Technische Universität München
Lehrstuhl für Bauklimatik und Haustechnik

Niko Heeren

Ecological potentials of load management in buildings

M.Sc. thesis, September 2011

Niko Heeren

niko.heeren@me.com

Table of Contents

Abbreviations & Definitions

Term	Description
CCS	Carbon Capture and Storage – '*Process of capturing carbon dioxide (CO_2) from large point sources, such as fossil fuel power plants, and storing it in such a way that it does not enter the atmosphere'* *
CHP	Combined Heat and Power – Cogeneration power plants, producing thermal and electrical energy simultaneously
CO	Cooking (as in Table 7)
CO_2	Carbon dioxide
CO_2-eq.	Carbon dioxide equivalent emissions. A measure to describe climate forcing effect of greenhouse gases. E.g., 1kg of nitrous oxide emissions has 298 times the climate forcing effect of 1kg CO_2 [*Forster et al. 2007*]
CP	Circulation pump (as in Table 7)
Curtailment	The process of throttling / powering down a power plant in order to avoid electricity network overload.
DHW	Domestic hot water (as in Table 7)
DSM	Demand Side Management – '*Modification of consumer demand for energy*'*. The term mostly refers to control of electrical appliances in order to shift electricity demand.
DW	Dish washer (as in Table 7)
EE	Energy Efficiency
EEX	European Energy eXchange – '*Operating market platforms for trading in electric energy, natural gas, CO_2 emission allowances and coal in Europe'* *
EH	Space heating (as in Table 7)
FR	Freezer (as in Table 7)
GHG	Greenhouse Gas
GW	GigaWatt (10^9 Watts)
HH	Household
Hz	Hertz – Unit of frequency
MW	MegaWatt (10^6 Watts)

NRE	Non-Renewable Energy – Energy from sources that cannot be replenished within a useful timeframe.
PV	PhotoVoltaics – Solar collectors that produce electrical energy
RE	Renewable Energy – Energy from renewable sources, such as sun, wind, geothermal energy and precipitation. According to the official energy balances (*BMWi 2011*) energy from waste is considered a renewable energy here.
Renewables	Abbreviation for Renewable Energies
RF	Refrigerator (as in Table 7)
Smart Grid	Intelligent network transporting electrical energy and information. The goal is to '*predict and intelligently respond to the behaviour and actions of all electric power users and providers connected to it*' *
Smart Home	Residential building that is capable to exchange information with energy providers
TD	Tumble dryer (as in Table 7)
TSO	Transmission System Operator
TW	TeraWatt (10^{12} Watts)
UCTE	Union for the Co-ordination of Transmission of Electricity
VPP	Virtual Power Plant – Power plants that can be controlled collectively in order to support the electricity network
W	Watt. A unit of power. 1 Joules per second.
Wh	Watt hour. A unit of energy. 3'600 Joules.
WM	Washing machine (as in Table 7)
η	Efficiency (Greek: Eta) – Describing the efficiency of energy conversion or storage processes

* Source: Wikipedia

Acknowledgements

This work would not have been possible without the support of my family. I thank my wife and my son for their patience and inspiration during this difficult time. Furthermore, I would like to thank the following persons:

Prof. Hausladen for encouraging me to realize this work.

Timm Rössel for providing valuable input as tutor

ClimaDesign team for their caring support

My employer for giving me the opportunity to follow the ClimaDesign programme

Flourentzos for his inspiring views and discussions

Summary

This work investigates the ecological potentials of load management in buildings. Per square meter approximately three times the thermal energy is irradiated, than it is consumed by an average German building per year. The aim of this work is to investigate possibilities to approach annual energy supply and demand. The first section identifies the environmental potentials of load management. It shows that it fosters utilization of Renewable Energies. Furthermore, the demand in operating reserve for electricity can be reduced. That is important since it can cause considerable environmental impacts.

The second section explores the different possibilities of load management in buildings. The current regime of electricity generation in Germany conflicts with the power generation from Renewable Energies. Thus, a possible pathway of electricity network transformation is presented. New technologies suggest that in the future new possibilities of load management will emerge. For instance, seasonal shift of thermal energy can be realised by means of exergy storage and heat generation by means of heat pumps. Another example is solar-thermal power plants that are able to provide daylong electricity from solar energy.

