Energy for Preparation and Storing of Food
- Models for calculation of energy use for cooking and cold storage in households

*Ulf Sonesson, Hans Janestad, Birgitta Raaholt*
Energy for Preparation and Storing of Food
- Models for calculation of energy use for cooking and cold storage in households

*Ulf Sonesson, Hans Janestad, Birgitta Raaholt*
Preface

This is a report from the project “Environmental Systems Analysis of Consumer-related Activities in the Food Chain” which is part of the research program FOOD 21. FOOD 21 is a research programme involving about a hundred researchers who are working together to find ways of achieving an ecologically and economically sustainable system of food production. The programme was started in 1997 and will terminate in 2004. The Swedish University of Agricultural Sciences (SLU) is responsible for the programme, but research is also being done at the universities of Uppsala, Gothenburg, Lund and Umeå as well as at SIK – The Swedish Institute for Food and Biotechnology and JTI - The Swedish Institute of Agricultural and Environmental Engineering. FOOD 21 is funded by MISTRA, the Foundation for Strategic Environmental Research.

Ulf Sonesson has been project leader and is also the main author. In the chapter on Microwave cooking, Ulf Sonesson is responsible for the modelling and Birgitta Raaholt has been involved in the background description. Hans Janestad has been involved in the chapters on boiling and oven cooking, he is also responsible for Appendix 1, description of the detailed boiling model.

In this project several persons besides the authors have been involved: Magnus Stadig, Erica Wallén, Emma Holmberg, Johan Widheden and Lars-Göran Vinsmo. We would like to thank them for their valuable contributions to the report.
Summary

In the life cycle of food the preparation within households often accounts for an important part of the total energy use. The methods often employed when assessing this energy use is to use single measurements as data, very seldom generalised knowledge based on any property of the equipment used or food to be prepared is used. There are also several publications on energy in food preparation that focus on the quality aspect of the food product, with no assessment of the amount of energy needed in the whole system, including equipment as stoves and kettles. Another important part of the energy use for food is cold storage. As for cooking, the reported energy use for cold storage often is based on data on single refrigerators or freezers.

The aim with the report is to present general models to calculate the energy needed for food preparation and cold storage in households. The preparation methods included should cover the most common means of all cooking done in Swedish households. We have not included deep frying and use of special equipment as rice cookers. Neither is cooking on gas stoves included.

The models are intended for use in Life cycle assessment (LCA) or similar environmental analyses for food systems. The models developed should rely on easily accessible input data, i.e. no specific inventory shall be needed to use the models. The results from the models need not be extremely accurate but good enough for systems studies of large systems. The methods used for building the models are depending on the cooking situation modelled, in some cases a mechanistic approach is used and in other a more statistical one.

The food preparation methods modelled are:

- Boiling in water on hotplate
- Boiling of water in electric kettles
- Frying in frying pan
- Oven cooking
- Microwave cooking

Besides the ones mentioned above, some short analyses of pressure boiling is included.

For cold storage refrigerators and freezers are modelled, both upright freezers and chest freezers.
# Table of Contents

**Introduction** .............................................................................................................................. 5  
Aim and Objectives .......................................................................................................................... 5  

**Food Preparation** ..................................................................................................................... 6  
Food Preparation and Thermodynamics .......................................................................................... 6  

**Boiling in water on hotplates** .................................................................................................... 8  
Modelling of boiling ....................................................................................................................... 8  
Validity range for the boiling model .............................................................................................. 16  
Availability of input data ................................................................................................................ 17  
Discussion of the boiling model ..................................................................................................... 17  
Alternative Methods for Boiling .................................................................................................... 17  

**Heating of water in electric kettles** .......................................................................................... 20  
Modelling of heating water in electric kettles ............................................................................... 20  
Discussion of the model of heating of water in electric kettles ...................................................... 21  

**Frying in frying pan** .................................................................................................................. 22  
Modelling of frying in pan .............................................................................................................. 22  
Validity range for the frying model ............................................................................................... 28  
Availability of input data .............................................................................................................. 28  
Discussion of the frying model ..................................................................................................... 28  

**Roasting and baking in electric oven** ...................................................................................... 30  
Modelling of roasting in electrical oven ....................................................................................... 30  
Validation Experiments ................................................................................................................ 33  
Validity range for the oven model ................................................................................................. 34  
Availability of input data .............................................................................................................. 34  
Discussion of the oven model ....................................................................................................... 34  

**Microwave cooking** ................................................................................................................ 36  
The microwave oven ...................................................................................................................... 36  
Power level in microwave ovens ................................................................................................... 37  
Factors which influence the power absorbed by a food load during microwave heating .......... 38  
Modelling of energy use for microwave heating ......................................................................... 41  
Validation of the model ................................................................................................................ 43  
Availability of input data .............................................................................................................. 46  
Validity range of the microwave cooking model ......................................................................... 46  
Discussion of the microwave cooking model ............................................................................. 46  

**Cold Storage of Food** ............................................................................................................. 47  
Background .................................................................................................................................... 47  
Modelling of storing in freezers and refrigerators ....................................................................... 47  
Validity range for the models ....................................................................................................... 52  
Availability of input data .............................................................................................................. 52  
Discussion of the cold storage models ......................................................................................... 52  

**General input data to all models** .............................................................................................. 54  

**Discussion and Conclusions** .................................................................................................. 55  

**List of all Models Presented in this Report** .......................................................................... 56  

**References** ................................................................................................................................ 59  

**Appendix 1. Detailed model of boiling in water** ...................................................................... 1
**Introduction**

Today there is a strong trend throughout the western world that the consumption of ready-to-eat meals increases whilst home cooking suffers a corresponding decrease. This industrially prepared food increases the use of energy, waste generation and transports within the food industry and retail, at the same time as the effort within households decreases (perhaps the home transport is an exception). In order to assess this presently strong trend the total environmental impact for the food chain has to be quantified; both the increase within industry and retail and the decrease in households. The former must be specifically inventoried for each industry since the processes are often site specific. For the latter, households, the situation is the other way around. The same unit process is performed in more or less all households when preparing the same food. This, and the fact that the numbers of households are very large, makes it impossible to make site-specific inventories, hence a general approach using simple models is appropriate.

There have been a large number of studies focusing on energy and environmental issues related to food performed in Sweden. They all conclude that food preparation accounts for a significant part of the life cycle energy use for food. Uhlin (1997) states that approximately 20% of the total energy consumption in the food chain, from farm to table, takes place during food preparation. Johannisson & Olsson (1997) studied the energy consumption from farm to table for boiled potatoes, French fries, chicken and meatballs. They found that between 50% (boiled potatoes) and 5% (chilled ready-fried meatballs) of the total energy consumption took place during preparation in the household. Of the life cycle energy for a pork chop, frying accounts for 15% according to Johannisson & Olsson (1998). In a study of a lunch restaurant in Stockholm it was shown that the direct energy consumption was 0.4 kWh electricity/served meal and 0.5 kWh heat/served meal (Oscarsson et al., 1996). Assuming that each person in Sweden eats 1.5 cooked meals per day would make 4.4 TWh/year, of which 1.3 TWh electricity. Another study presents the average consumption of electricity for cooking in 51 households; it was 172 kWh/person & year, which corresponds to 1.5 TWh/year for Sweden (NUTEK, 1994). Shanahan et al. (1995) presents data for five households in Göteborg. The mean electricity consumption was 208 kWh/person & year, corresponding to 1.9 TWh/year for Sweden’s 9 000 000 inhabitants. The total electricity consumption in Sweden was approximately 130 TWh for the year 2001 (Energimyndigheten, 2002).

One common thing in the literature on energy and food preparation is that there are several measurements on energy use, but rarely any attempts to generalise the data based on any property of the equipment or food to be prepared.

**Aim and Objectives**

The aim of this report is to present general models for quantifying the energy consumption for food preparation in private households. The models should be robust and easy to use, i.e. easily accessible information is used as input data and the resulting energy consumption is reasonably accurate. The models shall be structured in a way that they easily can be used in environmental systems analyses, as Life Cycle Assessments (LCA) or material flow studies (MFA), of food products as well as energy system studies. The accuracy of the models should be good enough to be used in such systems studies, for more detailed studies, specific measurements should be used.
The focus is on the most common methods for home cooking (frying, boiling, oven roasting and microwave cooking), but a brief outlook into future technologies for boiling will be done. Similar models for cold storage of food in household will also be presented, since for some foods cold storage cause significant electricity use.

**Food Preparation**

Food preparation aims at changing the quality of the raw materials, and results in both positive and negative effects. The following is largely based on a report by Bengtsson (1991). The positive and wanted effects are:

- Increased taste and availability, resulting from denaturation of protein and hydrolysis of connective tissues and formation of aroma compounds.
- Softening of tissues, swelling of starch (vegetables)
- Inactivation of bacteria and enzymes.

There are also changes that can be considered both positive and negative:

- Browning of the product, which creates taste in meat and bread, hamper oxidation of fat, but also are mutagen and / or carcinogen.

Finally there are changes that are unambiguously negative:

- Degradation of texture and loss of vitamins.
- Juice losses and shrinking (meat)
- Forming of volatile acids
- Changes in oxidation
- Forming of acrylamide

Even if there are negative effects, food preparation is indispensable since it allows humans to use foodstuffs otherwise inedible and moreover makes eating a pleasure.

**Food Preparation and Thermodynamics**

Almost all cooking principally works in the same way; energy is supplied which raises the temperature and the product is changed in the desired way.

This energy can be supplied in several ways, mainly by:

- Conduction, as frying in a frying pan
- Convection, as boiling or deep frying
- Heat radiation, as grilling
- Infrared radiation
- Microwaves, as in a microwave oven.

In all the above cases except microwaves, the energy is supplied at the surface of the food and are subsequently transferred inwards until the temperature in the centre is sufficient for the desired changes to occur.
As practically all foods have low heat transfer, the time it takes for the energy to be transferred between surface and centre is dimensioning the cooking time. This low heat transfer sometimes also results in large differences in temperature between surface and centre. This is most obvious when preparing large pieces in a conventional oven, where the surface temperature can reach several hundred degrees while at the same time the centre temperature is around 70°C.

At the same time as heat is transferred from the surface to the centre, a transport of water from centre to surface takes place. At the surface the water is either evaporated (frying and oven cooking) or mixed with water or oil (boiling and deep frying). The fact that water is evaporated when frying is the base for the surface browning, which occurs when the temperature exceeds 100°C and the chemical reactions responsible for browning (Maillard reactions) are activated.

In all cooking the supply of energy is larger than the theoretically necessary for raising the products temperature to the required level. This is a result of thermodynamical losses (the stove has to be heated, water is evaporated etc.), insufficient technology, habits, taste preferences and lack of knowledge about the thermodynamics of food preparation.
Boiling in water on hotplates

Boiling is a very common method for food preparation. Traditionally boiling has been used for all kinds of foods, meat, fish, and vegetables. The present trend in Sweden is that boiling is decreasing, especially of meats but also vegetables and fish is increasingly prepared by other means. The advantages with boiling are that the temperature never exceeds approximately 100°C, which inhibits the forming of carcinogenic substances as when frying and that the temperature difference between surface and centre can be kept down making the “overcooking” of the surface less of a problem. The disadvantages are mainly that the positive taste changes are not as obvious as when frying, and it takes longer time to reach the required centre temperature since the surface temperature is relatively low.

The model presented should cover boiling of food in water in a saucepan, in batch sizes normal in households, which we have chosen to set at maximum four litres of boiling water.

Boiling can be described rather well thermodynamically, and besides the easy-to-use boiling model we have constructed a model that builds on energy balances and heat transfer between product, water, hotplate, saucepan and the ambient air. This detailed model also provides possibilities to calculate other parameters besides energy consumption, as surface- and centre temperatures and required boiling time. The use of that model requires rather specific input data, thus it does not fulfil the objectives with the modelling in this report, namely that the models should be usable without detailed knowledge about the products and cooking situation. However, the detailed model is presented in Appendix 1 since it might be useful for certain purposes.

Modelling of boiling

There are several different situations that are relevant to cover in a boiling model, both technological differences as different types of hotplates and saucepans and also different amounts of food and water and the proportions between them.

Model structure description

Principally, the energy use for boiling on hotplate consists of five parts:

- Heating the equipment, hot plate, saucepan and to some extent the stove.
- Heating the water to the boiling point
- Heating the product to the intended temperature, i.e. fulfilling the purpose with the boiling operation
- Evaporation of water
- Warming up the air surrounding the system (heat losses)

The model however, builds on how boiling is mainly done practically; first the saucepan is heated with maximum effect until the boiling point, thereafter the power to the hot plate is lowered and kept at a level that maintains the boiling temperature.

This results in the following model structure:

\[ E_{\text{tot}} = E_{\text{HU}} + E_{\text{MT}} + E_{\text{HP}} \]
Where:

\( \text{EHU} = \text{Energy for heating the water to the boiling point. This includes heating the hot plate and saucepan, the water and also some evaporation, since water starts to evaporate before the water reaches the boiling point.} \)

\( \text{EMT} = \text{Energy for maintaining the temperature of the water at the boiling point. This equals the losses due to evaporation and heating the surrounding environment.} \)

\( \text{EHP} = \text{Energy for heating the product. This equals the minimum amount of energy needed to cook the food, i.e. it is a function of the heat capacity, mass and the intended temperature elevation of the food.} \)

Since mainly the \( \text{EMT} \) but to some extent also \( \text{EHU} \) is affected by the evaporation of water, we present two sets of parameters, for boiling with and without lid. Moreover, our experiences was that boiling on ceramic hot plates instead of cast iron hot plates causes different proportions between energy for heating up and maintaining, hence we also present two sets of parameters, for cast iron and ceramic hotplates.

The input data needed for the model is:

- \( m_p = \text{Amount of product to cook (g)} \)
- \( m_w = \text{Amount of water used in the boiling (g)} \)
- \( t = \text{Boiling time (minutes)} \)
- \( \Delta T = \text{Mean temperature elevation in the product (°C)} \)

The parameters needed, and which we present below are:

- \( e_{hu} = \text{Energy for heating one gram of water to boiling point, including heating the hot plate and saucepan. (MJ/g)} \)
- \( e_{mnt} = \text{Energy for maintaining the boiling temperature of one gram of water for one minute } [\text{MJ/(g*min)}] \)
- \( e_{hp} = \text{heat capacity of the food product (in literature often denoted } c_p [\text{MJ/(kg*°C)}]. \)

The energy consumption can be calculated as:

\[
E_{\text{tot}} = e_{hu} * m_w + e_{mnt} * m_w * t + e_{hp} * m_p * \Delta T
\]

The parameters \( e_{hu} \) and \( e_{mnt} \) is presented in Table 4, \( e_{hp} \) can be found in literature, but we present literature data for common foods in Table 27, under the heading “General indata for the boiling model ”. The temperature elevation is principally the difference between the initial temperature and the final mean temperature of the product. The final mean temperature is below, but close to, 100 °C, due to the geometry of products boiled (the largest part of a sphere’s mass is close to the surface, and to reach the correct temperature in the centre, typically 90°C, for a sphere with radius 3 cm, the mean temperature will be close to 98 °C).

Boiling time can be obtained from cookery books or other handbooks in cooking, and in some cases the amount of water used (for Swedish readers, “Mått för mat” can be recommended, ICA, 2000). The amount of water needed can easily be measured by testing how much water that is needed for a certain boiling situation.

**Experiments**

In order to attain figures for the parameters \( e_{hu} \) and \( e_{mnt} \) for the two types of hot plates we have boiled water on two different stoves, one with cast iron hotplates (AEG Competence) and one with ceramic hot plates (Electrolux CF 6075) and measured energy use for heating up and
maintaining the temperature. Volumes between 150 g and 4000 g of water were boiled since this would cover ordinary boiling in private households. The experiments were performed both with and without lid on the saucepan. Three different saucepans were used, they all were made of steel and were chosen to fit the size of the hotplate and the volume of water boiled and they all were in good condition. The intention was to mirror ordinary kitchen practices. The mass of the saucepans used for different water volumes are shown in Table 1. The results from the experiments on the cast iron hotplates are presented in Table 2 and the corresponding results from the ceramic hotplates are shown in Table 3.

