system of circulated water, designed to keep a tank of 10l water at 50 °C in between the two boxes. This means the first set of peltier element keeps the fridge at about 4 °C on its one side and the tank of water at 50 °C on its other side. The other set of peltier elements can then have 50 °C water circulating on its one side and 100 degrees paraffin on the other.

The water in the tank in the middle was used for the dishwasher. When taking in water, it is already 50 degrees but however quickly drops to heat up the inside of the dishwasher, the water is then heater again while passing the heat exchanger when it is pumped through the dishwashing process. The heat

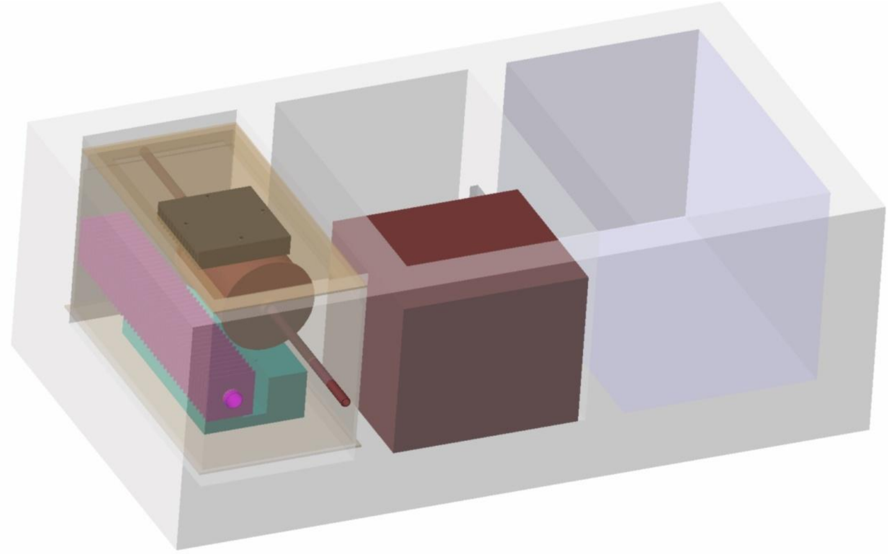

Figure 22: the three insulated compartments, to the left: the stove at 100C, in the middle the water tank at 50 °C and to the right the refrigerator at 4 °C

exchanger was also connected to the heat generated by the peltier element in two different set-ups: in the first experiment it was connected by a closed loop of water pumped through a radiator placed in the paraffin, in the second, remaining water from the 50 degrees tank was pumped through the stove side and past the heat exchanger in the dishwasher. The second one proved better since the paraffin is made to conduct heat slowly, it took about 8 minutes per degree to raise the water temperature inside the dishwasher. Also a small metal tank of water was placed inside the paraffin with one connection to water supply and the other to a tap, to make hot water instantly available for the user.