The third part of this work presents a model for the evaluation of electricity storage and Demand Side Management (DSM) of appliances. By means of the model it is illustrated, that direct ecological potential of load management is limited. Measures, such as energy efficiency and fuel switch for thermal energy production appear far more effective, in terms of abatement of greenhouse gas emissions.

Nonetheless, the concept of load management allows valuable possibilities to transform electricity networks in the future. DSM and energy storage are also a means to provide operating reserve. The magnitude that could be supplied by these measures exceeds the average operating reserve that is currently held by German network operators. Electricity from Renewable Energies conflicts with the baseload in the electricity network. The electricity network of the future should be able to make use of mostly Renewable Energies. Load management will be an important technique to establish such a network.

Zusammenfassung

Die vorliegende Arbeit befasst sich mit den ökologischen Potentialen von Lastmanagement in Gebäuden. Ausgehend von der Überlegung, dass, bezogen auf einen Quadratmeter knapp dreimal so viel thermische Energie eingestrahlt wird, als Gebäude im Schnitt pro Jahr benötigen, werden Möglichkeiten der Verschiebung von Energieangebot und –nachfrage untersucht. Im ersten Teil der Arbeit wird untersucht, welche ökologischen Vorteile aus einer solchen Verschiebung resultieren können. Hier ist zunächst die bessere Ausnutzung des Angebots von Erneuerbaren Energien zu nennen. Weiterhin ist es möglich den Bedarf an elektrischer Regelenergie zu reduzieren, da diese teilweise zu hohen Umweltbelastungen führt.

Im zweiten Teil der Arbeit werden verschiedene Möglichkeiten des Lastmanagements auf der Ebene von Gebäuden vorgestellt. Da die aktuelle Zusammensetzung der Energieträger, welche die elektrische Energie in Deutschland bereitstellen, relativ unflexibel ist und wenig Spielraum für den Zubau von Erneuerbaren Energien liefert, wird ein mögliches Szenario der Netzumgestaltung vorgestellt. Neuartige Ansätze, wie die saisonale Speicherung von Exergie, für die Bereitstellung von Heizenergie oder solarthermische Kraftwerke, welche 24 Stunden am Tag Elektrizität erzeugen können, zeigen, daß sich in Zukunft neue Möglichkeiten des Lastmanagements bieten werden.

Der dritte Teil der Arbeit stellt ein Modell zur Beurteilung verschiedener Szenarien des Lastmanagements vor. Anhand dieses Modells, werden das verbraucherseitige Lastmanagement (DSM) und elektrische Speichersysteme für den Wohngebäudepark Deutschland untersucht. Es zeigt sich, daß der direkte ökologische Nutzen von Lastmanagement relativ gering ist. Maßnahmen, wie Energieeffizienz oder der vermehrte Einsatz von Erneuerbaren Energien, haben einen weitaus größeren Hebel zur Reduzierung der jährlichen Treibhausgasemissionen.

Dennoch ist Lastmanagement eine wertvolle Möglichkeit das Elektrizitätsnetz in Zukunft grundlegend umzugestalten. Die Regelleistung welche durch DSM und Speicherung theoretisch bereitgestellt werden könnte, übersteigt die aktuell in Deutschland vorgehaltene Regelleistung. Aktuell stehen Erneuerbare Energien und die Bereitstellung von Grundlast im unmittelbaren Widerspruch. Ziels sollte die Etablierung eines Elektrizitätsnetzes, welches mehrheitlich aus Erneuerbaren Energien gespeist wird, sein. Dabei wird Lastmanagement eine wichtige Rolle spielen.

Structure & Objective

This work is divided into three sections:

I. Ecological benefits of load management

The objective of this chapter is to investigate the '*why'*. That means surveying the potential ecological benefits of Smart Grids, respectively Load management.

II. Possibilities and potential of load management

This chapter deals with the question *how* energy supply and demand can be theoretically and practically aligned by means of active and passive measures.

III. Expected outcome for the building stock

The findings of the previous chapters are transferred to a larger scale, e.g. building stock of Germany in order to identify the overall potential.