Table 1, Saucepans used in the experiments

<table>
<thead>
<tr>
<th>Mass of saucepan (g)</th>
<th>Used for experiments (water mass, g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>560</td>
<td>150, 300, 500, 650, 700, 800, 900, 1000</td>
</tr>
<tr>
<td>596</td>
<td>1320, 1500, 2000</td>
</tr>
<tr>
<td>1480</td>
<td>4000</td>
</tr>
</tbody>
</table>

Table 2. Results from experiments with boiling of water on cast iron hotplates

<table>
<thead>
<tr>
<th>Amount of water (g)</th>
<th>Boiling time (min)</th>
<th>Lid (Y/N)</th>
<th>$E_{HU}$ (MJ)</th>
<th>$E_{MT}$ (MJ)</th>
<th>$E_{TOT}$ (MJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>5</td>
<td>N</td>
<td>0.27</td>
<td>0.09</td>
<td>0.36</td>
</tr>
<tr>
<td>300</td>
<td>5</td>
<td>N</td>
<td>0.48</td>
<td>0.21</td>
<td>0.69</td>
</tr>
<tr>
<td>500</td>
<td>10</td>
<td>N</td>
<td>0.48</td>
<td>0.21</td>
<td>0.69</td>
</tr>
<tr>
<td>700</td>
<td>10</td>
<td>N</td>
<td>0.54</td>
<td>0.24</td>
<td>0.78</td>
</tr>
<tr>
<td>900</td>
<td>10</td>
<td>N</td>
<td>0.63</td>
<td>0.30</td>
<td>0.93</td>
</tr>
<tr>
<td>1500</td>
<td>10</td>
<td>N</td>
<td>0.90</td>
<td>0.34</td>
<td>1.24</td>
</tr>
<tr>
<td>2000</td>
<td>10</td>
<td>N</td>
<td>1.18</td>
<td>0.40</td>
<td>1.58</td>
</tr>
<tr>
<td>4000</td>
<td>10</td>
<td>N</td>
<td>2.41</td>
<td>0.78</td>
<td>3.19</td>
</tr>
<tr>
<td>150</td>
<td>5</td>
<td>Y</td>
<td>0.26</td>
<td>0.02</td>
<td>0.28</td>
</tr>
<tr>
<td>300</td>
<td>5</td>
<td>Y</td>
<td>0.32</td>
<td>0.02</td>
<td>0.34</td>
</tr>
<tr>
<td>500</td>
<td>10</td>
<td>Y</td>
<td>0.48</td>
<td>0.05</td>
<td>0.53</td>
</tr>
<tr>
<td>900</td>
<td>10</td>
<td>Y</td>
<td>0.50</td>
<td>0.09</td>
<td>0.59</td>
</tr>
<tr>
<td>1320</td>
<td>28</td>
<td>Y</td>
<td>0.56</td>
<td>0.24</td>
<td>0.80</td>
</tr>
<tr>
<td>1320</td>
<td>28</td>
<td>Y</td>
<td>0.52</td>
<td>0.30</td>
<td>0.82</td>
</tr>
<tr>
<td>2000</td>
<td>10</td>
<td>Y</td>
<td>1.00</td>
<td>0.14</td>
<td>1.14</td>
</tr>
<tr>
<td>4000</td>
<td>10</td>
<td>Y</td>
<td>2.23</td>
<td>0.17</td>
<td>2.40</td>
</tr>
</tbody>
</table>
Table 3. Results from experiments with boiling of water on ceramic hot plates

<table>
<thead>
<tr>
<th>Amount of water (g)</th>
<th>Boiling time (min)</th>
<th>Lid (Y/N)</th>
<th>$E_{HU}$ (MJ)</th>
<th>$E_{MT}$ (MJ)</th>
<th>$E_{TOT}$ (MJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>5</td>
<td>N</td>
<td>0.27</td>
<td>0.09</td>
<td>0.36</td>
</tr>
<tr>
<td>300</td>
<td>5</td>
<td>N</td>
<td>0.25</td>
<td>0.11</td>
<td>0.36</td>
</tr>
<tr>
<td>500</td>
<td>10</td>
<td>N</td>
<td>0.39</td>
<td>0.19</td>
<td>0.58</td>
</tr>
<tr>
<td>650</td>
<td>5</td>
<td>N</td>
<td>0.48</td>
<td>0.11</td>
<td>0.59</td>
</tr>
<tr>
<td>800</td>
<td>10</td>
<td>N</td>
<td>0.59</td>
<td>0.22</td>
<td>0.81</td>
</tr>
<tr>
<td>1000</td>
<td>10</td>
<td>N</td>
<td>0.66</td>
<td>0.24</td>
<td>0.90</td>
</tr>
<tr>
<td>2000</td>
<td>10</td>
<td>N</td>
<td>1.18</td>
<td>0.41</td>
<td>1.58</td>
</tr>
<tr>
<td>4000</td>
<td>10</td>
<td>N</td>
<td>2.41</td>
<td>0.78</td>
<td>3.19</td>
</tr>
<tr>
<td>150</td>
<td>5</td>
<td>Y</td>
<td>0.26</td>
<td>0.02</td>
<td>0.28</td>
</tr>
<tr>
<td>300</td>
<td>5</td>
<td>Y</td>
<td>0.26</td>
<td>0.04</td>
<td>0.30</td>
</tr>
<tr>
<td>500</td>
<td>10</td>
<td>Y</td>
<td>0.38</td>
<td>0.07</td>
<td>0.45</td>
</tr>
<tr>
<td>650</td>
<td>5</td>
<td>Y</td>
<td>0.47</td>
<td>0.03</td>
<td>0.50</td>
</tr>
<tr>
<td>800</td>
<td>10</td>
<td>Y</td>
<td>0.51</td>
<td>0.06</td>
<td>0.57</td>
</tr>
<tr>
<td>1000</td>
<td>10</td>
<td>Y</td>
<td>0.64</td>
<td>0.07</td>
<td>0.71</td>
</tr>
<tr>
<td>2000</td>
<td>10</td>
<td>Y</td>
<td>1.05</td>
<td>0.09</td>
<td>1.14</td>
</tr>
<tr>
<td>4000</td>
<td>10</td>
<td>Y</td>
<td>2.23</td>
<td>0.17</td>
<td>2.40</td>
</tr>
</tbody>
</table>

Model parameters

The parameters $e_{hu}$ and $e_{mt}$ on cast iron hotplates were plotted against the mass of water boiled (Figure 1, and Figure 2). From Figure 1 it was evident that $e_{hu}$ was a function of the amount of water boiled. We decided to split the curve in two parts, one ranging from 300 to 900 g and one between 900 and 4000 g. The parameter $e_{hu}$ for the first curve was assumed to be a linear function of the first degree of the amount of water heated, the function was fitted. The parameter $e_{hu}$ for the latter curve was assumed to be constant, and the average value was chosen as $e_{hu}$. The resulting figures and functions for $e_{hu}$ and $e_{mt}$ to be used in the model is presented in Table 4. The reason for not including the leftmost part of the curve was that the dependence of type of saucepan and of the method for control of the hotplate increases when the proportion between water and goods decreases. Moreover, most boiling situations in a household should be covered with a model ranging from 300-4000 g of water.
Figure 1. The parameter $e_{hu}$ as a function of mass of water heated, cast iron hotplates.

From Figure 2 it could be seen that also $e_{mt}$ was a function of the amount of water boiled. As for $e_{hu}$, the curve was split in two, one between 300 and 900 g, and the second between 900 and 4000 g. The rationale for excluding the 150 g experiment is the same as described above for $e_{hu}$ for cast iron hotplates.

Also as for $e_{hu}$, $e_{mt}$ for the first curve was fitted with a first order linear function of amount of water and the second part $e_{mt}$ was assumed to be constant.

Figure 2. The parameter $e_{mt}$ as a function of mass of water heated, cast iron hotplates.
The corresponding plots for ceramic hotplates are presented in Figure 3 and Figure 4. The same procedure for dividing the curve in two parts, one constant and one proportional as for cast iron hotplates was performed. The resulting values and functions for $e_{hu}$ and $e_{mt}$ are presented in Table 4.

**Figure 3.** The parameter $e_{hu}$ as a function of mass of water heated, ceramic hotplates

**Figure 4.** The parameter $e_{mt}$ as a function of mass of water heated, ceramic hotplates
Table 4. $e_{hu}$ and $e_{mt}$ used for different boiling situations in the model ($m_w$ is amount of water boiled)

<table>
<thead>
<tr>
<th>Hot plate</th>
<th>Situation</th>
<th>Range (g water)</th>
<th>$e_{hu}$ (MJ/g water)</th>
<th>$e_{mt}$ (MJ/(g water * minutes))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cast iron</td>
<td>Lid</td>
<td>300-900</td>
<td>$1.35<em>10^{-3} - (8.73</em>10^{-7} * m_w)$</td>
<td>$1.42<em>10^{-5} - (5.05</em>10^{-9} m_w)$</td>
</tr>
<tr>
<td>Cast iron</td>
<td>Lid</td>
<td>901-4000</td>
<td>$4.7*10^{-4}$</td>
<td>$6.5*10^{-6}$</td>
</tr>
<tr>
<td>Cast iron</td>
<td>No lid</td>
<td>300-900</td>
<td>$1.37<em>10^{-3} - (7.94</em>10^{-7} * m_w)$</td>
<td>$7.66<em>10^{-5} - (5.42</em>10^{-9} m_w)$</td>
</tr>
<tr>
<td>Cast iron</td>
<td>No lid</td>
<td>901-4000</td>
<td>$5.8*10^{-4}$</td>
<td>$2.1*10^{-5}$</td>
</tr>
<tr>
<td>Ceramic</td>
<td>Lid</td>
<td>300-900</td>
<td>$1.01<em>10^{-3} - (4.66</em>10^{-7} * m_w)$</td>
<td>$3.25<em>10^{-5} - (3.35</em>10^{-9} m_w)$</td>
</tr>
<tr>
<td>Ceramic</td>
<td>Lid</td>
<td>901-4000</td>
<td>$5.8*10^{-4}$</td>
<td>$5.2*10^{-6}$</td>
</tr>
<tr>
<td>Ceramic</td>
<td>No lid</td>
<td>300-900</td>
<td>$8.95<em>10^{-4} - (2.15</em>10^{-7} * m_w)$</td>
<td>$9.13<em>10^{-5} - (8.61</em>10^{-9} m_w)$</td>
</tr>
<tr>
<td>Ceramic</td>
<td>No lid</td>
<td>901-4000</td>
<td>$6.2*10^{-4}$</td>
<td>$2.1*10^{-5}$</td>
</tr>
</tbody>
</table>

Validation

For validation some experiments performed at SIK were used together with literature data on energy consumption for boiling. In Table 5 the results from the validation of the cast iron model are presented, and in Table 6 the corresponding results for ceramic hotplates are presented.
Table 5. Results from the validation of the boiling model for cast iron hotplates

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Source</th>
<th>Measured energy use (MJ)</th>
<th>Model result (MJ)</th>
<th>Ratio, model/measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 g potatoes, 500 g water, 21 minutes, lid</td>
<td>1</td>
<td>0.65</td>
<td>0.73</td>
<td>1.12</td>
</tr>
<tr>
<td>500 g potatoes, 500 g water, 20 minutes, lid</td>
<td>1</td>
<td>0.66</td>
<td>0.72</td>
<td>1.10</td>
</tr>
<tr>
<td>200 g rice, 500 g water, 20 minutes, lid</td>
<td>1</td>
<td>0.60</td>
<td>0.60</td>
<td>1.00</td>
</tr>
<tr>
<td>200 g rice, 500 g water, 20 minutes, lid</td>
<td>1</td>
<td>0.60</td>
<td>0.60</td>
<td>1.00</td>
</tr>
<tr>
<td>100 g pasta, 1000 g water, 10 minutes, no lid</td>
<td>1</td>
<td>1.12</td>
<td>0.80</td>
<td>0.71</td>
</tr>
<tr>
<td>100 g pasta, 1000 g water, 10 minutes, no lid</td>
<td>1</td>
<td>1.16</td>
<td>0.80</td>
<td>0.69</td>
</tr>
<tr>
<td>2000 g potatoes, 900 g water, 32 minutes, lid</td>
<td>2</td>
<td>0.89</td>
<td>1.19</td>
<td>1.34</td>
</tr>
<tr>
<td>630 g potatoes, 630 g water, 20.5 minutes, lid</td>
<td>2</td>
<td>0.76</td>
<td>0.83</td>
<td>1.09</td>
</tr>
<tr>
<td>630 g potatoes, 630 g water, 24 minutes, lid</td>
<td>2</td>
<td>0.76</td>
<td>0.84</td>
<td>1.11</td>
</tr>
<tr>
<td>1260 g potatoes, 1300 g water, 14 minutes, lid</td>
<td>2</td>
<td>1.12</td>
<td>1.10</td>
<td>0.98</td>
</tr>
<tr>
<td>1260 g potatoes, 1300 g water, 12 minutes, lid</td>
<td>2</td>
<td>1.12</td>
<td>1.08</td>
<td>0.96</td>
</tr>
<tr>
<td>280 g pasta, 2500 g water, 10 minutes, no lid</td>
<td>3</td>
<td>2.16</td>
<td>2.01</td>
<td>0.93</td>
</tr>
<tr>
<td>70 g pasta, 1000 g water, 10 minutes, no lid</td>
<td>3</td>
<td>0.85</td>
<td>0.80</td>
<td>0.94</td>
</tr>
<tr>
<td>130 g pasta, 1000 g water, 3 minutes, no lid</td>
<td>3</td>
<td>0.68</td>
<td>0.67</td>
<td>0.99</td>
</tr>
<tr>
<td>520 g pasta, 2500 g water, 3 minutes, no lid</td>
<td>3</td>
<td>1.64</td>
<td>1.70</td>
<td>1.04</td>
</tr>
<tr>
<td>240 g rice, 600 g water, 15 minutes, lid</td>
<td>3</td>
<td>0.48</td>
<td>0.63</td>
<td>1.31</td>
</tr>
<tr>
<td>60 g rice, 150 g water, 15 minutes, lid</td>
<td>3</td>
<td>0.34</td>
<td>0.22</td>
<td>0.65</td>
</tr>
<tr>
<td>180 g wheat, 350 g water, 12 minutes, lid</td>
<td>3</td>
<td>0.44</td>
<td>0.44</td>
<td>1.00</td>
</tr>
<tr>
<td>190 g potatoes, 600 g water, 24 minutes, lid</td>
<td>3</td>
<td>0.7</td>
<td>0.71</td>
<td>1.01</td>
</tr>
<tr>
<td>800 g potatoes, 1000 g water, 24 minutes, lid</td>
<td>3</td>
<td>1.2</td>
<td>0.86</td>
<td>0.72</td>
</tr>
<tr>
<td>40 g barley, 175 g water, 27 minutes, lid</td>
<td>3</td>
<td>0.47</td>
<td>0.28</td>
<td>0.60</td>
</tr>
<tr>
<td>160 g barley, 700 g water, 27 minutes, lid</td>
<td>3</td>
<td>0.72</td>
<td>0.74</td>
<td>1.03</td>
</tr>
<tr>
<td>300 g water, 0 minutes (just heating up), lid</td>
<td>3</td>
<td>0.25</td>
<td>0.33</td>
<td>1.32</td>
</tr>
</tbody>
</table>

1 = Swedish Consumer Agency, 1996b
2 = Experiments at SIK
3 = Carlsson-Kanyama & Broström-Carlsson, 2001
Table 6. Results from the validation of the boiling model for ceramic hotplates

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Source</th>
<th>Measured energy use (MJ)</th>
<th>Model result (MJ)</th>
<th>Ratio, model/measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 g potatoes, 500 g water, 22 minutes, lid</td>
<td>1</td>
<td>0.54</td>
<td>0.71</td>
<td>1.31</td>
</tr>
<tr>
<td>500 g potatoes, 500 g water, 22 minutes, lid</td>
<td>1</td>
<td>0.43</td>
<td>0.71</td>
<td>1.66</td>
</tr>
<tr>
<td>200 g rice, 500 g water, 20 minutes, lid</td>
<td>1</td>
<td>0.46</td>
<td>0.57</td>
<td>1.25</td>
</tr>
<tr>
<td>200 g rice, 500 g water, 20 minutes, lid</td>
<td>1</td>
<td>0.43</td>
<td>0.57</td>
<td>1.33</td>
</tr>
<tr>
<td>100 g pasta, 1000 g water, 10 minutes, no lid</td>
<td>1</td>
<td>0.88</td>
<td>0.84</td>
<td>0.96</td>
</tr>
<tr>
<td>100 g pasta, 1000 g water, 10 minutes, no lid</td>
<td>1</td>
<td>0.91</td>
<td>0.84</td>
<td>0.93</td>
</tr>
<tr>
<td>630 g potatoes, 600 g water, 25 minutes, lid</td>
<td>2</td>
<td>0.77</td>
<td>0.81</td>
<td>1.05</td>
</tr>
<tr>
<td>1250 g potatoes, 1300 g water, 29 minutes, lid</td>
<td>2</td>
<td>1.31</td>
<td>1.27</td>
<td>0.97</td>
</tr>
<tr>
<td>245 g pasta, 2500 g water, 8 minutes, no lid</td>
<td>2</td>
<td>2.18</td>
<td>2.00</td>
<td>0.92</td>
</tr>
<tr>
<td>120 g pasta, 1500 g water, 8 minutes, no lid</td>
<td>2</td>
<td>1.17</td>
<td>1.20</td>
<td>1.03</td>
</tr>
</tbody>
</table>

1 = Swedish Consumer Agency, 1996b
2 = Experiments at SIK

In Table 5 and Table 6 it shows that for most of the experiments the model predicts the energy use within 10% of the measured result. However, some experiments deviate significantly more, up to 66% higher prediction than measured results. The pattern is that the model overestimates the energy use for boiling relatively small amounts on ceramic hotplate, one explanation can be that we have used heavier saucepans than in the reference used.

For cast iron hotplates the results are more even, probably since the saucepans is a smaller part of the mass needed to be heated (hotplate + saucepan + water), which decreases the impact of saucepan mass.

