Abstract

It is generally accepted that the limit of intermittent energy resources like wind energy and photovoltaics in an electricity system cannot exceed 20% to 25% substantially. Reasons given for that are stability reasons and that electricity cannot be stored in large quantities.

The paper discusses a decoupling of electricity generation and electricity consumption not only by electricity storage but also by demand response measures. The paper concentrates on the perspectives and potentials of demand response activities for Germany. More detailed the following technologies are taken into account: storage heating systems and electrical water heating systems, ventilation and air-conditioning systems, circulation pumps and cold storage. Further more, changed user behaviour and integration of heat storage systems together with CHP and heat pump units are discussed.

Problem Description

In countries with ambitious targets concerning the integration of renewable energies into their supplies the limits of integration are on the agenda of every scientific and political discussion. Apart from the finiteness of fossil and nuclear energy sources and environmental necessities the substantial integration of renewable energies targets the interests of energy industry that has been grown for more than a century. It is generally accepted that the limit of intermittent energy resources like wind energy and photovoltaics in an electricity system cannot exceed 20% to 25% substantially. That is argued by stability reasons of integrated electricity networks and by the nature of electricity that cannot be stored in quantities needed in our today’s energy systems.

But decoupling of electricity generation and electricity consumption cannot only be done by electricity storage! Finally, electricity is converted into many different energy services. And those energy services convert electrical energy into other forms of energy – quite often into thermal energy – and those forms can much better be stored than the formerly electricity.

In this paper the results of investigations are presented that studied the potential of those demand response activities for Germany. The three levels of primary control, secondary control and balancing energy are considered.

More detailed the following technologies are taken into account: storage heating systems and electrical water heating systems, ventilation and air-conditioning systems, circulation pumps and cold storage. Further more, changed user behaviour and integration of heat storage systems together with CHP and heat pump units are discussed.
Storage Heating

Storage heating systems consist of a core that is mostly built of magnesite due to its high specific heat capacity and temperature stability up to 650 °C and a heat insulation surrounding the core [2]. Electricity is used to charge the core unit to high temperatures when electricity is cheap, e.g. during night times. Heat then is stored and discharged during times of peak demand of electricity.

The idea of shifting electricity consumption by means of storage heating is an old one – long before high shares of wind energy and other renewable energy sources had been discussed. In Germany utilities started in the 1960s to distribute night storage heating facilities in order to build up nowadays electricity supply structure. Figure 1 shows the development of the electricity consumption pattern since 1960 [3]. Without this type of demand response Germany’s today electricity generation with high shares of base load power stations like nuclear and coal power stations couldn’t have been realised. In the same way those facilities can be used in order to integrate not base load type power stations but resources of fluctuating nature.

Normal operation of night storage heating systems is to charge them during night time with low demand. The storage heating system is charged until the energy content is about the amount that is forecasted to be used during the next day. In the following night it is recharged again. When using those facilities for e.g. wind integration it can be necessary not only to charge them during night but at high wind loads. And it can be necessary to charge them in a way that they store the capacity for more than the next day when there is a longer lasting calm. Figure 2 shows the maximum possible discharge times of storage heating systems how they are installed today with respect to the ambient temperature [4].

When summarising the potential of positive control power of storage heating systems already existing in Germany one results in the power levels given in figure 3 – up to 14 GW [1, 5]. For negative control power potential is referred to [1].

Those buildings that are heated with electricity most often also have an electrical hot water heating system. The positive control power resulting from those systems add another 750 MW of positive control power. For details is referred to [1].
Figure 2. Maximum discharge times of storage heating systems for standard storage heating systems (upper curve) and flat storage heating systems (lower curve).

Figure 3. Positive control power potential of existing storage heating systems in Germany.
Ventilation Systems

A ventilation system does not by itself represent an electrical storage system. But together with the air inside a room or building the ventilation system can be operated like a storage system.

The storage media is the air and the indicator of the state of charge is the air quality. When air quality is good the storage device is charged. Therefore, the ventilation system can be switched off or can be operated with reduced power until air quality decreases to a preset limit. Then the storage device is discharged and the ventilation system has to be switched on again.

So, a ventilation system can be used to shift electricity demand and that is equivalent to the function of an electricity storage device. Figure 4 shows the principle of ventilation systems acting as storage device. Uncontrolled operated ventilation systems represent the mean power consumption $\bar{P}$ equal to the maximum positive control power $P_{dis}$ when they are switched off. The difference between all ventilation systems operated contemporarily and the mean power consumption $\bar{P}$ represent the maximum negative control power.