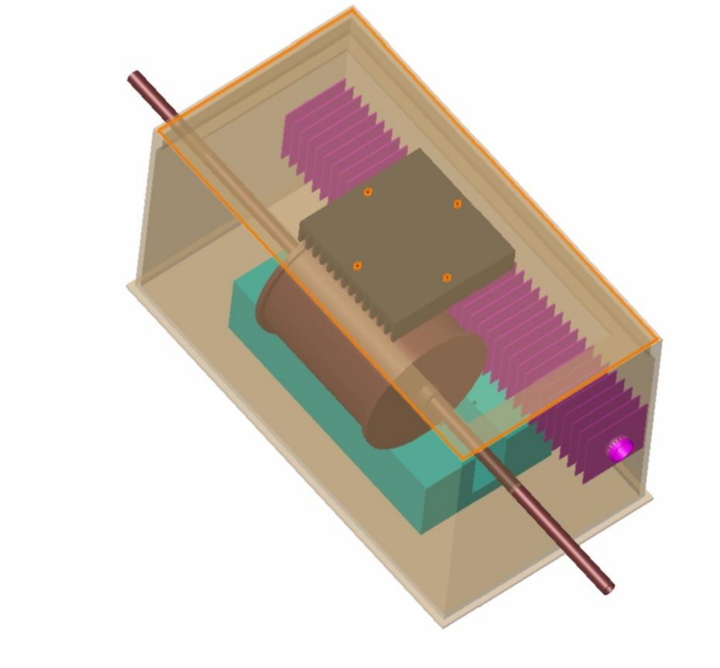

Figure 23: Close up on the stove with heat sinks on top and bottom and radiator and water tank placed inside.

# 6 Conclusive results

The results from the investigation of power consumption in Swedish household shows that stove, oven and dishwashers use more than 1.5kW at times in Swedish households. However the difference for the user would not be large if peak power demand is set to 1.5kW for theses devices and 500W for the rest in the kitchen. Several of the devices may very well be turned on at the same time, most critical is when both stove and oven are on (23% of the times the oven is used). In this case the allowed 1.5kW for the whole kitchen is often not enough. This means that either it can not be allowed that some devices are turned on at the same time or there must be energy stored in some device when a DC system is to be implemented with the described limitations of power.

If the cable cross-section is made larger for devices that need more power, then there will be small losses due to cable resistance in the DC system: 27kWh/year. The rectifier losses in the AC-system are unfortunately even smaller: 9.9 kWh but both rectifier losses in an AC houses and ohmic losses in a DC house are small compare to the potential gain from savings in the rest of the house with CIT's system.

The power consumption of the dishwasher need to be lowered, it uses 2kW for periods of 30 minutes. Hot inlet water will shorten this time drastically but to lower peak power demand it's standard 230V 2kW heater needs to be replaced. The prototype dishwasher shows that maximum power consumption in a dishwasher may be reduced to 80W if heat is applied from an external heat source such as solar collector, geothermal heat etc. This can be done with all parts of the dishwasher running on DC with less than 50V. The experiment where a prototype stove-refrigerator and dishwasher shows that it is possible to build a kitchen that runs on less than 500W peak power.

## 6.1 Conclusion

From the data of maximum power it seems that the kitchen devices may be used as normal in CIT's system but with some modification, the Dishwasher would however be recommended to have a 1500W power limitation also, rather than 500W. If however no intrusion is to be made on how quickly kitchen devices are used at all times, some sort of energy backup is needed, certainly also if several devices must be allowed to operate at the same time.

Low voltage DC can certainly save money for their users, cables of optimized thickness will guarantee that the losses due to high currents are kept low in the kitchen.

Storing energy as heat is messy and difficult to do efficiently. If energy is to be stored in house hold devices, further research is first recommended. Most recommended is research on using super-capacitors in this purpose which has most the benefits of batteries but with less environmental impact.

## 6.2 Recommendations

Washingmachines and clothes-dryers work in a similar manner as a dishwasher, if a DC-house is built with water-heated radiators, it is recommended to investigate if dishwasher, washing-machine and clothes-dryer can use heat from this water as done in this report.

If a DC house is connected both to the AC-grid with a good rectifier and to solar cells, then the solar cells could in theory power the whole house during the hours of sunlight. One recommendation for further studies is how well theses hours of sunlight corresponds to the power consumption in Swedish households in the same manner as done here in Chapter 2.4. This could then give an estimation of how much extra power would be needed from the grid.

This could also estimate the power from the solar cells that are unused by the house and if this can generate income for the owner when supplied to the AC grid.

Storing energy in a block of ice rather than as hot paraffin can be an feasible way of utilizing the peltier effect to save energy. Melting ice have higher energy storage capacity per volume than any material that stores energy as heat. With a stove-top on a refrigerator, energy can be saved each time the stove is used by cooling the refrigerator whit a space for water/ice. This energy will then be stored as future cooling of the refrigerator. The power demand of the stove will not be lowered more than the peltier effect allows at high temperature difference but the stored energy will endure for long without more leakage than normally in a refrigerator, the difference to room temperature is smaller than in paraffin heated up temperatures for cooking.