Validity range for the boiling model

The model will give reasonably good results if it used in the following boiling situations:

- Boiling in water
- The amount of water is between 300 and 4000 g
- The amount of product is between 0 and 2000 g

These ranges are partly determined by how the experiments were performed, and partly as a result of the variation of energy demand for boiling very small amounts of water. In such cases the dependency of how the boiling is controlled and the weight of the saucepan is large, which makes the model less useful. If such boiling situations are interesting for a study, single experiments with setups close to the situation studied could be used. For situations with larger amounts, the model could probably be used with good results, according to how the figures (Figure 1 to Figure 4) looks and also to the logical reason that the larger the amount of water the less impact of saucepan and hotplate.
Availability of input data

The following input data is needed to use the boiling model:

- Weight of the product. This should be very easy to obtain.
- Amount of water needed, which is depending on amount of the product and to some extend boiling instructions (e.g. if the water should cover the food). Can be obtained from cookery books.
- Boiling time. This can be obtained from cookery books etc.
- Energy needed to heat the product boiled. This data can be either calculated using the formula or the specific data presented in Table 27 under the heading “General input data to all models”

Discussion of the boiling model

The energy needed for heating the equipment, hotplate and saucepan is depending partly on the weight and material and partly on the heat transfer between hotplate and saucepan. Since the model presented is based on experiments with just a few saucepans and two stoves, this could pose a problem. According to tests performed at the Swedish Consumer Agency the variation in energy needed for heating one litre of water from 15 to 90 ºC with different saucepans was 0.16 – 0.20 kWh for small saucepans (Ø 145 mm) and 0.26 – 0.33 kWh for large saucepans (Ø 180 mm) on cast iron hotplates. For ceramic hotplates the corresponding figures were 0.14 – 0.16 kWh 0.26 – 0.28 kWh respectively (Råd & Rön, 1995). These figures indicate that there is a variation between saucepans but in our context it is relatively small. This is true as long as they are in good shape and the plate is even and clean. The difference for the maintaining phase should be lower, since once the saucepan is heated the energy needed (for evaporation and compensate for losses) is not dependent on the weight of the saucepan.

The difference in energy use from different stoves and hotplates is larger when boiling small amounts of water and for shorter boiling times, as a result of that in those situations the part of energy used that is needed for heating the hotplate and saucepan is larger compared to heating water and maintaining the temperature. Conclusively, the model generates more accurate results when boiling large volumes and for longer boiling times but even for the opposite situation the model’s results are reasonably accurate.

The matter of hotplates and saucepans being uneven is more difficult. If the contact between hotplate and saucepan is uneven relatively much heat is lost to the air. We have considered it infeasible to model this; it would require very detailed information on the equipment and the purpose of the models are not to cover all boiling situations in deep detail. The best way to handle the occurrence of uneven contact surfaces is to perform sensitivity analyses when using the model. In a report by Carlsson-Kanyama & Boström-Carlsson (2001) it is stated that the energy use can be 30% higher if uneven or dirty hotplates or saucepans are used. This figure can be used as a worst case for a sensitivity analysis.

Alternative Methods for Boiling

The boiling described above is dealing with the conventional method. There are however other technologies available for boiling that are more energy efficient. We have tested pressure cooker and boiling of food in an electric saucepan. The latter is not a method in use; it is an example on a principal method that could be implemented if new appliances were developed.
The experiments below are intended as an example to see if any improvement in energy efficiency can be achieved by using alternative technologies that are relatively simple, and not as a detailed description of new technology.

**Pressure boiling**
In the 1950’s, pressure cooking was still used in Swedish households, mainly for food preservation in jars; this was before freezers became common in households. Also dishes with long boiling times were prepared in pressure cookers. The advantage with pressure cooking is that the higher pressure gives higher temperature, hence the boiling time is shorter; the temperature gradient from surface to interior is higher which gives faster heat transfer within the product. The equipment is fairly simple; a pot with a lid that is tightly closed and a pressure valve working with a small weight on top of a small opening, the weight is lifted at a certain pressure inside the cooker. The cooker is placed on a hotplate. In the experiments pressure cookers of two sizes were tested, and potatoes were boiled. Lately pressure cookers have reappeared on the market.

*Table 7. Experiments with boiling of potatoes in pressure cooker*

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Mass of potatoes (g)</th>
<th>Mass of water (g)</th>
<th>Boiling time (minutes)</th>
<th>Total energy use (kJ)</th>
<th>Relative energy use (kJ/g food)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small cooker 1</td>
<td>563</td>
<td>200</td>
<td>15</td>
<td>1028</td>
<td>1.83</td>
</tr>
<tr>
<td>Small cooker 2</td>
<td>527</td>
<td>200</td>
<td>14</td>
<td>1248</td>
<td>2.37</td>
</tr>
<tr>
<td>Large cooker 1</td>
<td>1120</td>
<td>250</td>
<td>15</td>
<td>1142</td>
<td>1.02</td>
</tr>
<tr>
<td>Large cooker 2</td>
<td>830</td>
<td>200</td>
<td>16</td>
<td>1044</td>
<td>1.26</td>
</tr>
</tbody>
</table>

The results in Table 7 can be compared to the energy need for boiling potatoes with conventional methods (Table 5). If those measurements are calculated as kJ/g potatoes the results for boiling 500-630 g potatoes ranges between 1.21 and 1.32 kJ/g. For 800 to 2000 g potatoes the corresponding figures are: 0.44 to 1.5 kJ/g. Conclusively, pressure cooking does not seem to be a very efficient way to decrease the energy use, at least not for boiling potatoes. However, the relatively high energy use indicates that the power supply during boiling was too high. When performing the experiments it was difficult to control the boiling, which probably lead to too high power input.

**Boiling in electric kettle**

Since a certain amount of the energy needed for boiling is used for heating the hotplate and kettle before the water is heated, tests were performed with direct heating of the water. This was facilitated by putting a metal mesh above the heating element in an electric kettle (for description of electric kettles, see below under the heading “Heating of water in electric kettles”). In this way food could be placed in the kettle without being in contact with the heating element. The power supply was controlled by an on-off switch that turned the power off when the water temperature exceeded 101 °C and turned the power on at 98 °C. This equipment was the one used for boiling potatoes and pasta, and the results are presented in Table 8.
Table 8. Experiments with boiling of potatoes and pasta in an electric kettle.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Mass of food (g)</th>
<th>Mass of water (g)</th>
<th>Boiling time (minutes)</th>
<th>Total energy use (kJ)</th>
<th>Relative energy use (kJ/g food) a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potatoes 1</td>
<td>550</td>
<td>1500</td>
<td>30</td>
<td>1152</td>
<td>2.09</td>
</tr>
<tr>
<td>Potatoes 2</td>
<td>573</td>
<td>1400</td>
<td>29</td>
<td>1008</td>
<td>1.76</td>
</tr>
<tr>
<td>Pasta 1</td>
<td>395</td>
<td>1800</td>
<td>14</td>
<td>936</td>
<td>2.37</td>
</tr>
<tr>
<td>Pasta 2</td>
<td>395</td>
<td>1800</td>
<td>14</td>
<td>936</td>
<td>2.37</td>
</tr>
</tbody>
</table>

a For pasta, the mass of food refers to the input of dry pasta.

The corresponding figures for conventional boiling (calculated from Table 6) are for 500-630 g potatoes 1.21 and 1.32 kJ/g, and for pasta, 280 g and 520 g, 7.71 and 3.15 kJ/g respectively. For potatoes it is obvious that we used very much more water when boiling in an electric kettle compared to kettles on hotplates. The reason was practical; there was a large volume under the metal mesh that had to be filled with water before the water level reached the food, which lead to high energy consumption. For pasta on the other hand, the water amount was similar for cooking both in kettles on hotplates and in electric kettles, which lead to a lower relative energy use in electric kettles. The conclusion is that it is possible to save energy by heating the water directly, but the equipment must be designed so the amount of water needed is minimized.
Heating of water in electric kettles

Water can also be heated in electric kettles, and such appliances can be used for cooking, even if the food is not prepared in the kettle. Examples are preparation of couscous or mashed potatoes from powder, where the water is heated and then poured over the food. Hence energy use for heating water in electric kettles is appropriate to include in this report.

Electric kettles are principally constructed as a kettle with an electric heating element in the bottom, the water is heated directly by the element, and thus little energy is used for heating the equipment, so the energy efficiency is higher than for indirect heating as when hotplates are used.

Modelling of heating water in electric kettles

In a report from The Swedish Consumer Agency (1996a) energy use for heating between 0.25 to 1.5 litres of water from 15°C to 90°C is presented. In total 28 kettles were tested, with a minimum amount of water (for kettles with lower minimum capacity than 0.5 litres), 0.5 litres, 1.0 litres and 1.5 litres (for kettles with such large capacity). A summary of the experiments is presented in Table 9.

Table 9. Summary of experiments with heating of water in electric kettles (The Swedish Consumer Agency, 1996a).

<table>
<thead>
<tr>
<th>Amount heated (l)</th>
<th>Number of kettles tested</th>
<th>Efficiency (% of energy theoretically needed to heat the water)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Average</td>
</tr>
<tr>
<td>0.25</td>
<td>5</td>
<td>61.2</td>
</tr>
<tr>
<td>0.3</td>
<td>16</td>
<td>69.9</td>
</tr>
<tr>
<td>0.5</td>
<td>27</td>
<td>78.4</td>
</tr>
<tr>
<td>1.0</td>
<td>28</td>
<td>86.5</td>
</tr>
<tr>
<td>1.5</td>
<td>25</td>
<td>89.8</td>
</tr>
</tbody>
</table>

As can be seen from Table 9 the efficiency increases with increasing amount, which is logical since the proportion between water and equipment increases. Moreover, the efficiencies presented for different kettles are rather similar when boiling the same amount of water. The model structure suggested is the same as for boiling on hotplates: the efficiency is a linear function of mass heated, with different parameters for two ranges:

0.25-0.5 litres:
\[ E=48.45+61.1*m_w \]

0.5-1.5 litres:
\[ E=73.45+11.47*m_w \]

Where:
$m_w = \text{mass of water heated (kg)}$

$E = \text{efficiency} \, (%)$

When the efficiency is calculated the energy need can be calculated by using the theoretical energy need for heating water. An approximate figure that can be used in the model is presented below (in reality it varies slightly depending on temperature, but that can be omitted):

Heating water between 0-100°C, at 1 Bar pressure: 4.18 MJ/(kg * °C).

An example of how the model is used is presented below:

Heating 0.7 liter water from 10 to 95 °C.

Energy need (MJ) = \(\frac{(73.45+11.47*0.7)}{100*(95-10)}*4.18\)

**Discussion of the model of heating of water in electric kettles**

This model has not been validated, but the large number of experiments used and the small differences between kettles suggest that this is not necessary. Regarding validity range, we suggest that the model should not be used for volumes larger than 1.5 litres or smaller than 0.25 litres.
Frying in frying pan

Frying of food in a frying pan is one of the most common methods of food preparation in Sweden. A wide range of foods are fried, fish, vegetables and all kinds of meats, both fresh and cured. There are several reasons, e.g. most people like fried food, it is a quick method and it is rather simple. The fast heat transfer is a result of that heat is transferred by direct contact between the hot pan and the food, compared to boiling and oven preparation were a medium is heated (water and air respectively) and thereafter the heat is transferred to the food. Moreover, the temperature in the pan (150-190ºC) is higher than the boiling temperature, and almost as high as in oven roasting. The high temperature gives some disadvantages too, the mass- and water transport in the product is limited, in order to reach the desired temperature in the centre the surface temperature often gets to high, i.e. it gets overcooked with large juice losses and risk for a burnt surface.

The method for frying is that the pan and possibly some frying fat are heated to its desired temperature which is normally between 150 and 190 ºC, depending on what type of food to be fried. As a rule foods that are thick and require longer frying times are fried at lower temperatures while thin objects with short frying times are fried at higher temperatures. As opposed to ovens there are normally no thermostats on frying pans so the temperature is actually assumed by using experience and colour of the frying fat used. Thereafter the food is placed in the pan and left there for some time, very different times for different food products and sizes and shapes of the item to be fried. The temperature during frying is assessed by looking at and listening to the food and pan, and the power to the hotplate is adjusted manually. Especially for meat there is a large variation in how consumers judge the food to be ready, some like their meat red and some more well-done.

Modelling of frying in pan

As described above frying is more of a handcraft than oven roasting and boiling, it depends on taste and experience how it is performed. The process is performed during a short time with often relatively heavy equipment as cast iron pans. This suggests that the part of the energy used that is needed for heating the product itself is comparably small, a lot of energy is needed to heat the equipment. Hence the heating of the product is not included in the model. The energy needed for evaporation of water is also omitted since it is very difficult to get data on and also it varies a lot depending on who performs the frying.

This leads to a principal model structure where the energy consumption is built up of three parts:

- Heating the stove
- Heating the empty pan
- Maintaining the temperature of the pan

The first two parts, heating the stove and pan, are combined in the model presented.

Practically, frying is done at one of three temperature levels, high medium and low, according to cooking books. This is taken into account by using different factors for both the heating up and maintaining phase of the frying.

The model structure is presented below:
\[ E = E_{HU} + E_{MT} \]

Where:

\( E \) = Total energy use for frying (MJ)

\( E_{HU} \) = Energy for heating the pan and stove to frying temperature, which depends on type of hotplate (cast iron or ceramic) and weight, material and area of the frying pan

\( E_{MT} \) = Energy needed to maintain the temperature during frying, which depends on type of hotplate, temperature level, frying time and area of the frying pan.

The parameters \( E_{HU} \) and \( E_{MT} \) are calculated as follows:

\[ E_{HU} = m_{fp} \times \rho + e_{hu} \times A_{fp} \]

Where:

\( m_{fp} \) is mass of the frying pan (g)

\( \rho \) is the heat capacity of the pan (MJ/g*K)

\( A_{fp} \) is the area of the frying pan (cm²)

\( e_{hu} \) is a constant that is presented below (MJ/cm²).

\[ E_{MT} = t_{f} \times e_{mt} \times A_{fp} \]

Where:

\( A_{fp} \) is the area of the frying pan (cm²)

\( t_{f} \) = Time for frying (minutes)

\( e_{mt} \) = is a constant that is presented below (MJ/(minute*cm²))

Different \( e_{hu} \) is presented for cast iron and ceramic hotplates since the energy for heating the system differs significantly between these two types. The same applies to \( e_{mt} \) and additionally three values for \( e_{hu} \) and \( e_{mt} \) are presented for the three temperature levels (low, medium and high). Altogether six values for \( e_{mt} \) and \( e_{hu} \) respectively.

When using the model, data on heat capacity of the pan (\( \rho \)) is needed, and the heat capacity for iron and aluminium are \( 4.5 \times 10^{-7} \) MJ/(g * °C) and \( 9 \times 10^{-7} \) MJ/(g * °C), respectively.

**Experiments**

Test with empty frying pans have been performed at SIK during 2002. The used electricity was measured as are the weight of the pans. Both cast iron hotplates and ceramic hotplates were used as well as both steel and aluminium pans. The temperature at the surface of the pan was kept at 160°C. The same stoves as in the boiling and oven tests were used. The results from these experiments are presented in Table 10 and Table 11.
<table>
<thead>
<tr>
<th>Experiment no.</th>
<th>Material of frying pan</th>
<th>Weight of frying pan (g)</th>
<th>Area of frying pan (cm²)</th>
<th>Temperature level</th>
<th>Frying time (minutes)</th>
<th>Energy for heating up (MJ)</th>
<th>Energy for maintaining (MJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CI 1</td>
<td>Iron</td>
<td>2382</td>
<td>95</td>
<td>Low</td>
<td>6</td>
<td>0.628</td>
<td>0.132</td>
</tr>
<tr>
<td>CI 2</td>
<td>Iron</td>
<td>2382</td>
<td>95</td>
<td>Low</td>
<td>6</td>
<td>0.620</td>
<td>0.120</td>
</tr>
<tr>
<td>CI 3</td>
<td>Aluminium</td>
<td>621</td>
<td>71</td>
<td>Low</td>
<td>6</td>
<td>0.382</td>
<td>0.108</td>
</tr>
<tr>
<td>CI 4</td>
<td>Aluminium</td>
<td>621</td>
<td>71</td>
<td>Low</td>
<td>6</td>
<td>0.400</td>
<td>0.110</td>
</tr>
<tr>
<td>CI 5</td>
<td>Iron</td>
<td>1545</td>
<td>71</td>
<td>Low</td>
<td>6</td>
<td>0.392</td>
<td>0.086</td>
</tr>
<tr>
<td>CI 6</td>
<td>Iron</td>
<td>2382</td>
<td>95</td>
<td>Low</td>
<td>6</td>
<td>0.648</td>
<td>0.160</td>
</tr>
<tr>
<td>CI 7</td>
<td>Iron</td>
<td>2382</td>
<td>95</td>
<td>Low</td>
<td>6</td>
<td>0.702</td>
<td>0.128</td>
</tr>
<tr>
<td>CI 8</td>
<td>Iron</td>
<td>2382</td>
<td>95</td>
<td>Low</td>
<td>6</td>
<td>0.684</td>
<td>0.122</td>
</tr>
<tr>
<td>CI 9</td>
<td>Aluminium</td>
<td>621</td>
<td>71</td>
<td>Low</td>
<td>6</td>
<td>0.428</td>
<td>0.112</td>
</tr>
<tr>
<td>CI 10</td>
<td>Iron</td>
<td>1545</td>
<td>71</td>
<td>Low</td>
<td>6</td>
<td>0.390</td>
<td>0.094</td>
</tr>
<tr>
<td>CI 11</td>
<td>Iron</td>
<td>2382</td>
<td>95</td>
<td>Medium</td>
<td>6</td>
<td>0.610</td>
<td>0.324</td>
</tr>
<tr>
<td>CI 12</td>
<td>Iron</td>
<td>2382</td>
<td>95</td>
<td>Medium</td>
<td>6</td>
<td>0.610</td>
<td>0.324</td>
</tr>
<tr>
<td>CI 13</td>
<td>Iron</td>
<td>1267</td>
<td>95</td>
<td>Medium</td>
<td>6</td>
<td>0.670</td>
<td>0.237</td>
</tr>
<tr>
<td>CI 14</td>
<td>Iron</td>
<td>1267</td>
<td>95</td>
<td>Medium</td>
<td>6</td>
<td>0.680</td>
<td>0.256</td>
</tr>
<tr>
<td>CI 15</td>
<td>Aluminium</td>
<td>621</td>
<td>71</td>
<td>Medium</td>
<td>6</td>
<td>0.406</td>
<td>0.158</td>
</tr>
<tr>
<td>CI 16</td>
<td>Iron</td>
<td>2382</td>
<td>95</td>
<td>High</td>
<td>6</td>
<td>0.632</td>
<td>0.308</td>
</tr>
<tr>
<td>CI 17</td>
<td>Iron</td>
<td>2382</td>
<td>95</td>
<td>High</td>
<td>6</td>
<td>0.612</td>
<td>0.318</td>
</tr>
<tr>
<td>CI 18</td>
<td>Iron</td>
<td>2382</td>
<td>95</td>
<td>High</td>
<td>6</td>
<td>0.754</td>
<td>0.298</td>
</tr>
<tr>
<td>CI 19</td>
<td>Iron</td>
<td>2382</td>
<td>95</td>
<td>High</td>
<td>6</td>
<td>0.744</td>
<td>0.344</td>
</tr>
<tr>
<td>CI 20</td>
<td>Iron</td>
<td>1267</td>
<td>95</td>
<td>High</td>
<td>30</td>
<td>0.640</td>
<td>1.836</td>
</tr>
<tr>
<td>CI 21</td>
<td>Iron</td>
<td>1267</td>
<td>95</td>
<td>High</td>
<td>20</td>
<td>0.620</td>
<td>1.314</td>
</tr>
</tbody>
</table>
Table 11. Results from experiments with frying on ceramic hotplates