![Figure 4. principle of ventilation systems acting as storage device](image)

Taking into account the installed capacity of ventilation systems in Germany [6, 7, 8] the resulting positive control power is illustrated in figure 5. For negative control power potential is referred to [1].

Refrigeration

Similar to ventilation systems all kind of refrigeration device (refrigerators, freezers, etc.) can be considered as an electricity storage device, too. Electricity is converted into thermal energy (cold) and the thermal energy is stored in the refrigeration compartments. That means that compressor operation can be shifted in order to a transition to a flexible electricity demand.
Figure 5. Positive control power potential of ventilation systems

Table 1 and table 2 explain the electricity consumption for refrigeration in Germany [9]. Out of that by far big potential only refrigeration in the food branch are taken into account here and out of the food branch only the part on “distribution” and “households” are taken into consideration because all other processes have been considered as to be too complex and diverse to be integrated into the study.

Table 1. Energy consumption for refrigeration in Germany

<table>
<thead>
<tr>
<th></th>
<th>Energy Consumption [GWh/a]</th>
<th>Primary energy [GWh/a]</th>
<th>Cold energy [GWh/a]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Electr.  Non-el.  Total</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Foodstuff</td>
<td>48.050  3.071   51.121</td>
<td>153.909</td>
<td>108.058</td>
</tr>
<tr>
<td>Industry</td>
<td>6.845   0        6.845</td>
<td>20.795</td>
<td>5.255</td>
</tr>
<tr>
<td>Air-condition</td>
<td>9.705   7.776    17.481</td>
<td>50.349</td>
<td>48.548</td>
</tr>
<tr>
<td>Others</td>
<td>1.579   65        1.644</td>
<td>4.981</td>
<td>3.066</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>66.179</strong></td>
<td><strong>10.912</strong></td>
<td><strong>77.091</strong></td>
</tr>
</tbody>
</table>

Table 2. Energy consumption for refrigeration in foodstuff branch

<table>
<thead>
<tr>
<th></th>
<th>Energy Consumption [GWh/a]</th>
<th>Primary energy [GWh/a]</th>
<th>Cold energy [GWh/a]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Electr.  Non-el.  Total</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Generation</td>
<td>19.616  0       19.616</td>
<td>59.436</td>
<td>54.929</td>
</tr>
<tr>
<td>Transport</td>
<td>0        3.071    3.071</td>
<td>8.316</td>
<td>7.751</td>
</tr>
<tr>
<td>Distribution</td>
<td>9.805   0        9.805</td>
<td>29.708</td>
<td>19.146</td>
</tr>
<tr>
<td>Household</td>
<td>18.630  0       18.630</td>
<td>56.449</td>
<td>26.232</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>48.050</strong></td>
<td><strong>3.071</strong></td>
<td><strong>51.121</strong></td>
</tr>
</tbody>
</table>

In many publications the time span in which a refrigerator is able to store thermal energy is by far overestimated and values are often given to up to 24 hours. A detailed study has shown
that a refrigerator itself is almost not able to store thermal energy because the thermal capacity of a refrigerator is negligible. Only a filled refrigerator can store thermal energy over several hours because the storage capacity belongs to the cooled goods themselves [10]. That does not mean that a refrigerator construction with long storage periods is impossible. Examples show that storage times for several days can be realised with phase change materials [11-15] but that is not the refrigerator type sold in markets with grid connected electricity.

Figures 6, figure 7 and figure 8 show the control power potential of household refrigerator, household freezers and refrigeration in food stores, respectively [1].

![Figure 6](image1.png)

**Figure 6. Control power potential of household refrigerators**

![Figure 7](image2.png)

**Figure 7. Control power potential of household freezers**
Hot Water Heating Systems

At first view it is surprising that hot water heating systems are mentioned here because normally in those systems heat is generated by oil, gas or district heating. Electricity consumption in hot water heating systems comes from the circulation pumps that transport the generated heat from e.g. the gas burner to the radiator in the different rooms.

The storage function is not represented by the heating system itself but in combination with a heat insulated building. When the heating or the electricity consuming circulation pump is switched off the building will keep temperature over a certain time resulting from the heat capacity of the surrounding walls and furniture. Figure 9 shows the room temperature after the heating is switched off with an ambient temperature of 0 °C. The temperature decreases quite fast to the slightly lower wall temperature as the heat capacity of the air can be neglected. Then temperature is kept almost constant over a certain time (up to hours depending on the wall construction and the heat insulation) until it starts to decrease again [16].
In Germany the electricity consumption of circulation pumps is 15 TWh what is equivalent to 3.5% of the total consumption [17]. Again, for circulation pumps the power consumption and time the consumption can be switched off depends on the ambient temperature. Figure 10 describes the positive control power potential of hot water heating systems.