The findings of this work shall provide an indication for building owners and politics whether and to what extent load management in buildings is ecologically beneficial. Therefore, an estimate of the potential thermal and electrical energy sink capacity of buildings is determined.

Germany is used as case study, since it has distinct day/night and summer/winter variations, a high share of Renewable Energies (RE), and good data availability.

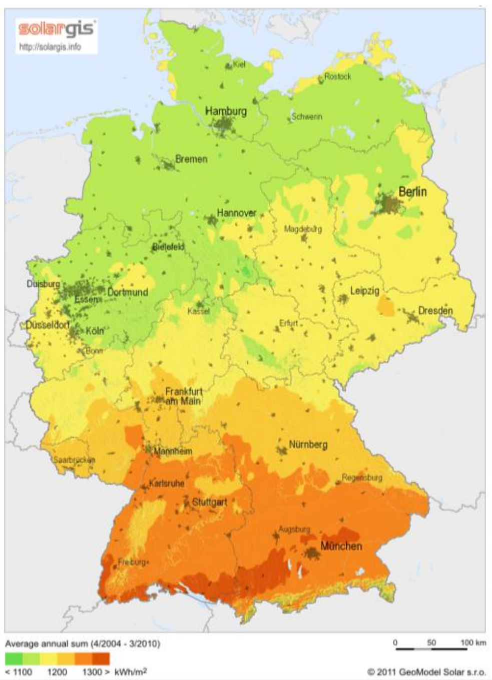
I. BENEFITS OF LOAD MANAGEMENT

The first section of this work looks into the ecological benefits of load management in buildings. Certain strategies of load management or demand side management (DSM) are well known and also applied for many years. For instance most energy providers offer on and off-peak prices, in order to provide consumers incentives for ‘valley filling’ (cf. Table 3, *Clark and Gellings 2009* respectively). In the past, these strategies were mostly applied for economic or process-related reasons. However, with the increasing share of Renewable Energies (RE) in the network and the German ban on nuclear energy, the question arises if load management can also be beneficial in an environmental sense.

I-1. Supply & demand gap

When talking about ‘sustainable’ or environmentally friendly buildings today, it is usually referred to energy-efficient buildings, which consume little energy or emit small amounts of greenhouse gases (GHG). Moderate climates typically have more energy per square meter available than it is consumed. However this potential is hardly ever fully utilised.

For a typical German site, the global irradiation constant is around 1200 kWh/m^{2}a. Even a low efficiency hybrid solar energy converter[1], with efficiencies of $\eta_{thermal}$=0.50 and $\eta_{electric}$=0.10, would supply 600 kWh$_{th}$ and 120 kWh$_{el}$ per year and square meter. An average building in Germany consumed in 2009 ca. 190 kWh$_{th}$/m^{2}a and 31 kWh$_{el}$/m^{2}a (*BMWi 2011, Enerdata 2011*).



	Thermal energy kWh$_{thermal}$/(m^{2}a)	Electric energy kWh$_{electric}$/(m^{2}a)
Solar global irradiation	1200	
Conversion factor	0.50	0.10
Final energy supply	600	120
Useful energy supply	540	120
Average HH demand	182	31
Ratio demand / supply	*3.0*	*3.9*
Efficient building HH demand	25	30
Ratio demand / supply	*21.6*	*4.0*