<table>
<thead>
<tr>
<th>Experiment no.</th>
<th>Material of frying pan</th>
<th>Weight of frying pan (g)</th>
<th>Area of frying pan (cm²)</th>
<th>Temperature level</th>
<th>Frying time (minutes)</th>
<th>Energy for heating up (MJ)</th>
<th>Energy for maintaining (MJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ce 1</td>
<td>Iron</td>
<td>2382</td>
<td>95</td>
<td>Low</td>
<td>6</td>
<td>0.380</td>
<td>0.130</td>
</tr>
<tr>
<td>Ce 2</td>
<td>Iron</td>
<td>2382</td>
<td>95</td>
<td>Low</td>
<td>6</td>
<td>0.380</td>
<td>0.130</td>
</tr>
<tr>
<td>Ce 3</td>
<td>Iron</td>
<td>1545</td>
<td>71</td>
<td>Low</td>
<td>6</td>
<td>0.304</td>
<td>0.100</td>
</tr>
<tr>
<td>Ce 4</td>
<td>Aluminium</td>
<td>621</td>
<td>71</td>
<td>Low</td>
<td>8</td>
<td>0.260</td>
<td>0.146</td>
</tr>
<tr>
<td>Ce 5</td>
<td>Aluminium</td>
<td>621</td>
<td>71</td>
<td>Medium</td>
<td>6</td>
<td>0.264</td>
<td>0.156</td>
</tr>
<tr>
<td>Ce 6</td>
<td>Aluminium</td>
<td>621</td>
<td>71</td>
<td>Medium</td>
<td>6</td>
<td>0.254</td>
<td>0.154</td>
</tr>
<tr>
<td>Ce 7</td>
<td>Iron</td>
<td>2382</td>
<td>95</td>
<td>Medium</td>
<td>6</td>
<td>0.384</td>
<td>0.176</td>
</tr>
<tr>
<td>Ce 8</td>
<td>Iron</td>
<td>2382</td>
<td>95</td>
<td>Medium</td>
<td>5</td>
<td>0.400</td>
<td>0.126</td>
</tr>
<tr>
<td>Ce 9</td>
<td>Iron</td>
<td>1545</td>
<td>71</td>
<td>Medium</td>
<td>5</td>
<td>0.308</td>
<td>0.098</td>
</tr>
<tr>
<td>Ce 10</td>
<td>Aluminium</td>
<td>621</td>
<td>71</td>
<td>Medium</td>
<td>6</td>
<td>0.268</td>
<td>0.154</td>
</tr>
<tr>
<td>Ce 11</td>
<td>Iron</td>
<td>1267</td>
<td>95</td>
<td>High</td>
<td>5</td>
<td>0.460</td>
<td>0.212</td>
</tr>
<tr>
<td>Ce 12</td>
<td>Iron</td>
<td>1267</td>
<td>95</td>
<td>High</td>
<td>6</td>
<td>0.440</td>
<td>0.300</td>
</tr>
<tr>
<td>Ce 13</td>
<td>Iron</td>
<td>1267</td>
<td>95</td>
<td>High</td>
<td>24.5</td>
<td>0.390</td>
<td>1.340</td>
</tr>
<tr>
<td>Ce 14</td>
<td>Iron</td>
<td>1267</td>
<td>95</td>
<td>High</td>
<td>29</td>
<td>0.440</td>
<td>1.440</td>
</tr>
</tbody>
</table>

Using the results presented in Table 10 and Table 11, values for $e_{hu}$ and $e_{nt}$ for each experiment could be calculated, they are presented in Table 12 to Table 17. The data from Table 10 and Table 11 was used to calculate $e_{hu}$ and $e_{nt}$. The average values for $e_{hu}$ and $e_{nt}$ for the different hotplates and temperature ranges were chosen as parameters for the model and are presented in Table 18.
Table 12. Calculated values for $e_{hu}$ and $e_{nt}$ for all experiments performed at low temperature level on cast iron hotplates. Data from Table 10 is used for the calculations

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$e_{hu}$ (MJ/cm²)</th>
<th>Relative value (average for all experiments=100)</th>
<th>$e_{nt}$ (MJ/cm²)</th>
<th>Relative value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CI 1</td>
<td>4.92*10^{-3}</td>
<td>103</td>
<td>2.32*10^{-4}</td>
<td>98</td>
</tr>
<tr>
<td>CI 2</td>
<td>4.83*10^{-3}</td>
<td>101</td>
<td>2.10*10^{-3}</td>
<td>89</td>
</tr>
<tr>
<td>CI 3</td>
<td>4.21*10^{-3}</td>
<td>88</td>
<td>2.54*10^{-3}</td>
<td>108</td>
</tr>
<tr>
<td>CI 4</td>
<td>4.46*10^{-3}</td>
<td>94</td>
<td>2.59*10^{-3}</td>
<td>110</td>
</tr>
<tr>
<td>CI 5</td>
<td>4.06*10^{-3}</td>
<td>85</td>
<td>2.02*10^{-3}</td>
<td>86</td>
</tr>
<tr>
<td>CI 6</td>
<td>5.13*10^{-3}</td>
<td>108</td>
<td>2.81*10^{-3}</td>
<td>119</td>
</tr>
<tr>
<td>CI 7</td>
<td>5.70*10^{-3}</td>
<td>119</td>
<td>2.24*10^{-3}</td>
<td>95</td>
</tr>
<tr>
<td>CI 8</td>
<td>5.51*10^{-3}</td>
<td>115</td>
<td>2.14*10^{-3}</td>
<td>91</td>
</tr>
<tr>
<td>CI 9</td>
<td>4.86*10^{-3}</td>
<td>102</td>
<td>2.63*10^{-3}</td>
<td>112</td>
</tr>
<tr>
<td>CI 10</td>
<td>4.03*10^{-3}</td>
<td>85</td>
<td>2.21*10^{-3}</td>
<td>94</td>
</tr>
</tbody>
</table>

* The heat capacity of steel and aluminium are 4.5*10^{-7} MJ/(g*K) and 9*10^{-7} MJ/(g*K) respectively

Table 13. Calculated values for $e_{hu}$ and $e_{nt}$ for all experiments performed at medium temperature level on cast iron hotplates. Data from Table 10 is used for the calculations

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$e_{hu}$ (MJ/cm²)</th>
<th>Relative value (average for all experiments=100)</th>
<th>$e_{nt}$ (MJ/cm²)</th>
<th>Relative value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CI 11</td>
<td>4.73*10^{-3}</td>
<td>90</td>
<td>5.68*10^{-4}</td>
<td>120</td>
</tr>
<tr>
<td>CI 12</td>
<td>4.73*10^{-3}</td>
<td>90</td>
<td>5.68*10^{-4}</td>
<td>120</td>
</tr>
<tr>
<td>CI 13</td>
<td>6.15*10^{-3}</td>
<td>116</td>
<td>4.16*10^{-4}</td>
<td>88</td>
</tr>
<tr>
<td>CI 14</td>
<td>6.26*10^{-3}</td>
<td>118</td>
<td>4.49*10^{-4}</td>
<td>95</td>
</tr>
<tr>
<td>CI 15</td>
<td>4.54*10^{-3}</td>
<td>86</td>
<td>3.72*10^{-4}</td>
<td>78</td>
</tr>
</tbody>
</table>

* The heat capacity of steel and aluminium are 4.5*10^{-7} MJ/(g*K) and 9*10^{-7} MJ/(g*K) respectively
Table 14. Calculated values for $e_{hu}$ and $e_{mt}$ for all experiments performed at high temperature level on cast iron hotplates. Data from Table 10 is used for the calculations

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$e_{hu}$ (MJ/cm²)</th>
<th>Relative value (average for all experiments=100)</th>
<th>$e_{mt}$ (MJ/cm²)</th>
<th>Relative value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CI 16</td>
<td>4.96*10^{-3}</td>
<td>89</td>
<td>5.40*10^{-4}</td>
<td>91</td>
</tr>
<tr>
<td>CI 17</td>
<td>4.75*10^{-3}</td>
<td>85</td>
<td>5.58*10^{-4}</td>
<td>94</td>
</tr>
<tr>
<td>CI 18</td>
<td>6.24*10^{-3}</td>
<td>112</td>
<td>5.23*10^{-4}</td>
<td>88</td>
</tr>
<tr>
<td>CI 19</td>
<td>6.14*10^{-3}</td>
<td>110</td>
<td>6.03*10^{-4}</td>
<td>102</td>
</tr>
<tr>
<td>CI 20</td>
<td>5.83*10^{-3}</td>
<td>104</td>
<td>6.44*10^{-4}</td>
<td>109</td>
</tr>
<tr>
<td>CI 21</td>
<td>5.62*10^{-3}</td>
<td>101</td>
<td>6.91*10^{-4}</td>
<td>117</td>
</tr>
</tbody>
</table>

The heat capacity of steel and aluminium are 4.5*10^{-7} MJ/(g*K) and 9*10^{-7} MJ/(g*K) respectively.

Table 15. Calculated values for $e_{hu}$ and $e_{mt}$ for all experiments performed at low temperature level on ceramic hotplates. Data from Table 11 is used for the calculations

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$e_{hu}$ (MJ/cm²)</th>
<th>Relative value (average for all experiments=100)</th>
<th>$e_{mt}$ (MJ/cm²)</th>
<th>Relative value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ce 1</td>
<td>2.31*10^{-3}</td>
<td>93</td>
<td>2.28*10^{-4}</td>
<td>96</td>
</tr>
<tr>
<td>Ce 2</td>
<td>2.31*10^{-3}</td>
<td>93</td>
<td>2.28*10^{-4}</td>
<td>96</td>
</tr>
<tr>
<td>Ce 3</td>
<td>2.82*10^{-3}</td>
<td>114</td>
<td>2.35*10^{-4}</td>
<td>99</td>
</tr>
<tr>
<td>Ce 4</td>
<td>2.49*10^{-3}</td>
<td>100</td>
<td>2.57*10^{-4}</td>
<td>109</td>
</tr>
</tbody>
</table>

The heat capacity of steel and aluminium are 4.5*10^{-7} MJ/(g*K) and 9*10^{-7} MJ/(g*K) respectively.

Table 16. Calculated values for $e_{hu}$ and $e_{mt}$ for all experiments performed at medium temperature level on ceramic hotplates. Data from Table 11 is used for the calculations

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$e_{hu}$ (MJ/cm²)</th>
<th>Relative value (average for all experiments=100)</th>
<th>$e_{mt}$ (MJ/cm²)</th>
<th>Relative value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ce 5</td>
<td>3.13*10^{-3}</td>
<td>110</td>
<td>3.67*10^{-4}</td>
<td>113</td>
</tr>
<tr>
<td>Ce 6</td>
<td>2.99*10^{-3}</td>
<td>105</td>
<td>3.62*10^{-4}</td>
<td>112</td>
</tr>
<tr>
<td>Ce 7</td>
<td>2.35*10^{-3}</td>
<td>83</td>
<td>3.09*10^{-4}</td>
<td>95</td>
</tr>
<tr>
<td>Ce 8</td>
<td>2.52*10^{-3}</td>
<td>89</td>
<td>2.65*10^{-4}</td>
<td>82</td>
</tr>
<tr>
<td>Ce 9</td>
<td>2.87*10^{-3}</td>
<td>101</td>
<td>2.77*10^{-4}</td>
<td>85</td>
</tr>
<tr>
<td>Ce 10</td>
<td>3.19*10^{-3}</td>
<td>112</td>
<td>3.62*10^{-4}</td>
<td>112</td>
</tr>
</tbody>
</table>

The heat capacity of steel and aluminium are 4.5*10^{-7} MJ/(g*K) and 9*10^{-7} MJ/(g*K) respectively.
Table 17. Calculated values for $e_{hu}$ and $e_{mt}$ for all experiments performed at high temperature level on ceramic hotplates. Data from Table 11 is used for the calculations.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$e_{hu}$ (MJ/cm$^2$)</th>
<th>$e_{mt}$ (MJ/cm$^2$)</th>
<th>Relative value (average for all experiments=100)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ce 11</td>
<td>3.94*10^{-3}</td>
<td>4.46*10^{-4}</td>
<td>108</td>
</tr>
<tr>
<td>Ce 12</td>
<td>3.73*10^{-3}</td>
<td>5.26*10^{-4}</td>
<td>102</td>
</tr>
<tr>
<td>Ce 13</td>
<td>3.20*10^{-3}</td>
<td>5.76*10^{-4}</td>
<td>111</td>
</tr>
<tr>
<td>Ce 14</td>
<td>3.73*10^{-3}</td>
<td>5.23*10^{-4}</td>
<td>101</td>
</tr>
</tbody>
</table>

*a The heat capacity of steel and aluminium are 4.5*10^{-7} MJ/(g*K) and 9*10^{-7} MJ/(g*K) respectively

Table 18. Values for $e_{hu}$ and $e_{mt}$ used in the model for different frying situations.

<table>
<thead>
<tr>
<th>Hotplate</th>
<th>Temperature range</th>
<th>$e_{hu}$</th>
<th>$e_{mt}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cast iron</td>
<td>Low</td>
<td>4.77*10^{-3}</td>
<td>2.36*10^{-4}</td>
</tr>
<tr>
<td>Cast iron</td>
<td>Medium</td>
<td>5.28*10^{-3}</td>
<td>4.75*10^{-4}</td>
</tr>
<tr>
<td>Cast iron</td>
<td>High</td>
<td>5.59*10^{-3}</td>
<td>5.93*10^{-4}</td>
</tr>
<tr>
<td>Ceramic</td>
<td>Low</td>
<td>2.48*10^{-3}</td>
<td>2.37*10^{-4}</td>
</tr>
<tr>
<td>Ceramic</td>
<td>Medium</td>
<td>2.84*10^{-3}</td>
<td>3.24*10^{-4}</td>
</tr>
<tr>
<td>Ceramic</td>
<td>High</td>
<td>3.65*10^{-3}</td>
<td>5.18*10^{-4}</td>
</tr>
</tbody>
</table>

Validity range for the frying model

The model gives reliable results when used for calculating energy demand for frying on cast iron and ceramic hotplates of household sizes, using frying pans in good shape (even and clean) and that have correct size compared to the hotplate. The accuracy of the model is neither tested for frying on very low temperatures, below 150ºC, nor very high temperatures, above 180ºC.

Availability of input data

When the model is used, assumptions are made on the average size and material of the frying pans used, the proportion between cast iron and ceramic hotplates and what type of frying situations is relevant for the food studied. The latter can be obtained from cooking books etc., and the question about hotplates and frying pans can be assessed by statistics on sales, or it might be the variable one wants to study the effects of. These assumptions will give all indata needed to use the model in a reasonably easy way.

Discussion of the frying model

The model is a simplification of the physical reactions taking place when frying food in a pan. The system is complicated and to make a detailed model of the energy need for frying would require rather detailed indata, thus this was not an option is this study. The model does not take evaporation of water and thawing into account (as the oven model), which could pose a
risk that the energy use is underestimated when frozen food or food that lose large amounts of
water during preparation. The first problem, underestimating energy use when frozen foods
are prepared, is compensated for by the fact that cooking instructions on frozen foods either
states that the temperature must be higher or the frying time longer, which leads to higher
energy use presented by the model. The same applies more or less to very wet foods.
Moreover, such products are rarely fried, since the point with frying is to get high surface
temperature which is prevented by very high water content.
Roasting and baking in electric oven

Preparing food in an electric oven is a common method to cook several dishes. Meat, fish and vegetables are cooked in oven. Baking of bread is also a common use of the oven. Regarding meat it is often larger portions that are roasted, as joint of roast. For fish, sliced and thin pieces are roasted as well as large fish. Potatoes are the most common vegetable that is roasted in oven. The advantage with roasting is that the heat transfer is rather slow which decreases the water losses compared to frying a pan, but the surface temperature is high enough to facilitate browning of the surface, which gives the desired change in taste. The slow heat transfer also makes it possible to cook larger pieces without overheating the surface; the temperature gradient is lower than in a frying pan. This latter advantage is larger when the temperature is lower, but at the same time the browning of the surface is less intense. The disadvantages are formation of unwanted substances in the surface browning processes and that oven roasting takes longer time than pan frying.