![Figure 10. Positive control power potential of hot water heating systems](image)

Hot water heating systems do not possess a negative control power potential. Either the heating system is in operation then the circulation pump can be switched off for a certain time. Or the heating system is out of operation. Then it would not make sense to switch the pumps on in order to provide negative control power.

**Influencing User Behaviour**

Apart from electricity consumers with intrinsic storage capacity a further transition to a flexible electricity demand can be obtained when users change their pattern of electricity usage.

Users can be encouraged to do so e.g. by dynamic electricity tariffs. Large-scale experiments have shown that at least a certain fraction of the electricity consumption can be shifted by providing users with those kinds of tariffs [18-22].

Another possibility to shift electricity consumption in households is the automation of electricity consumers. Current activities of utilities with so-called advanced metering concepts
that allow remote meter reading, remote connection and disconnection of users [23] and research projects [24] move into that direction.

Figure 11 shows the distribution of household electricity consumption in Germany [25]. Taking into account only typical consumers like dish washers, washing machines and dryers that are suited to be shifted according to dynamic tariffs one results in a shift potential of 15.2 TWh per year. Figure 12 shows the daily electricity consumption for those applications [26]. This is also the theoretical positive control power potential for influenced user behaviour. For negative control power potential is referred to [1].

![Figure 11. Distribution of household electricity consumption in Germany](image)

![Figure 12. Daily electricity consumption profile for dish washers, washing machines and dryers. The profile is equivalent to the theoretical positive control power potential.](image)
Chp And Heat Pumps With Thermal Storage

A further possibility to balance fluctuating renewable energy sources are combined heat and power plants and heat pumps. But only when they are combined with thermal storage devices.

The political framework in Germany results in a combined heat and power plant configuration that demands those power plants to be operated almost continuously to be economic efficient. The showcase of Denmark shows that it is possible to promote other solutions with bigger rated capacities installed and in combination with thermal storage [27]. With that plant configuration principle power plant operation can be planned almost independent from heat demand but with respect to control power needed to balance fluctuating wind energy.

If the Danish plant configuration principle would be applied to German combined heat and power plants a positive control power potential could be accessed that is presented in figure 13. The boundary condition taken into consideration for that figure are that the installed combined heat and power capacity in Germany approximately is 19 GW with an average CHP coefficient of 0.46 [28]. Thermal storage devices with a capacity of 12 hours at the coldest day of year are assumed. For further boundary conditions and negative control power potential is referred to [1].

![Figure 13. Theoretical positive control power potential of German CHP plants](image)

Heat pumps are consuming electrical energy in order to provide heat energy. When heat energy is generated during off-peak times and stored the heat pumps can be switched off in order to provide positive control power. Taking into account the installed capacity in Germany [29-32] a positive control power potential could be accessed like shown in figure 14.

**Summary And Conclusions**

Future electricity supply systems with high penetration of renewable energy sources as wind energy and photovoltaics and efficient energy sources as combined heat and power systems are characterised by an increased need for energy storage. That results out of the fluctuating nature of wind and solar energy and the simultaneous production of heat and electricity with combined heat and power systems. When the fluctuating supply has to be adapted to the electricity demand an increased storage need can be derived from that.
Electrical energy storage is a very cost intensive matter. E.g. the cost of thermal energy storage is by magnitudes smaller. Therefore, thermal energy storage has to be preferred to electricity storage whenever a shift of the electrical load can be achieved by thermal energy storage. Those non-electrical energy storage devices have been investigated with emphasis on a transition to a flexible electricity demand (demand response) with the aim to adapt electricity generation and electricity consumption. Those possibilities can be divided into three categories:

1. Transition to a flexible electricity demand by loads with intrinsic storage capacities. The big advantage of this kind of demand response is on the one hand that one doesn’t have to invest in storage capacity – it is already part of the electricity consumer. And on the other hand by this kind of demand response the user is not affected at all. The energy service is always to his/her disposal. To this category belong:
   - Storage heating systems
   - Electrical warm water heating systems
   - Ventilation systems
   - Refrigeration
   - Circulation pumps in hot water heating systems

2. Transition to a flexible electricity demand by changing user behaviour. Unlike to category one here the user is affected in his/her daily life.