An interesting research would be how small a solar panel or solar collector could be and still supply energy to store enough latent heat energy for a modern kitchen in developing countries. In this way more people could get access to kitchen devices outside the electric grid infrastructure without costly batteries and transformers.

# 7 Discussion

## 7.1 About the prototypes and household appliances in low voltage DC houses

The original dishwasher in this project heats its water at an average of 1 to 2 degrees every minute (see Figure 12). With the prototype dishwasher, water was on one hand found increase in temperature at a faster rate as long as the temperature difference between this and the exchange water is more than 20 degrees. However at lower temperature difference the rate of heating decreases. This made it only possible to reach temperatures 20 degrees lower than the exchange water temperature within the same time as the original dishwasher. Although with a larger heat exchanger the effect could be increased in the prototype.

The set-up of the prototype refrigerator and stove together with the dishwasher does not really use less energy, only less power. Energy saving could theoretically be made when utilizing the peltier effect to share energy between refrigerator and stove but if it is used as here, to store heat, there will always be leakage and therefore loss of energy, especially in this case of a mere prototype unit.

The production of kitchen devices for low voltage DC houses may still fall upon the hobbyist who wants to build an off grid vacation house or similar. But with a developed and commercial low voltage DC system, there should be a small extra part of the market where producers of kitchen devices can tap in by enabling their products to run on low voltage DC. Companies already producing DC devices for living in trailers and boats may have a special interest in this.

## 7.2 About project management

When conducting this project, a lot of time was spent preparing further experiments until oderered components had arrived or unexpected searching for non-expensive parts that could be ordered in single units for a prototype rather than large bulks for mass-production etc. Oral comunications with people that have conducted similar projects and experts in different feilds was of course very good when planning and mannaging the project but some documentation on the practical aspects in previous works could have been very useful.
The authors would therefore like to include a small table of lessons learned (Table 13) for others conducting mastes thesis prototype projects or similar.

Table 13: Lessons Learned document, a collectoin of observations made by the authors that may be of interest for those initiating a similar prototype project for the first time.

| | | | |
|---|---|---|---|
| Summary | Project Background | | Product development of a Dishwasher that runs on Low voltage DC includes energy storage. |
| | Key words for search | | Product development, prototype, DC home appliance. |
| Process Performance | Planning | Observations | Hard to estimate the exact dates |
| | | Possible Improvements | Calculate dates relatively. |
| | Prestudy | Observations | Large amount of data is available on electricity consumption but may be time consuming to sort and analyse |
| | | Possible Improvements | Prior knowledge in SQL databases |
| | Concept development | Observations | Uneven knowledge initially to compare concepts in matrices. |
| | | Possible Improvements | Start by elimination of concepts ,concept groups iteratively |
| | Component sourcing | Observations | Components from various suppliers or brand are not compatible |
| | | Possible Improvements | Preferable choose one supplier or brand. Plan tasks parallel to waiting for components to arrive. |
| | Prototype construction | Observations | Custom-built parts are probably unavoidable, construction of these are time consuming - outsourcing of manufacturing are to expencive for prototype projects and can not guarrantee desired quality compatible |
| | | Possible Improvements | Find access to varoius labs, tools and workshops at an early stage |
| Tools Performance | Observations | | CATIA is strong in solid modeling and suitable for extracting 2D sketches as well. |
| Schedule Performance | Observations | | Project always overshot estimates of time on postal reasons. |
| | Schedule Possible Improvements | | Have to be aware of stakeholders of the project being away from office when fixing schedules |
| Cost Performance | Observations | | Cost of deliveries are fixed. |
| | Cost Possible Improvements | | It saves money to order all the material at a time from one source. |

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