Modelling of roasting in electrical oven

The energy use for food preparation in an electrical oven can be separated in the following parts:

- Heating the oven to the desired temperature (Heating up, \( E_{HUoven} \)). This part is depending on the volume of the oven, temperature elevation and to some extent losses to the surroundings.
- Maintaining the temperature (\( E_{MToven} \)). This is a function of volume, temperature difference to the surrounding room and how long time the temperature is to be maintained, i.e. compensating for heat losses.

This will cover the energy needed for an empty oven; additionally, energy is needed for the food to be prepared:

- Raising the temperature of the food to a level when it can be considered ready to eat (\( E_{RToven} \)). This is a function of the temperature raise, amount of product and heat capacity of the product.
- Evaporation of water (\( E_{EWoven} \)). This is a function of the amount of water evaporated and the evaporation energy.
- Thawing, if frozen products are prepared (\( E_{TPoven} \)). This is a function of amount of product that has to be thawed and thawing energy for the product.

Using this separation, a principal model for calculating energy consumption for food preparation in an electrical oven can be formulated:

\[
E_{toven} = E_{HUoven} + E_{MToven} + E_{RToven} + E_{EWoven} + E_{TPoven}
\]

The input data needed for the model is:

- \( m_p \) = Amount of product to prepare (g)
- \( V \) = volume of the oven (litres)
- \( T \) = Temperature in the oven, minus initial temperature
- $t =$ time the temperature is maintained (minutes)
- $\Delta T =$ Temperature elevation in the product ($^\circ$C)

The parameters needed, and which we present below are:

- $e_{hu} =$ Energy for heating one litre of oven volume. $[(MJ/(litre*^\circ C))]$
- $e_{mt} =$ Energy for maintaining a certain oven temperature in one litre for one minute $[MJ/(litre*min)]$
- $e_{hp} =$ heat capacity of the food product (in literature often denoted $c_p$) $[MJ/(kg*^\circ C)]$.

The energy consumption can be calculated as:

$$E_{totoven} = e_{hu}*V + e_{mt}*V*t + e_{hp} * m_p * \Delta T$$

We have used oven tests performed at The Swedish Consumer Agency for estimating the constants for $e_{hu}$ and $e_{mt}$. There were 122 ovens tested of nine brands: 4 AEG, 13 Bosch, 12 Cylinda, 22 Electrolux, 19 Elektro Helios, 20 Husqvarna, 16 Siemens, 8 UPO and 8 Whirlpool. The sample is not representative of the sales in Sweden but we did not weigh the impact of different types by their sales. In the tests the electricity consumption for heating up the oven from 20 to 200 $^\circ$C and thereafter maintaining the temperature for 60 minutes was measured (The Swedish Consumer Agency, 2002). Data on the tests and results are presented in Table 19.

Table 19. Results from tests at The Swedish Consumer Agency (2002) ($n$=122)

<table>
<thead>
<tr>
<th>Average volume (litres)</th>
<th>48.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max-min volumes (l)</td>
<td>65-18</td>
</tr>
<tr>
<td>Average $e_{hu}$ [MJ/(litre*°C)]</td>
<td>2.0*10^{-4}</td>
</tr>
<tr>
<td>Max $e_{hu}$ [MJ/(litre*°C)]</td>
<td>3.3*10^{-4}</td>
</tr>
<tr>
<td>Min $e_{hu}$ [MJ/(litre*°C)]</td>
<td>1.0*10^{-4}</td>
</tr>
<tr>
<td>Standard deviation $e_{hu}$</td>
<td>4.6*10^{-5}</td>
</tr>
<tr>
<td>Average $e_{mt}$ [MJ/(litre*°C*minute)]</td>
<td>4.3*10^{-6}</td>
</tr>
<tr>
<td>Max $e_{mt}$ [MJ/(litre*°C*minute)]</td>
<td>6.1*10^{-6}</td>
</tr>
<tr>
<td>Min $e_{mt}$ [MJ/(litre*°C*minute)]</td>
<td>2.7*10^{-6}</td>
</tr>
<tr>
<td>Standard deviation $e_{mt}$</td>
<td>4.6*10^{-5}</td>
</tr>
</tbody>
</table>

In order to examine if the assumption that $e_{hu oven}$ and $e_{mt oven}$ is independent of oven size, the ovens tested at The Swedish Consumer Agency (2002) were divided in three groups: small (18-40 litres), medium (40-50 litres) and large (50-65 litres) ovens. The resulting parameters per group are presented in Table 20.
Table 20. Results from tests at The Swedish Consumer Agency (2002), divided in groups according to oven volume

<table>
<thead>
<tr>
<th>Oven size (litres)</th>
<th>No of ovens in group</th>
<th>$e_{hu}$ [MJ / (litre*C) * 10^{-4}]</th>
<th>$e_{mt}$ [MJ / (litre<em>C</em>minute) * 10^{-6}]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Max</td>
<td>Min</td>
</tr>
<tr>
<td>18-40</td>
<td>23</td>
<td>2.16</td>
<td>3.33</td>
</tr>
<tr>
<td>41-50</td>
<td>47</td>
<td>1.76</td>
<td>2.17</td>
</tr>
<tr>
<td>51-65</td>
<td>63</td>
<td>2.11</td>
<td>3.13</td>
</tr>
</tbody>
</table>

The parameters $e_{hu}$ and $e_{mt}$ are assumed to be independent of oven temperature within certain ranges. To test these assumptions some experiments were performed at SIK. Oven temperatures were set between 150 and 225 °C and ovens with 23 to 59 litres volume were used. The results from the experiments and the calculated values for $e_{hu}$ and $e_{mt}$ are presented in Table 21.

Table 21. Results from oven tests at SIK

<table>
<thead>
<tr>
<th>Mean Temperature (HU/MT) $^a$</th>
<th>No of test in each group</th>
<th>$e_{hu}$ [MJ / (litre*C) * 10^{-4}]</th>
<th>$e_{mt}$ [MJ / (litre<em>C</em>minute) * 10^{-6}]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Max</td>
<td>Min</td>
</tr>
<tr>
<td>153/157</td>
<td>6</td>
<td>1.38</td>
<td>1.86</td>
</tr>
<tr>
<td>216/212</td>
<td>6</td>
<td>1.32</td>
<td>1.60</td>
</tr>
<tr>
<td>241/234</td>
<td>7</td>
<td>1.61</td>
<td>1.83</td>
</tr>
</tbody>
</table>

$^a$ The temperature when the thermostat first turned off differed from the mean temperature during the maintaining phase

From Table 20 it is obvious that both parameters $e_{hu}$ and $e_{mt}$ show no clear difference between the size groups. From Table 21 it seems that $e_{mt}$ increases with increasing oven temperature, and also $e_{hu}$ shows tendencies to increase with temperature. These increases are however rather small and will be omitted in the model. All results from the tests at SIK (Table 21) shows figures that are lower than averages from the Swedish Consumer Agency (Table 20), but they are within the range.

Hence the average values for $e_{hu}$ and $e_{mt}$ from Table 19 are used as parameters in the model.

\[
\begin{align*}
&e_{hu} = 2.0 \times 10^{-4} \text{ [MJ / litre * °C]} \\
&e_{mt} = 4.3 \times 10^{-6} \text{ [MJ / litre * C * minute]} \\
\end{align*}
\]

The food-specific parameters are set by using basic physical data on heat capacity and melting and evaporation energies, described below:

The heat capacities ($c_{hp}$) of food products are presented under the heading “General input data to all models” (Table 27).

\[
\begin{align*}
&e_{ew} = 2.26 \times 10^{-3} \text{ [MJ / g water evaporated]} \\
\end{align*}
\]
The amount of water evaporated is approximated to the weight loss during preparation.
\[ e_{hp} = 3.34 \times 10^{-4} \, [\text{MJ} / \, \text{g product initially frozen}] \]

The figure is the melting energy for water. For reasons of simplicity, we approximate that the melting energy of the dry matter in food is the same as water, this is not correct since there is no melting of the dry matter of the product, but frozen products generally have high water content, hence the simplification is justified.

The discussion above together result in the following model:
\[
E_{\text{totaloven}} (\text{MJ}) = 2.0 \times 10^{-4} \times V \times T + 4.3 \times 10^{-6} \times V \times T \times t + e_{hp} \times m_{\text{tot}} \times \Delta T + 2.26 \times 10^{-3} \times m_{\text{wevap}} + 3.34 \times 10^{-4} \times m_{\text{frozen}}
\]

\( V = \) Volume of the oven [litres]
\( T = \) Oven temperature during preparation minus initial temperature which is assumed to be 20 °C
\( t = \) time for preparation (i.e. time after the desired temperature is reached) [minutes]
\( m_{\text{tot}} = \) mass of the product put into the oven [g]
\( m_{\text{wevap}} = \) mass of water evaporated [g]
\( m_{\text{frozen}} = \) mass of the product if frozen [g]

**Validation Experiments**

In order to validate the model experiments with food products were performed at SIK.

- Two experiments with French fries
- Two experiments with sponge cake, one in a small oven and one in a large
- Two experiments with cookies, one in a small oven and one in a large

The input data is presented in Table 22.

**Table 22. Input data for validation experiments**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>V (litres)</th>
<th>T (°C)</th>
<th>t (minutes)</th>
<th>m_{\text{tot}} (g)</th>
<th>m_{\text{wevap}} (g)</th>
<th>m_{\text{frozen}} (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>French fr. 1</td>
<td>59</td>
<td>225</td>
<td>29</td>
<td>1001</td>
<td>378</td>
<td>1001</td>
</tr>
<tr>
<td>French fr. 2</td>
<td>59</td>
<td>225</td>
<td>29</td>
<td>1000</td>
<td>382</td>
<td>1000</td>
</tr>
<tr>
<td>Sponge cake 1</td>
<td>23</td>
<td>150</td>
<td>45</td>
<td>593</td>
<td>56</td>
<td>0</td>
</tr>
<tr>
<td>Sponge cake 2</td>
<td>59</td>
<td>150</td>
<td>46</td>
<td>795</td>
<td>54</td>
<td>0</td>
</tr>
<tr>
<td>Cookies 1</td>
<td>23</td>
<td>200</td>
<td>10</td>
<td>196</td>
<td>19</td>
<td>0</td>
</tr>
<tr>
<td>Cookies 2</td>
<td>59</td>
<td>200</td>
<td>8.5</td>
<td>263</td>
<td>24</td>
<td>0</td>
</tr>
</tbody>
</table>

The results from the model and the measured energy consumption are presented in Table 23.
Table 23. Results from validation experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$E_{HU}$ (MJ)</th>
<th>$E_{tot}$ (MJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Model Measured</td>
<td>Ratio Model/Measured</td>
</tr>
<tr>
<td>French fries 1</td>
<td>2.48</td>
<td>2.49</td>
</tr>
<tr>
<td>French fries 2</td>
<td>2.48</td>
<td>2.58</td>
</tr>
<tr>
<td>Sponge cake 1</td>
<td>0.71</td>
<td>0.83</td>
</tr>
<tr>
<td>Sponge cake 2</td>
<td>1.77</td>
<td>1.64</td>
</tr>
<tr>
<td>Cookies 1</td>
<td>0.92</td>
<td>0.92</td>
</tr>
<tr>
<td>Cookies 2</td>
<td>2.36</td>
<td>1.96</td>
</tr>
</tbody>
</table>

As can be seen from Table 23 the model presents results that show relatively good correspondence with the measured energy use.

Validity range for the oven model

The model can be used if the oven sizes are within the range 18-65 litres and the temperatures are between 150-250 °C, according to the experiments performed. The model is valid for oven using electric heat as energy source, not microwave assisted or infrared ovens.

Availability of input data

The following input data is needed to use the oven model:

- Weight of the product. This should be very easy to obtain.
- Roasting time. This can be obtained from cookery books etc., i.e. the data is easy to get.
- Required temperature for the product prepared. This can be obtained from handbooks for cooking (for Swedish readers “Mått för Mat”, ICA, 2000, can be recommended)
- Temperature during preparation. As above, however the fact that the thermostats seem to be working with low accuracy will make the predictions less exact. On the other hand, the higher or lower temperature will probably affect the time which will at least partly even out the differences.
- Amount of water evaporated during preparation. This data might be difficult to obtain, but there are data published in various literature sources. As for required temperature, ICA (2000), can be used.
- Energy needed to heat the product roasted. This data can either be calculated using the information presented under the heading “General input data to all models” (Table 27)

Discussion of the oven model

When using an oven it is common that the oven-door is opened several times during use, this is not considered in the model. The amount of energy removed by the hot air flowing out from the oven is very small since the heat capacity of air is low and the mass of the air is very low.
In the validation experiments the oven-door was opened once and the model still worked reasonably well.

Another aspect is that almost always a baking-plate or similar is used, which principally would increase the total energy since it will be heated to the temperature of the oven. In the validation experiments with French fries the weight of the baking-plate was 874 g. To heat 874 g of steel to 245 °C requires 0.09 MJ (specific heat capacity 460 J / kg°C, temperature difference 220 °C), which can be omitted since it is such a small portion of the total energy demand.

The model structure assumes that there is a linear relationship between oven volume and energy consumption both for heating up and maintaining temperature. This is not correct, the geometry gives that the heat losses per litre (which for maintaining is the only energy use and for heating up a part of the energy use) from the oven should increase with decreasing size. Considering the purpose of the model, this is omitted but the model will not generate reliable results if ovens smaller or larger than the ones included in the modelling or validation (18-65 litres) are studied.

One weakness of the model could be that the parameters for heating up and maintaining the temperature of the oven are based on a non-weighted average. It could be argued that the sales of the ovens should be included in the modelling. We have, however, decided not to do that, mainly because of the purpose with the model; to assess the energy use for oven roasting generally, not specifically for Swedish circumstances.
Microwave cooking

When microwaves are used to heat food the energy is supplied also inside the product, as opposed to the other means of food preparation dealt with in this report. This also means that the food is the direct receiver of energy, no hotplate and saucepan has to be heated first, the plates and equipment are heated indirect via the food, by heat conduction.

In general, cooking of foods in a microwave oven gives lower energy consumption as compared to conventional cooking methods\(^1\). One reason for this is that the energy efficiency is considerably higher for microwave cooking applications. Household microwave ovens have an energy efficiency which exceeds 50%, while traditional ovens typically give less than 20% energy efficiency for this application (% of supplied energy that is transferred to the food).

The energy transfer to the food in a microwave oven depends on a large number of concurrent factors. In this chapter the main factors are described and the mechanisms that affect the transmission of microwave energy to the food in the oven. How this in turn affects the energy use for food preparation is discussed.

The microwave oven

Microwaves are a type of electromagnetic waves with wavelengths between one meter and one millimetre, which corresponds to frequencies in the interval from 0.3 GHz to 300 GHz (Figure 5).

\[^1\] This is valid, as a rough rule of thumb, at least as long as the amount of foodstuff to be cooked does not exceed about 4 portions.

Figure 5. The electromagnetic spectrum. 2.45 marks the normal frequency for household microwave ovens

Here follows a brief description of how microwave energy is transferred from the microwave inlet openings to the foodstuff.

In a microwave oven, the microwaves are generated by the so called magnetron. During microwave heating, the magnetron generates microwaves of the frequency 2.45 GHz, which are transferred to the oven cavity. The antenna of the magnetron emerges into a so called
waveguide. The microwaves are led from the waveguide system either directly into the oven cavity or in a feed system with a metallic mode stirrer and thereafter into the cavity. The microwaves are reflected in all possible directions in the cavity, where they may be absorbed by the foodstuff.

These microwaves consist of both electric and magnetic fields, coupled to each other, but for foodstuffs – which are non-metallic – only the electric fields in the oven cavity will contribute to the microwave heating. However, the magnetic fields will of course contribute to the field pattern in the oven. A more detailed description of the heating mechanisms during microwave heating is found e.g. in (Buffler, 1993).

Figure 6. Example of an oven cavity.

**Power level in microwave ovens**

For household microwave ovens, several different power levels are often available, e.g. 0, 90, 160, 350, 500, 650, 750, 850 and 1000 W. These power levels do not indicate the real output power, but determines the duty-cycle of the magnetron. There are standardised methods to measure the microwave power output which will be delivered by a microwave oven to a 1000 g water load.

*An example of microwave cooking*

An example of the heating pattern of a lasagne after microwave cooking in a traditional microwave oven is given in Figure 7.
Figure 7. An example of the heating pattern of a lasagne after microwave cooking (the unit on the axis is °C)

By measuring the dielectric and thermo-physical properties and use them as input data in simulations of the heating result in a microwave oven, it is possible to predict the microwave heating pattern of food products. The water and salt content of the food will affect the dielectric properties to a large extent.

**Absorbed power**

The quantitative measure of the power absorbed in a food product during microwave heating is determined by Eqn. 1-1.

\[ P_v = \frac{2\pi f\varepsilon_0\varepsilon'' E^2}{}\]  

(Eqn. 1-1)

Where:

- \( P_v \) = power absorbed per unite volume (W/m³)
- \( f \) = frequency (Hz)
- \( E \) = the electric field in the food product during heating (V/m), which may vary considerably over the food volume
- \( \varepsilon_0 \) = the dielectric constant \( \cong 8.854 \times 10^{-12} \) (As/Vm)
- \( \varepsilon'' \) = dielectric loss factor

**Factors which influence the power absorbed by a food load during microwave heating**

When cooking foods in a microwave oven, the rate of heating – and thus the power absorbed by a foodstuff in a microwave oven – is affected by several factors, which interact in a complex fashion. These factors are summarised below.
The energy efficiency during microwave cooking may depend on several factors, among which are the so called “the microwave coupling” (see below), the amount of food load to be heated (volume of the foodstuff in relation to the oven cavity volume), food load geometry, position of the food load in the cavity and the oven parameters (cavity size, cavity geometry, cavity material, microwave feed system etc). The temperature of the food load is also central, since the dielectric properties – which determine the absorbed power – are temperature dependent in a complicated way. There are also several other factors, which may be important, e.g. the power supply. The power supply circuit may affect the output power by giving a ±15% influence on the microwave output power.