3. Transition to a flexible electricity demand by loads (and generation, respectively) that convert electricity into another kind of effective energy. This energy then is stored in order to achieve the desired transition to a flexible electricity demand. To this category belong:
   - Combination of heat pumps with thermal energy storage
   - Combination of combined heat and power systems with thermal energy storage
   - Refrigeration with cold/ice storage

It has to be mentioned that not all possibilities of demand response with non-electrical energy storage devices have been taken in to account. Among them are all electrical water heaters that do not have thermal energy storage in the range of one day. Because of the diversity of
refrigeration the complete branch of industry refrigeration, air-conditioning and in food industry the branch of food generation has not considered. Even not all of the refrigeration potential contains intrinsic energy storage but at least with the help of cold/ice storage this potential could be opened up. That would be equivalent to 4.3 GW of continuous power.

Another completely unconsidered branch is industrial process heat that comprises 65.9 % of industrial energy consumption. Among that 12.8 % is covered electrically what is equivalent to 54 TWh [33] or 6.2 GW of continuous power. A further not considered potential are indoor and outdoor swimming pools that are normally heated in Germany. The pools represent by themselves thermal energy storage. When heating is done by combined heat and power or by heat pumps they can used for a transition to a flexible electricity demand.

In figure 15 the summarised potential for positive control power is presented. The figure is cut off after 72 hours as the available power is getting very small afterwards. In figures 16 and 17 the storage capacity is given in dependence of the outdoor temperature. Again, after 72 hours the figures are cut off.

The summary of the single results shows that the different considered technologies complement each other very good. That means that for both the maximum available power and the available time there are no significant seasonal (from outdoor temperature depending) differences. The biggest fraction of available control power derive from storage heating systems and combined heat and power systems. These two categories possess characteristics in the opposite direction with regard to their dependence on outdoor temperature. Thereby the available control power is close to be constant all over the year.
Figure 16. Storage capacities of different demand response categories (capacities are taken into account until hour 72)

![Graph showing storage capacities of different demand response categories.]

Figure 17. Storage capacities given as share of the total capacity in dependence on ambient temperature

If one would neglect that fraction resulting from the combination of combined heat and power systems and heat storage devices or from heat pumps and heat storage devices the result would be a completely different one. That means if one would disclaim on a system configuration according the Danish example the available control power would strongly depend on outdoor temperatures. With low ambient temperatures the available control power...
would be high and with higher ambient temperatures the control power would decrease significantly. The potential then is clearly dominated by the storage heating facilities.

The results would be inversely when one disclaims the use of storage heating and hot water heating systems with thermal storage. Now the combination of combined heat and power systems with thermal storages dominate the pattern. That would result in a high available control power at times with high ambient temperatures and lower powers at cold ambient temperatures.

If only those technologies are considered with intrinsic thermal storage – all kind of refrigeration, hot water heating, ventilation systems and the potential coming from adapted user behaviour the results are completely different. On the first view the results are disappointing. There are no nameable available control powers that last for longer than 24 hours and those that have a longer duration result from the changed user behaviour by an automated operation of dish washers, washing machines and dryers. But nevertheless available control power during those times is high:

The complete demand on primary and secondary control power could be covered by demand response with electrical consumers with intrinsic storage capacities!

Even in minute reserve power this category could be involved. With that an increase of efficiency of conventional power stations could be obtained as they don’t have to keep reserves for control power purposes and could operate with nominal capacity.

In any case the argument that an installed wind power capacity of 48 GW in Germany can not be integrated into the electricity network because of missing control power that is hold out by conventional power plants:

There is no theoretical upper limit for the integration of renewable energies into electricity networks!

Apart from providing control power demand response measures could contribute to a significant reduction of the annual peak power consumption. Again conventional power station capacity could be saved. Figure 18 shows the electricity consumption of the week with annual peak demand. The fraction of storage heating is already marked. The mean consumption is approximately 65 GW. During 13 hours electricity consumption is above average. To shift electricity consumption above average into periods where it is below the average consumption 78.7 GWh have to be shifted:

With intrinsic storage capacities in electricity consumers peak consumption completely could be shifted into off-peak times!

But the result also shows that longer periods with less wind or with much wind cannot only be balanced with by demand response activities that use the intrinsic storage capacity of electrical consumers:

A longer lasting balance of fluctuating renewable energies can only be realised by additional heat and cold storage devices!
Figure 18. Electricity consumption of the week with annual peak demand

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