Microwave cooking in general gives an energy efficiency which is often higher than 50% for high quality ovens. Furthermore, for many good ovens the energy efficiency may be as much as 55-65% (Risman, 2003). The energy efficiency during the heating process in household microwave ovens is determined by several factors:

- The **efficiency of the power supply** which transforms line power (4230/400 V 50 Hz) to the high voltage DC current which is required by the microwave generator (magnetron) is a very important factor. Today’s power supplies of so called switch mode type are expected to have an efficiency of 86% for household microwave ovens, (% of energy supplied to the power supply delivered to the magnetron) (Risman, 2003).
- The **magnetron**, which is the source of the microwave energy. Its power supply (see above) and specification determines the available power which may be delivered to the food load. The efficiency of today’s 2450 MHz magnetrons (1kW) is typically 71-74 % (% of energy supplied to the magnetron delivered as microwaves from the magnetron) (Risman, 2003), in ovens with a good microwave coupling (see below). If the cooling system of the magnetron is poorly constructed, as may be the case for ovens of a lower price range, the oven will show an initial decrease of power. The power decrease may be as much as 20%, and often occurs during the first 5-10 minutes of use (Greenwood-Madsen and Voss, 1988).
- The **efficiency will depend significantly on the so called microwave coupling of the oven**, i.e. the microwave efficiency of the oven cavity, including the feed system. This may in turn vary with factors like the size and geometry of the food to be heated. The microwave coupling is an important factor; a well tuned microwave coupling gives optimal energy efficiency for the areas of application which the oven is intended and developed for. High coupling efficiency requires a high-qualitative design of the feed system and mode stirrer. The microwave transfer efficiency, i.e. the part of the microwave energy absorbed by the food, to a large food product may be as much as 95% (Risman, 2003). Relationships between oven parameters, load placement, and load geometry have so far not been established. However, simulation tools in order to find the factors which give the largest influence on the microwave heating of a specific foodstuff have been demonstrated (Wäppling-Raaholt et al., 1999, Wäppling-Raaholt et al., 2001).
- The **amount of food to be heated at each occasion** plays an important role. The “filling factor”, i.e. the load volume in relation to the size of the oven cavity affects the amount of power which the load may absorb (Gerling 1987, Buffler 1990). For each specific microwave oven, the power absorbed will decrease with the “filling factor”. This is valid for filling factors occurring in normal household use. Buffler (1993) use the ratio \( r \), defined as the ratio between the proportion of the power absorbed by a 500 ml water load and that of a 1000 ml water load to indicate in what way the power of a specific oven will decrease with the filling volume. Typically, the ratio \( r \) is > 0.8.
A small food product (small in the sense that the area of the food product is small in relation to that of the cavity wall area) gives higher losses.

- **Other oven parameters**, such as the size and geometry of the cavity, and the cavity material.

- **The heating uniformity in the food** to be heated. Uneven heating results on the one hand in increased loss due to vaporisation, on the other hand in increased heating times in order to achieve the desired result during heating. Cold spots in some food product cause energy losses, since the rest of the foodstuff is often overheated to compensate for the cold spots. Today, computational methods are available to calculate how food components should be designed in order to achieve as uniform heating as possible (Wäppling-Raaholt et al., 1999). The heating uniformity is affected by several interacting factors, such as position and geometry of the foodstuff, size of the food product in relation to cavity size, and relative dimensions of the food product.

- The dielectric and thermo-physical properties of the food products will affect the absorbed power. Since those properties are temperature dependent in a complex way, the product temperature will affect the power absorbed in a food load. The temperature and specific heat capacity of the package or vessel may give rise to a usually small decrease in absorbed power from the food load into the vessel or package.

There are standardised methods (IEC, 1999) to measure the microwave power output delivered to a so called 1000 g water load\(^2\). In this context, Risman (1993) also compares with a smaller 350 g water load and with a model food substance with similar dielectric properties. Risman (1993) shows that the smaller water load (à 350 g) is less suitable to represent real reheating of foods, due to so called internal resonance phenomena which occur during heating of this smaller amount of water. He also concludes that the available output efficiency of the oven must be used together with other characteristics in order to give an accurate enough description of the heating rate – and thereby of the energy efficiency. However, it is very complicated to predict what input microwave power the microwave oven will give in each specific case.

**The microwave oven efficiency**

A microwave oven with a line voltage which is specified to \(U\) (Volt) and a current specification of \(I\) (A), will have a microwave input power of \(P=UI\). Let us assume that the microwave input power is 1400 W. If a measurement of the microwave power output according to the IEC standard (IEC, 1999), using a water load, gives a value of the microwave power output of 770 W, the efficency of power transfer from the line receptacle to the water would be \(1400/770 = 0.55\) or 55%, for this specific case.

An illustration of the power flow in a typical microwave oven is found in Figure 8 (Buffler 1993, Risman, 2003). Note that once the microwave power is generated by the magnetron, the energy efficiency to the load can be quite high, 95% for loads with a high filling factor. The high efficiency of microwave ovens is caused by the fact that no energy is needed to heat the surrounding air or the cooking vessel. Instead, most of the energy is transferred directly to the food load.

---

\(^2\) 1 kg of a water load in a standard glass container, according to the IEC-standard (1).
Figure 8. Efficiency of a microwave oven; schematic picture. Efficiency means the percentage of the energy supplied to the "component" that is delivered from the component.

**Modelling of energy use for microwave heating**

As discussed above, the efficiency of microwave ovens are very difficult to predict without very detailed information on the food to be heated, since the energy absorption of the food differs with factors as size, placement, composition etc. This means that the model presented will not give very accurate results and if detailed information about energy requirements for a specific food type is needed, more detailed models should be used.

The model builds on that the efficiency for the energy transfer to the food is calculated. Thereafter the theoretically minimum energy requirement for heating the food to the desired temperature is calculated. Finally these two factors are combined to get the energy needed for the cooking. We have chosen to exclude thawing of frozen foods since both the properties of foods and the microwave efficiency are very different from thawed foods.

The theoretical energy need for heating a food item is calculated using data on heat capacity ($c_p$), mass of the food and temperature elevation and finally the energy needed to evaporate water. Data on heat capacity for various foods are presented in Table 27. The theoretical energy need is calculated as follows:

$$E_{\text{heat}} = m_{\text{food}} \times T_{\text{elev}} \times c_p + m_{\text{evap}} \times e_w$$

Where:

- $E_{\text{heat}}$ = Energy needed for heating the food to the desired temperature (MJ).
- $m_{\text{food}}$ = mass of the food heated (g).
- $T_{\text{elev}}$ = Temperature elevation ($^\circ$C) (for example from 8 $^\circ$C to 100 $^\circ$C for boiling of vegetables).
- $c_p$ = Heat capacity [MJ/(g*$^\circ$C)], data presented in Table 27.
- $m_{\text{evap}}$ = mass of water evaporated
e_{ew} = 2.26 \times 10^{-3} \ [MJ / g \ water \ evaporated] 

The second part of the model, the efficiency, is a function mainly of the figures presented in Figure 8, combined with assumptions on how the efficiency is dependent on mass of the food heated, as presented in Buffler (1993).

The following efficiencies presented in Figure 8 are used for the microwave oven model:

- **Fan, lamp and controller**: 95%
- **Magnetron power supply (transformation)**: 86%
- **Magnetron**: 73%
- **Microwave coupling**: This efficiency is described below

The relationship between load and microwave coupling efficiency are very complex, but Buffler (1993) states that the load volume is the most important parameter.

In the modelling, the efficiency due to the microwave coupling is assumed to be a linear function of volume, within a certain range of volumes. Buffler (1993) states that between 1000 g water load and 500 g water load the ratio of efficiency is 0.8 i.e. the 500 g load absorbs 80% of the energy the 1000 g load absorbs. Assuming that the efficiency due to microwave coupling for the 1000 g load is 95% (Figure 8), the efficiency for a 500 g load will be:

\[ E_{500} = 0.8 \times 95 = 76\% \]

We assume that the relationship between load volume and efficiency are linear. Then we can use the efficiencies for 500 g and 1000 g to calculate the linear function of efficiency as a function of volume of the food. Hence the following relationship can be stated for the interval 500-1000 g load:

\[ e_{mwcoupl} = 0.57 + 3.8 \times 10^{-4} \times V_{food} \]

Where:

- \( e_{mwcoupl} \) = efficiency due to the microwave coupling
- \( V_{food} \) = Volume of the food (ml)

This relationship is of course not absolutely correct; it is only useful within a range of volumes, 200 to 1000 ml, based on the experiments performed (see below). Below this range the model will not give reliable results, as the efficiency drops radically as the amount of food gets very small (Buffler, 1993). Moreover, it is very difficult in practice to cook small amounts without overheating the food. Above the range the microwave coupling efficiency is assumed to be 95%. In the modelling we assume that the volume can be replaced with weight, for most foods the density is rather close to 1000 kg/m\(^3\), and in order to simplify the data gathering mass is easier to use.

Formal description of the model:

\[ E_{heat} = \frac{(m_{food} \times T_{elev} \times c_p + (m_{evap} \times e_{ew}))}{e_{totmw}} \]

Where:

- \( e_{totmw} = e_{support} \times e_{trans} \times e_{magn} \times e_{mwcoupl} \)
- \( e_{support} = 0.95 \) (efficiency for fan, lamp and controls)
- \( e_{trans} = 0.86 \) (efficiency for transformation)
\[ e_{magn} = 0.73 \text{ (efficiency for the magnetron)} \]
\[ e_{mw coup} = 0.57 + 3.8 \times 10^{-4} \times m_{food} \text{ (for } 200 < m_{food} < 1000 \text{ g)} \]
\[ e_{mw coup} = 0.95 \text{ (for } m_{food} > 1000 \text{ g)} \]

Together this gives:

200 g < \( m_{food} < 1000 \) g:
\[ E_{\text{heat}} = \frac{m_{food} \times T_{\text{elec}} \times c_p + (m_{\text{evap}} \times e_{\text{ew}})}{(0.95 \times 0.86 \times 0.73 \times (0.57 + 3.8 \times 10^{-4} \times m_{\text{food}}))} \]
\[ = \frac{m_{food} \times T_{\text{elec}} \times c_p + (m_{\text{evap}} \times e_{\text{ew}})}{(0.34 + 2.28 \times 10^{-4} \times m_{\text{food}})} \]
\[ m_{food} > 1000 \text{ g:} \]
\[ E_{\text{heat}} = \frac{m_{food} \times T_{\text{elec}} \times c_p + (m_{\text{evap}} \times e_{\text{ew}})}{(0.95 \times 0.86 \times 0.73 \times 0.95)} \]
\[ = \frac{m_{food} \times T_{\text{elec}} \times c_p + (m_{\text{evap}} \times e_{\text{ew}})}{0.57} \]

**Validation of the model**

In order to validate the model, experiments were carried out at SIK. The energy used for cooking meatloaf and baked potatoes was measured. For both products one and four portions were cooked in four different ovens, the experiments are presented in Table 24 and Table 25.

The model was supplied with the data from the experiments and compared to the energy use measured. For temperature, the temperature elevation is calculated assuming that the initial temperature was 5°C. The validation result (Table 24 and Table 25) shows that for four portions the model predicts the energy need fairly well, but some experiments deviate rather much from the predictions of the model. A general comment is that for four portions the model underestimates the energy needed while for one portion it overestimates the energy need.
<table>
<thead>
<tr>
<th>Oven</th>
<th>No. of portions</th>
<th>Weight before/after (g)</th>
<th>Power level (^a)</th>
<th>Cooking time (min/s)</th>
<th>Temperature (°C) (^b)</th>
<th>Measured energy use (MJ)</th>
<th>Model result for energy use</th>
<th>Ratio model/measured energy use</th>
<th>Efficiency calculated with the model (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whirlpool MD 121</td>
<td>4</td>
<td>625/515</td>
<td>750</td>
<td>12/20</td>
<td>80</td>
<td>0.90</td>
<td>1.13</td>
<td>1.25</td>
<td>50</td>
</tr>
<tr>
<td>Whirlpool MT 226</td>
<td>4</td>
<td>637/552</td>
<td>750</td>
<td>12/20</td>
<td>71</td>
<td>0.90</td>
<td>0.74</td>
<td>0.82</td>
<td>49</td>
</tr>
<tr>
<td>LG MS-1907C</td>
<td>4</td>
<td>645/537</td>
<td>800</td>
<td>11/34</td>
<td>65</td>
<td>0.86</td>
<td>0.77</td>
<td>0.90</td>
<td>49</td>
</tr>
<tr>
<td>Daewo KOR63DB9A</td>
<td>4</td>
<td>644/529</td>
<td>700</td>
<td>13/13</td>
<td>80</td>
<td>0.86</td>
<td>0.87</td>
<td>1.01</td>
<td>49</td>
</tr>
<tr>
<td>Whirlpool MD 121</td>
<td>1</td>
<td>156/132</td>
<td>750</td>
<td>3/5</td>
<td>67</td>
<td>0.22</td>
<td>0.23</td>
<td>1.08</td>
<td>38</td>
</tr>
<tr>
<td>Whirlpool MT 226</td>
<td>1</td>
<td>157/139</td>
<td>750</td>
<td>3/5</td>
<td>72</td>
<td>0.22</td>
<td>0.20</td>
<td>0.95</td>
<td>38</td>
</tr>
<tr>
<td>LG MS-1907C</td>
<td>1</td>
<td>156/132</td>
<td>800</td>
<td>2/53</td>
<td>80</td>
<td>0.22</td>
<td>0.25</td>
<td>1.16</td>
<td>38</td>
</tr>
<tr>
<td>Daewo KOR63DB9A</td>
<td>1</td>
<td>158/135</td>
<td>700</td>
<td>3/18</td>
<td>82</td>
<td>0.22</td>
<td>0.25</td>
<td>1.15</td>
<td>38</td>
</tr>
</tbody>
</table>

\(^a\) Note that it is not the power supplied to the food, but power level, to be distinguished from the microwave output power.

\(^b\) Measured as centre temperature, which is assumed to be average temperature of the food.
Table 25. Results from experiments with baked potatoes and the predictions of the model for the same experiments

<table>
<thead>
<tr>
<th>Oven</th>
<th>No. of portions</th>
<th>Weight before /after (g)</th>
<th>Power level a</th>
<th>Cooking time (min/s)</th>
<th>Temperature (°C) b</th>
<th>Measured energy use (MJ)</th>
<th>Model result for energy use</th>
<th>Ratio model/measured energy use</th>
<th>Calculated efficiency with the model (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whirlpool MD 121</td>
<td>4</td>
<td>1335/1229</td>
<td>750</td>
<td>15/0</td>
<td>95</td>
<td>1.12</td>
<td>1.02</td>
<td>0.92</td>
<td>0.57 c</td>
</tr>
<tr>
<td>Whirlpool MT 226</td>
<td>4</td>
<td>1498/1445</td>
<td>750</td>
<td>15/0</td>
<td>96</td>
<td>1.08</td>
<td>1.03</td>
<td>0.95</td>
<td>0.57 c</td>
</tr>
<tr>
<td>LG MS-1907C</td>
<td>4</td>
<td>1477/1430</td>
<td>800</td>
<td>14/0</td>
<td>94</td>
<td>1.04</td>
<td>0.98</td>
<td>0.94</td>
<td>0.57 c</td>
</tr>
<tr>
<td>Daewo KOR63DB9A</td>
<td>4</td>
<td>1492/1441</td>
<td>700</td>
<td>16/0</td>
<td>95</td>
<td>1.08</td>
<td>1.01</td>
<td>0.94</td>
<td>0.57 c</td>
</tr>
<tr>
<td>Whirlpool MD 121</td>
<td>1</td>
<td>303/280</td>
<td>750</td>
<td>4/30</td>
<td>100</td>
<td>0.32</td>
<td>0.37</td>
<td>1.14</td>
<td>41</td>
</tr>
<tr>
<td>Whirlpool MT 226</td>
<td>1</td>
<td>313/303</td>
<td>750</td>
<td>4/30</td>
<td>93</td>
<td>0.32</td>
<td>0.28</td>
<td>0.88</td>
<td>41</td>
</tr>
<tr>
<td>LG MS-1907C</td>
<td>1</td>
<td>259/245</td>
<td>800</td>
<td>3/0</td>
<td>96</td>
<td>0.22</td>
<td>0.28</td>
<td>1.30</td>
<td>40</td>
</tr>
<tr>
<td>Daewo KOR63DB9A</td>
<td>1</td>
<td>279/264</td>
<td>700</td>
<td>4/0</td>
<td>87</td>
<td>0.25</td>
<td>0.28</td>
<td>1.10</td>
<td>40</td>
</tr>
</tbody>
</table>

a Note that it is not the power supplied to the food, but power level, to be distinguished from the microwave output power.
b Measured as centre temperature, which is assumed to be average temperature of the food
c This is the constant efficiency factor for food mass above 1000 g, according to the model
Availability of input data

Most data needed to use the microwave cooking model are all rather accessible; mass of the food prepared, temperature elevation and heat capacity are either presented in this report (heat capacity), assumed using statistics on household sizes etc. (mass of food cooked each time) or available from cookery books (heat elevation). The amount of water evaporated during preparation might be difficult to obtain, but there are data published in various literature sources. As for required temperature, ICA (2000), can be used.

Validity range of the microwave cooking model

As mentioned above, the validity range regarding mass of food prepared is 200-1500 g, based on Buffler (1993) where diagrams of energy uptake as a function of volume are presented. The model is also limited to normal household ovens with 2450 MHz frequency and around 1 kW power input. The model will not present reliable results for foods with extremely low water contents.

Discussion of the microwave cooking model

As mentioned, the energy efficiency of microwave cooking is difficult to model in great detail. The interaction between food load and the oven are complex, not only the volume and composition of the food affects the energy uptake, also the placement in the oven cavity is of importance as is the geometrical shape of the food item. Thus the model presented here is not very accurate, but it will fulfil the purpose of the report; a model that will present the energy required for food preparation without detailed input data, based on a simplified model of the physics of the heating process. The validity is limited to “normal” use in households with regards to both amount and types of food prepared and also types of ovens used. By presenting the efficiency for the different parts of the process it is possible to adjust these if more data are available or in order to make sensitivity analyses. A weak point in the model is that thawing of frozen products is not included. The properties of frozen foods are very different from thawed foods, and the phase shift impose dramatic effects on the thermal properties of foods. This is of course a weakness in the modelling since thawing of frozen products is a task often performed with microwave ovens.

The results from the validation experiments show the difficulties when modelling energy use for microwave ovens, the measured energy use differed significantly especially when small amounts were cooked. This has to be taken into account when using the model for calculations for small amounts, sensitivity analyses should be performed.
Cold Storage of Food

Background

Food products are often perishable and require careful storing to keep their quality, both hygienic and eating quality. A very common method to slow down the degradation of food is to store it at low temperatures. Fresh foods as dairy products, vegetables, meats and prepared products that are to be consumed within the nearest time is often stored in refrigerators. When long time storage is the aim freezing is a very common practice. Refrigerators typically supply temperatures between 4 and 8°C and freezers around -18°C. Both freezers and refrigerators principally consist of a well insulated container with a heat pump that uses electricity to move energy from within the cabinet to the surrounding environment. This means that the energy removed from inside is heating the air in the room where the appliance is located, which is beneficial during wintertime in cold climates and can be a problem in warm climates.

Modelling of storing in freezers and refrigerators

The amount of energy needed to maintain the desired temperature inside a freezer or refrigerator is composed of three parts: cooling the items put into the cabinet, compensate for heat transfer through walls and finally compensate for inflow of warm air when the door or lid is opened.

The first part, cooling the item, is calculated using the heat capacity ($C_p$) for different foods, presented in Table 27, combined with an assumed temperature difference, freezing energy for water combined with water content of the food to get the freezing energy. Finally the cold factor, i.e. the efficiency for the heat pump is added to the calculation to get the use of electricity for chilling the product.

The second part, compensating for heat transfer through walls, is calculated using published data on energy consumption for different appliances. This part is presented below.

The third part, compensating for inflow of warm air when the door or lid is opened, is omitted from the model. Air has low heat capacity and the flow of warm air into the cabinet does not carry any large amount of energy. Assuming that 150 litres of warm air is flowing in to an upright freezer when the door is opened (probably a large figure). This means that 0.002 kWh per opening has to be removed from the cabinet. With a cold factor of 1.7 (rule of thumb for freezers) this gives 0.0034 kWh/opening. If the freezer is opened twice a day the yearly energy used for opening is around 2.5 kWh. For freezers larger than 150 litres this figure is less than 1% of the energy use (calculated from Table 26). Hence the energy due to opening the door can be omitted. The corresponding energy use for chest freezers and refrigerators are lower, for chest freezers due to that less warm air is flowing in when the lid is opened and for refrigerators due to that the temperature of the appliance is higher, hence less energy is needed to cool the inflowing air.

The model structure for both freezers and refrigerators proposed is that the total energy use per year is allocated to the food product in relation to how large part of the total used volume in the cabinet is used by the product under study. This structure demands the following input data:

- Energy use for the cabinet per day.
- The portion of the cabinet’s volume used in total on average
• Storing time for the food under study.
• Heat capacity for the food under study (only for freezers).

\[ \text{E}_{\text{tot product}} = \text{E}_{\text{loss}} \times \frac{V_{\text{product}}}{V_{\text{used}}} + \text{E}_{\text{chill}} \]

Where:

- \( \text{E}_{\text{tot product}} \) = Energy use for storing the product under study (MJ)
- \( \text{E}_{\text{loss}} \) = Energy use for maintaining the temperature (MJ)
- \( V_{\text{product}} \) = Volume of the product under study (litres)
- \( V_{\text{used}} \) = Volume of all products stored in the cabinet (litres)
- \( \text{E}_{\text{chill}} \) = Energy for lowering the temperature of the product under study (only for freezing).

This is composed of two parts, one for lowering the temperature and the second the energy needed for freezing the water to ice. The freezing energy is assumed equivalent to the energy needed to freeze the water in the product, \( 3.34 \times 10^{-4} \) (MJ/g water). For lowering the temperature of the product figures presented in Table 27 can be used together with data on how much the temperature is decreased (for freezing a product at 20º the temperature difference is 38ºC).

**Energy use for maintaining the temperature (E\text{\_loss})**

In order to acquire data on energy need for maintaining the temperature, information from the Swedish consumer agency was used. For chest freezers, 54 appliances had been tested, 12 Electrolux, 11 Whirlpool, 10 Gram, 6 Cylinda, 6 Electro Helios, 5 Zanussi, 2 Bosch and 2 Siemens. For upright freezers 132 appliances had been tested, 23 Electrolux, 14 Gram, 12 Bosch, 12 Husqvarna, 12 Siemens, 11 Whirlpool, 6 Cylinda, 6 Electro Helios, 5 AEG, 5 Gorenje, 5 Miele, 4 UPO, 4 Zanussi, 3 Selectro, 2 De Dietrich, 2 Gaggenau, 2 Helkama, 1 Ariston, 1 Bauknecht, 1 Candy and 1 Hoover.

For refrigerators 119 cabinets had been tested, 22 Electrolux, 15 Whirlpool, 13 Bosch, 12 Husqvarna, 10 Siemens, 7 Gram, 6 AEG, 6 Electro Helios, 6 Gorenje, 5 Miele, 3 De Dietrich, 3 Selectro, 3 UPO, 3 Zanussi, 2 Helkama, 1 Bauknecht, 1 Candy and 1 Hoover.

In Table 26 volumes and energy use per litre and year for freezers and refrigerators, calculated from data presented by Swedish Consumer Agency (2002), is presented.

**Table 26. Results from measurements on freezers presented by Swedish Consumer Agency (2002)**

<table>
<thead>
<tr>
<th></th>
<th>Chest freezers</th>
<th>Upright freezers</th>
<th>Refrigerators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of tests</td>
<td>54</td>
<td>132</td>
<td>119</td>
</tr>
<tr>
<td>Average volume (litres)</td>
<td>270</td>
<td>202</td>
<td>272</td>
</tr>
<tr>
<td>Min/Max volumes (litres)</td>
<td>101/503</td>
<td>38/314</td>
<td>51/400</td>
</tr>
<tr>
<td>Average Energy use [MJ/(litre*year)]</td>
<td>4.81</td>
<td>7.37</td>
<td>2.84</td>
</tr>
<tr>
<td>Max Energy use [MJ/(litre*year)]</td>
<td>8.84</td>
<td>22.74</td>
<td>12.92</td>
</tr>
<tr>
<td>Min Energy use [MJ/(litre*year)]</td>
<td>2.82</td>
<td>3.87</td>
<td>1.65</td>
</tr>
<tr>
<td>Standard deviation Energy use</td>
<td>1.57</td>
<td>3.15</td>
<td>1.56</td>
</tr>
</tbody>
</table>

Since the number of data was large, the energy use per litre volume was plotted against volume of the cabinet and the function was identified.
Chest freezers

The plot for chest cabinets could not be fitted with one function so the set was divided in two ranges, 101-190 litres and 191-503 litres. The lower range is presented in Figure 9.

![Chest freezers, 101-189 litres](image)

*Figure 9. Energy use (MJ/litre * year) plotted against cabinet volume (litres) for chest cabinets with volumes between 101-190 litres*

The function that fitted the data best was linear:

\[ E = 14.232 - 0.0532V \]

Where:

- \( E \) = Energy use (MJ/(litre*year))
- \( V \) = Cabinet volume (litres)

The \( R^2 \) value was 0.8557

The higher range, between 200-503 litres did not show any clear relationship between volume and energy use. The average energy use for the range was 4.36 MJ/(litre*year).

**Range 200-500 litres:**

\[ E = 4.36 \times V \]

Where:

- \( E \) = Energy use (MJ/(litre*year))
- \( V \) = Cabinet volume (litres)

Upright freezers

In Figure 10, the data for upright freezers is presented.
Figure 10. Energy use (MJ/litre * year) plotted against cabinet volume (litres) for upright cabinets with volumes between 38-314 litres

The identified function is presented below.

\[ E = 195.59 \times V^{-0.6429} \]

Where:

\( E \) = Energy use (MJ/(litre*year))

\( V \) = Cabinet volume (litres)

The \( R^2 \) value is 0.7841

Refrigerators

For refrigerators the data are presented in Figure 11.
Refrigerators, all volumes

Figure 11. Energy use (MJ/litre * year) plotted against cabinet volume (litres) for refrigerators with volumes between 51-400 litres

The identified function is presented below.

\[ E = 371.59 \times V^{-0.8982} \]

Where:
- \( E \) = Energy use (MJ/(litre*year))
- \( V \) = Cabinet volume (litres)
- The \( R^2 \) value was 0.8482

**Proposed models**

The models for calculating energy use for cold storage are presented below:

**Chest freezers:**

Range 100-200 litres

\[ E_{\text{product}} = (14.232 - 0.0532 \times V_{\text{cabinet}}) \times (D_{\text{stored}}/365) \times (V_{\text{product}}/ V_{\text{used}}) \]

Range 201-500 litres

\[ E = (4.36 \times V_{\text{cabinet}}) \times (D_{\text{stored}}/365) \times (V_{\text{product}}/ V_{\text{used}}) \]

**Upright Freezers:**

\[ E_{\text{product}} = 195.59 \times V_{\text{cabinet}}^{-0.6429} \times (D_{\text{stored}}/365) \times (V_{\text{product}}/ V_{\text{used}}) \]

For all freezers an extra energy use is added if products are put into the cabinet that are not frozen before:

\[ E_{\text{chill}} = (w_{\text{product}} \times m_{\text{product}} \times 3.34 \times 10^{-4}) + (m_{\text{product}} \times C_{\text{product}} \times \Delta T) \]

\[ E_{\text{product}} = \text{Energy use for storing the product in a freezer (MJ).} \]
\[ D_{\text{stored}} = \text{Time the food is in storage (Days)} \]

\[ V_{\text{cabinet}} = \text{Volume of the cabinet} \]

\[ V_{\text{product}} = \text{Volume of the product (litres) this is the practical volume, i.e. including package.} \]

\[ V_{\text{used}} = \text{Volume of all other objects in the cabinet. This is used to get the proportion of the product under study to the total volume products stored in the cabinet.} \]

\[ w_{\text{c product}} = \text{Water content of the product, wet base (0-1).} \]

\[ m_{\text{product}} = \text{Mass of the product under study (g)} \]

\[ C_{\text{p product}} = \text{Heat capacity of the product under study (MJ/(g °C)). (It should be noted that C} \]

\[ \Delta T = \text{Temperature difference when freezing the product. This value is typically 38°C when a product at room temperature is frozen.} \]

Refrigerators:

\[ E_{\text{product}} = 371.59 \times V_{\text{cabinet}}^{(-0.8982)} \times \left( \frac{D_{\text{stored}}}{365} \right) \times \left( \frac{V_{\text{product}}}{V_{\text{used}}} \right) \]

Denotation is the same as for freezers above.

Validity range for the models

The model will give reliable energy use if applied on the sizes of appliances used in the modelling work presented in this report, 100-500 litres for chest freezers, 38-314 litres for upright freezers and 51-400 litres for refrigerators.

Availability of input data

The data needed to use the models are:

- Time the food is in storage (Days). This must be assumed or investigated by interviews for every product studied.
- Volume of the cabinet, this data can be obtained by sales statistics.
- Volume of the product can be measured or calculated.
- Volume of other objects in the cabinet. This is probably the most difficult input data to obtain, and we have not found it in literature.
- Water content of the product, wet base can be obtained in literature or from information on packages.
- Mass of the product under study should be easy to obtain.
- Heat capacity of the product under study, some data and a “rule-of-thumb-formula” is presented in this report (Table 27), data for other products are available in literature.
- The temperature difference when freezing the product is easy to obtain. This value is typically 40°C when a product at room temperature is frozen.

Discussion of the cold storage models

The models are based on relatively large numbers of data, which probably make them rather reliable. However, the variation in energy use is large, as can be seen in Table 26 which can
be a problem. The models should logically be more accurate for large cabinets, it can be seen that the dependence on cabinet volume is smaller the larger the cabinet, so probably the models generate fairly good results for appliances somewhat larger than mentioned in the validity range. For very small cabinets the model should not be used under the validity range, the dependence on volume is strong and very little data support it.

The assumption on volume of other objects in the cabinet is difficult to make in a controlled way, since no information about it has been found. Our suggestion is that sensitivity analyses are done on that parameter when the models are used.

Neglecting the effects of opening the door on refrigerators can be a problem. For some products that are frequently taken from the refrigerator during the storage time, as milk used for coffee, the number of door openings can be so large that it significantly contributes to the total energy use.
General input data to all models

When using the models in this report, most parameters are general, i.e. they can be used for all food preparation situations, since they handle heating of water, ovens, frying pans, stove and kettle. Heating the product itself however, differs depending on type of product, the ehp. This value is very dependent on the water content of the product; drier products generally have lower ehp. There are literature data that can be used, and they are presented in Table 27. If other products than the ones presented in Table 27 are studied, there is a general, empirical based formula presented in Okos (1986) that can be used:

\[ cp = 0.84 + 0.034 \times mc \]

where mc is the water content in percent, wet basis. The formula is valid for non-frozen products. The formula was tested on the literature data in Table 27 and showed good agreement.

Table 27. Literature data for ehp (cp) that can be used in the model, non frozen products

<table>
<thead>
<tr>
<th>Food product</th>
<th>ehp [MJ/(g*ºC)]</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potato</td>
<td>3.43*10^{-6}</td>
<td>Lewis (1987)</td>
</tr>
<tr>
<td>Pasta a</td>
<td>1.46-1.80*10^{-6}</td>
<td>Lewis (1987)</td>
</tr>
<tr>
<td>Cod</td>
<td>3.76*10^{-6}</td>
<td>Lewis (1987)</td>
</tr>
<tr>
<td>Lamb</td>
<td>2.8*10^{-6}</td>
<td>Lewis (1987)</td>
</tr>
<tr>
<td>Egg, whole with shell</td>
<td>3.31*10^{-6}</td>
<td>Rao &amp; Rizvi (1986)</td>
</tr>
<tr>
<td>Haddock</td>
<td>3.73*10^{-6}</td>
<td>Rao &amp; Rizvi (1986)</td>
</tr>
<tr>
<td>Beef</td>
<td>3.52*10^{-6}</td>
<td>Rao &amp; Rizvi (1986)</td>
</tr>
<tr>
<td>Onion</td>
<td>3.81*10^{-6}</td>
<td>Rao &amp; Rizvi (1986)</td>
</tr>
<tr>
<td>Carrot</td>
<td>3.9*10^{-6}</td>
<td>Rao &amp; Rizvi (1986)</td>
</tr>
</tbody>
</table>

\textit{a data for wheat, but pasta consists almost entirely of wheat and have similar water content.}
Discussion and Conclusions

The energy needed in all appliances modelled in this report is only partly needed for the purpose of the appliance, i.e. heating or cooling food. The rest is lost as heat to the surrounding. In cold climates this decreases the need for energy to heat the house. This means that heat losses from household appliances could be considered as avoided “energy input” for heating, which in turn means less environmental impact in total. On the contrary, in warm climates and during summertime in cold climates, the heat loss entails inconveniences or energy use for air conditioning. The models presented in this report are intended to be rather general; hence it is not appropriate to include such effects as mentioned above. Our suggestion is that for each study an assessment is made on how large part of the heat losses that can be considered to either replace house heating energy or involve increased energy need for air conditioning.

The models presented in this report are based on experiments and statistics from Sweden, using appliances that are used in Sweden. This means that the parameters presented might be less useful when used in other countries. However, the energy use for electrical appliances is rather similar between different manufacturers (even if there are exceptions) as shown in this report. The use of gas stoves probably changes the energy use for cooking, especially for short cooking times, since less goods has to be heated.

The present work deals with energy use for cooking and storing in households. Since an increasing part of the meals are consumed in restaurants, institutional kitchens, caterers etc. the energy use for such cooking should be investigated. According to some studies the variation between restaurants and institutional kitchens are large, as are the variation between different dishes.

Another area of investigation is the washing up, which consumes large and rather varying amount of hot water. Hot water is an important contributor to a households total energy use and washing up is a direct effect of home cooking and eating. This area should include private households as well as restaurants and institutional kitchens.

Conclusively we would like to stress that the models presented does not give very accurate results. The advantage is that they do not require specific input data; hence they can easily be used and present results accurate enough for screening purposes. If the food preparation shows to be important in a life cycle perspective more detailed investigations can be done. In many cases the accuracy of the models is sufficient.

Another conclusion is that the energy use for preparing food in households varies a lot. The reasons are differences in equipment and perhaps even more how the equipment is used. This implies that the improvement potential is large even without introducing new equipment. If new and improved equipment is used, i.e. heat supplied directly to where it is needed much energy could be saved. This is exemplified by the tests with boiling pasta in an electric kettle. Also an increased use of microwave energy, perhaps in combination with heat radiation, seems to be a way of using less energy for food preparation.
List of all Models Presented in this Report

Below a list of all models developed in the report is presented. Only the models are presented, all information on the background etc. is presented in the chapters above.

Boiling in water on hotplates

\[ E_{\text{tot}} = e_{\text{hu}} * m_w + e_{\text{mt}} * m_w * t + e_{\text{hp}} * m_p * \Delta T \]

Where:
- \( m_p \) = Amount of product to cook (g)
- \( m_w \) = Amount of water used in the boiling (g)
- \( e_{\text{hu}} \) and \( e_{\text{mt}} \) are presented in Table 4
- \( e_{\text{hp}} \) can be found in literature, but we present literature data for common foods in Table 27.
- \( \Delta T \) = Temperature elevation in the product

Heating of water in electric kettles

The efficiency of the kettle is a linear function of mass of the water heated, with different parameters for two ranges:

- **0.25-0.5 litres**:
  \[ E = 48.45 + 61.1 * m_w \]

- **0.5-1.5 litres**:
  \[ E = 73.45 + 11.47 * m_w \]

Where:
- \( m_w \) = mass of water heated (kg)
- \( E \) = efficiency (%)

When the efficiency is calculated the energy need can be calculated by using the theoretical energy need for heating water.

Frying in frying pan

\[ E = \left( m_{\text{fp}} \right. * \left. \rho + e_{\text{hu}} * A_{\text{fp}} \right) + (t_r * e_{\text{mt}} * A_{\text{fp}} ) \]

Where:
- \( E \) = Total energy use for frying (MJ)
- \( m_{\text{fp}} \) = mass of the frying pan (g)
- \( \rho \) = heat capacity of the pan (MJ/g*K)
- \( A_{\text{fp}} \) = area of the frying pan (cm\(^2\))
- \( t_r \) = time for frying (minutes)
- \( e_{\text{hu}} \) = a constant that is presented in Table 18 (MJ/cm\(^2\)).
- \( e_{\text{mt}} \) = a constant that is presented in Table 18 (MJ/(minute*cm\(^2\))

---

56
Roasting and baking in electric oven

\[ E_{tot} (MJ) = 2.0 \times 10^{-4} \times V \times T + 4.3 \times 10^{-6} \times V \times T \times t + 4.18 \times 10^{-6} \times m_{tot} \times \Delta t + 2.26 \times 10^{-3} \times m_{wevap} + 3.34 \times 10^{-4} \times m_{frozen} \]

- \( V \): Volume of the oven [litres]
- \( T \): Oven temperature during preparation minus initial temperature (assumed to be 20 °C)
- \( t \): time for preparation (i.e. time after the desired temperature is reached) [minutes]
- \( m_{tot} \): mass of the product put into the oven [g]
- \( m_{wevap} \): mass of water evaporated [g]
- \( m_{frozen} \): mass of the product if frozen [g]

Microwave cooking

\[ E_{heat} = \frac{(m_{food} \times T_{elev} \times c_p + (m_{evap} \times e_{ew}))}{(0.34 + 2.28 \times 10^{-4} \times m_{food})} \]

- \( m_{food} \): mass of the food heated (g).
- \( T_{elev} \): Temperature elevation (°C) (for example from 8 °C to 100 °C for boiling of chilled vegetables).
- \( c_p \): Heat capacity [MJ/(g*°C)], data presented in Table 27.
- \( m_{evap} \): mass of water evaporated
- \( e_{ew} = 2.26 \times 10^{-3} \) [MJ / g water evaporated]

Cold Storage of Food

Three types of cold storage is modelled; chest freezers, upright freezers and refrigerators.

**Chest freezers 100-200 litres:**

\[ E_{product} = (14.232 - 0.0532 \times V_{cabinet}) \times (D_{stored}/365) \times (V_{product}/V_{used}) \]

**Chest freezers 200-500 litres:**

\[ E = (4.36 \times V_{cabinet}) \times (D_{stored}/365) \times (V_{product}/V_{used}) \]

**Upright Freezers:**

\[ E_{product} = 195.59 \times V_{cabinet}^{(-0.6429)} \times (D_{stored}/365) \times (V_{product}/V_{used}) \]

For all freezers extra energy use is added if products are put into the cabinet that are not frozen before:

\[ E_{chill} = (w_{cproduct} \times m_{product} \times 3.34 \times 10^{-4}) + (m_{product} \times C_{pproduct} \times \Delta T) \]

- \( E_{product} \): Energy use for storing the product in a freezer (MJ).
- \( D_{stored} \): Time the food is in storage (Days)
- \( V_{cabinet} \): Volume of the cabinet (litres)
- \( V_{product} \): Volume of the product (litres) this is the practical volume, i.e. including package.
- \( V_{used} \): Volume of all other object in the cabinet (litres). This is used to get the proportion of the product under study to the total volume products stored in the cabinet.
\[ wc_{\text{product}} = \text{Water content of the product, wet base (0-1)}. \]
\[ m_{\text{product}} = \text{Mass of the product under study (g)} \]
\[ C_{p_{\text{product}}} = \text{Heat capacity of the product under study (MJ/(g * °C)). Can be found in Table 27} \]
\[ \Delta T = \text{Temperature difference when freezing the product. This value is typically 40°C when a product at room temperature is frozen.} \]

**Refrigerators:**

\[ E_{\text{product}} = 371.59 \times V_{\text{cabinet}}^{-0.8982} \times \left( \frac{D_{\text{stored}}}{365} \right) \times \left( \frac{V_{\text{product}}}{V_{\text{used}}} \right) \]

Denotation is the same as for freezers above.
References

Bengtsson, N. 1991, Matlagningsteknik I hemmet (Home cooking technology, in Swedish), Livsmedelsteknik 8-9, also SIK-publikation 567, SIK - The Swedish Institute for Food and Biotechnology, Göteborg, Sweden.


ICA, 2000, Mått för mat - provköken förklarar (Measures for food - the experimental kitchens explains, in Swedish), ICA Bokförlag, Västerås, Sweden


Johannisson, V. & Olsson, P., 1997, Energiåtgång från jord till bord för råvara, hel- och halvfabrikat (Energy use from farm to plate for foods with different level of industrial processing, in Swedish), SIK- The Swedish Institute for Food and Biotechnology, Göteborg Sweden.


Lewis, M J., 1987, Physical properties of foods and food processing systems: Ellis Horwood, Chichester, West Sussex, UK.

NUTEK, 1994, Hushållsel i småhus - mätning av elanvändning i 66 småhus och av konsekvenserna av att byta hushållsapparater (Household electricity in one-family houses - measurements of electricity use in 66 one-family houses and the effects of changing equipment, in Swedish), Rapport B 1994:11, NUTEK, Stockholm


Okos, M R., (editor), 1986, Physical and Chemical Properties of Food: American Society of Agricultural Engineers, St. Joseph, Michigan, USA


Swedish Consumer Agency, 1996a, Energieffektivare matlagning - Provning av elektriska vattenkokare, energieffektivitet och metallutlösning (Energy efficient cooking - experiments with electric kettles, energy efficiency and release of metals), Swedish Consumer Agency, Stockholm, Sweden

Rao, M A. & Rizvi, S S H. (editors), 1986, Engineering properties of foods: Marcel Dekker Inc., New York, USA


Risman, P.O., 2003, Personal discussions regarding total power flow in microwave ovens, energy losses during microwave heating.


Appendix 1. Detailed model of boiling in water

Background
In the main report rather simple models for calculating energy use for boiling is presented. In some situations, however, there is a need for more detailed models. If a certain boiling situation is under study regarding equipment and product, a more detailed model can be useful since the results will be more accurate. We have constructed a model that builds on energy balances and heat transfer between product, water, hotplate, kettle and the ambient air. This detailed model also provides possibilities to calculate other parameters besides energy consumption, as surface and centre temperatures and required boiling time. The use of this model requires rather specific input data; hence it differs from the other models presented in the report.

Modelling

Introduction
A simplified physical model for cooking of food in a saucepan is constructed. The model is based on an energy balance between a heating medium (hotplate) and a load, where the energy loss to the surrounding air also is considered. However; the evaporation of water during boiling is not taken into account. The load consists of a saucepan with a content of water and food to be cooked such as potato, rice or pasta. The model calculates elapsed time/temperature profile in the water as well as in the product. In addition accumulated energy and losses are estimated. The model is calibrated and validated by experiment performed at SIK. The thermal properties of the food were estimated by use of a method (ThermEst) developed at SIK. The form of the food is initially limited to be spherical.

Nomenclature

General
\( t \) Time, s
\( m \) Weight, kg
\( A \) Area, \( m^2 \)
\( V \) Volume, \( m^3 \)
\( E \) Energy, J
\( Q \) Power, W

Below, means \( \{i\} \) input data to the simulation.

Process and equipment
\( t_{\text{end}} \) Time for cooking, s \( \{i\} \)
\( h_{wp} \) Heat transfer coefficient (water->product), \( W/m^2 \degree C \{i\} \)
\( h_p \) Heat transfer coefficient (hot-plate->saucepan), \( W/m^2 \degree C \{i\} \)
\( h_a \) Heat transfer coefficient (saucepan->surrounding air), \( W/m^2 \degree C \{i\} \)

\( T_{\infty}(t) \) Temperature of the hot-plate, \( \degree C \{i\} \)
\( T_a(t) \) Temperature in surrounding air, \( \degree C \{i\} \)
\( r \) Radius of saucepan/hot-plate, m \{i\}
\( A \) Area of hot-plate, \( m^2 \{i\} \)
\( z_c \) \hspace{1cm} \text{Height of water and product in the saucepan, m}

**Food product (in the form of a sphere)**

- \( r_{pp} \) \hspace{1cm} \text{Radius, m \{i\}}
- \( r_p \) \hspace{1cm} \text{Radial coordinate, m, } 0 \leq r_p \leq r_{pp}
- \( T_p(t, r_p) \) \hspace{1cm} \text{Temperature in radial coordinate } r_p \text{ at time } t, ^\circ \text{C}
- \( \rho_p \) \hspace{1cm} \text{Density, kg/m}^3 \{i\}
- \( \lambda_p \) \hspace{1cm} \text{Thermal conductivity, W/m \degree \text{C} \{i\}}
- \( \alpha_p \) \hspace{1cm} \text{Thermal diffusivity, m}^2/\text{s}
- \( c_{pp} \) \hspace{1cm} \text{Specific heat, J/kg \degree \text{C} \{i\}}
- \( n_p \) \hspace{1cm} \text{Number of spheres \{i\}}
- \( m_p \) \hspace{1cm} \text{Weight of one sphere, kg \{i\}}
- \( A_p \) \hspace{1cm} \text{Area of one sphere, m}^2 \{i\}
- \( V_p \) \hspace{1cm} \text{Volume of one sphere, m}^3 \{i\}

**Water**

- \( T_w(t) \) \hspace{1cm} \text{Temperature at time } t, ^\circ \text{C}
- \( \rho_w \) \hspace{1cm} \text{Density, kg/m}^3 \{i\}
- \( c_{pw} \) \hspace{1cm} \text{Specific heat, J/kg \degree \text{C} \{i\}}
- \( V_w \) \hspace{1cm} \text{Volume, m}^3

**Model description**

The saucepan is considered to be a standing cylinder placed on a heating medium (in the form of a circular plate), with a content of water and possibly food products in the form of spheres. In the model of the cooking process, a sphere is assumed to be surrounded by water in a certain volume proportion. If the volume of the water is \( V_w \), the volume in proportion that surrounds the sphere is defined to be \( V_p = \frac{V_w}{n_p} \), where \( n_p \) stands for the number of spheres.

If \( n_p \) is known the radius \( r_{pp} \) of a sphere easily could be calculated when \( V_p \) is known, that is:

\[
r_{pp} = \sqrt[3]{\frac{3V_w}{4\pi n_p}} \text{ by use of the formula } V_p = \frac{4\pi}{3} r_p^3.
\]

For modelling of the heat loss from the saucepan, we assume that the saucepan is an ideal cylinder with radius \( r \).

The energy losses are the sum of the loss from the upper surface in the saucepan (with area \( A = \pi r^2 \)) and the loss from the vertical cylinder (with area \( A_{sat} = 2\pi z_c \)). The height of the water level in the saucepan \( z_c \) is defined by:

\[
z_c = \frac{V_{tot}}{A} \text{ where } V_{tot} = V_w + n_p V_p.
\]

**Energy balance (\( Q_s \) in W)**

Heat transfer from the hot-plate to the product by convection (Holman (1)):

(1) \( Q_s = h_i A(T_s(t) - T_w(t)) \).

Accumulated heat in the water (Holman (1)):
(2) \[ Q_{aw} = \rho_w c_{pw} V_w \frac{dT_w(t)}{dt}. \]

Heat transfer from the water to the product by convection (Holman(1)):

(3) \[ Q_p = h_{wp} A_p (T_w(t) - T_p(t, r_{pp})). \]

Heat transfer in the product by conduction and convection at the surface, is defined by the heat conduction equation (Incropera (2)):

(3.1) \[ \frac{\partial T_p(t,r_p)}{\partial t} = \alpha_p \left( \frac{\partial^2 T_p(t,r_p)}{\partial r_p^2} + \frac{2}{r_p} \frac{\partial T_p(t,r_p)}{\partial r_p} \right), 0 \leq r_p \leq r_{pp}, t \geq 0, \]

\[ \lambda_p \left[ \frac{\partial T_p(t,r_p)}{\partial r_p} \right]_{r_p=r_{pp}} = h_{wp} (T_w(t) - T_p(t, r_{pp})), \]

\[ T_p(0, r_p) = T_{tp}. \]

The thermal diffusivity \( \alpha_p \), m\(^2\)/s, is defined by: \( \alpha_p = \frac{\lambda_p}{c_{pp} \rho_p} \).

Heat transfer from the saucepan and water surface to the air by convection:

(4) \[ Q_{loss} = h_A A_L (T_w(t) - T_a(t)) \text{ where } A_1 = A_{lat} + A. \]

The following energy balance is valid:

(5) \[ Q_s = Q_{aw} + Q_p + Q_{loss}. \]

Using (1), (2), (3) and (4) in (5) gives:

(6) \[ \frac{dT_w(t)}{dt} = g_{12} (T_w(t) - T_w(t)) - g_{42} (T_w(t) - T_p(t, r_{pp})) - g_{32} (T_w(t) - T_a(t)) \]

where \( g_{12} = \frac{f_1}{f_2} \), \( g_{32} = \frac{f_3}{f_2} \) with \( g_{42} = \frac{f_4}{f_2} \) and

\[ f_1 = h_A A, \quad f_2 = \rho_w c_{pw} V_w, \quad f_3 = h_A A \text{ och } f_4 = h_{wp} A_p. \]

Rearrangement of (6) gives
The ordinary differential equation (7) is solved numerically with the “Euler forward” method (Råde(3)), where \( t_k = kh \) , \( k = 1,2,... \) denotes the discrete time points and \( h = t_{k+1} - t_k \) the time step.

By use of the “Euler forward” method the discrete version of equation (7) will be:

\[
\frac{T_{w,k+1} - T_{w,k}}{h} = -uT_{w,k} + v^k , \quad k = 1,2,3,...
\]

\[
T_{w,1} = T_{w,0} \text{ (known at start)} , \quad \text{or equivalent}
\]

\[
T_{w,k+1} = T_{w,k} + h( -uT_{w,k} + v^k ) , \quad k = 1,2,3,...
\]

\[
T_{w,1} = T_{w,0} \text{ (known at start)} .
\]

The notation \( X_k \) means the value of \( X \) at time point \( t_k \).

In analogy; the temperature calculation in the product takes form by use of the “Euler backward” method (Råde(3)) for the heat conduction equation (3.1). Especially is the surface temperature \( T_p(t,r_p) \) obtained and substituted into equation (7) and (9).

**Energy calculations**

By use of the formula (Holman(1)):

\[
E_k \approx \rho c_p V dT_k ,
\]

the accumulated energy during cooking can be calculated both for the water and the load. Index \( k \) stands for the time \( t_k \) and \( dT_k = T_k - T_{k-1} \) for the temperature difference in the interval \([t_{k-1},t_k]\).

Hence, the accumulated energy is given by

\[
E_{k,ack} = E_{k,ack} + E_k , \quad k = 1,2,...,K , \quad \text{where index K stands for the cooking time } t_{end} ,
\]

or transformed to the unit Wh /kg:

\[
E_{cum, Wh/kg} = \frac{E_{k,ack}}{m} 10^{-3} = \frac{E_{k,ack}}{3.6} .
\]

To calculate the energy loss from the saucepan and water surface equation (4) is used, hence:

\[
E_{k,ack,loss} = E_{k,ack,loss} + h_1 Q_{loss} , \quad k = 1,2,...,K ,
\]
or transformed to the unit Wh:

\[ E_{k,ack,loss,Wh} = E_{k,ack,loss} \frac{10^{-3}}{3.6}, \quad k = 1, 2, \ldots, K. \]

**Simulations**

The following calculations can be performed with the mathematical model:

- elapsed time/temperature profile in the water and food
- accumulated energy

Input parameters (variables) to the simulation are:

- temperature of hot-plate
- saucepan size
- amount of water
- product quantity
- size of the product
- boiling time
- thermal properties
- heat transfer coefficients
- cooking technique (lid or not during warming)

**Examples**

The upper part of figure 2 shows the result for simulation of potato cooking for different radius (r). The lower part displays the accumulated energy in the unit Wh/kg.

![Figure 2. Simulation of potato cooking](image-url)
The figure below displays the result for heating 1.3 litre of water without a lid.

![Graphs showing temperature, energy loss, and energy accumulation over time.]

**Figure 3.** Simulation of water boiling

**References**