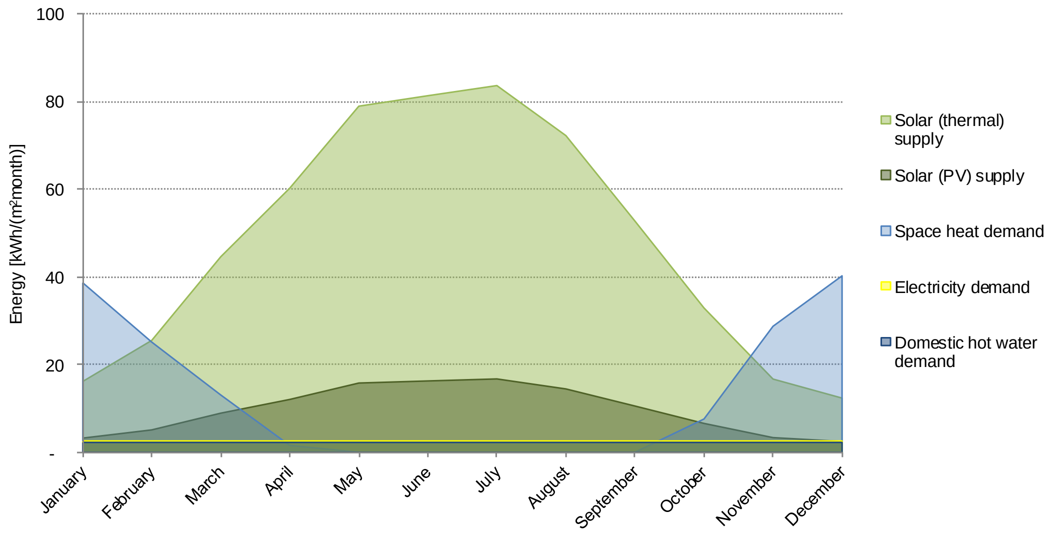
Figure 1 Annual global irradiation map for Germany (left) and typical demand / supply ratios for a German site[2]

That means, in case of ideal energy storage, a three-storey building could be provided with on-site energy throughout a year. Respectively, a two-storey building would require a storage system with an <u>annual</u> efficiency of $\eta_{thermal}$ = 0.67, $\eta_{electric}$ = 0.52 respectively.

[1] Hybrid solar converter produces electrical, as well as thermal energy from solar irradiation.

[2] Image source: *http://solargis.info/doc/_pics/freemaps/1000px/ghi/SolarGIS-Solar-map-Germany-en.png* (Access date 25. Aug. 2011); Source household demand: *BMWi 2011, Enerdata 2011* (Data for Germany, 2008)

Energy efficient buildings, e.g. passive houses, consume around 25 kWh_{th}/m^2a (including domestic hot water) and approximately 30 kWh_{el}/m^2a. That means a three-storey building would require storage efficiency of $\eta_{thermal}$=0.14, $\eta_{electric}$=0.75 respectively.



Coverage	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Thermal	39%	93%	291%	1580%	3507%	3613%	3715%	3208%	2342%	335%	54%	29%
Electrical	63%	99%	174%	234%	307%	316%	325%	281%	205%	128%	65%	48%

Figure 2 Monthly residential energy demand & solar energy supply per square meter (graph) and monthly coverage (table) [*Meteotest 2010*, *BMWi 2011*]

This simplified example[3] illustrates clean renewable energy is abundant for buildings – if considering an entire year. However the earth's rotation causes an important fluctuation in renewable energy supply on a daily (day/night) and annual (summer/winter) basis. In Figure 2, the example above is depicted on a monthly basis. For simplicity, it is assumed that domestic hot water demand (2.3 $kWh/(m^2month)$) and electricity demand (2.6 $kWh/(m^2month)$) remain constant throughout the year. Supply in solar thermal energy does not cover demand in wintertime. Only 30-40% of thermal, respectively 50-60% of electrical energy, are available from solar sources. Electricity demand is approximately equal to supply in wintertime.

Vice versa solar energy supply is highest in summertime, while thermal energy demand for space heat becomes zero. Thus, a massive solar energy supply excess is the consequence (factor 30, cf. Figure 2). Annually $^2/_3$ of the thermal supply and $^3/_4$ of electrical respectively, remains unused and is therefore lost.

I-2. Electricity from Renewable Energies

The previous section illustrates the ratio of energy supply and demand of buildings by considering a unit square meter. However, especially in cities, it is often difficult to provide equal amounts of collector and habitable surface on-site.

Electricity (being basically a transport medium) represents an interesting option to access further potentials of renewable energies – also off-site the building area. Hence, electricity will play an increasingly important role in the future. Electricity demand is increasing, due to

[3] Although global irradiation is considered in this example horizontal, it should be mentioned, that solar collectors usually cannot be realized on the entire roof surface. Especially inclined collectors need to respect certain spacing due to self-shading and fixation. In practice approximately 40% of the roof surface can be exploited (e.g. *Gutschner and Nowak 1998*, *IEA 2002*).

an increase in the number of appliances in households (*Eurostat 2011, Hofer 2007*). Currently households obtain approximately 20% of final energy by means of electricity [*BMWi 2011*].

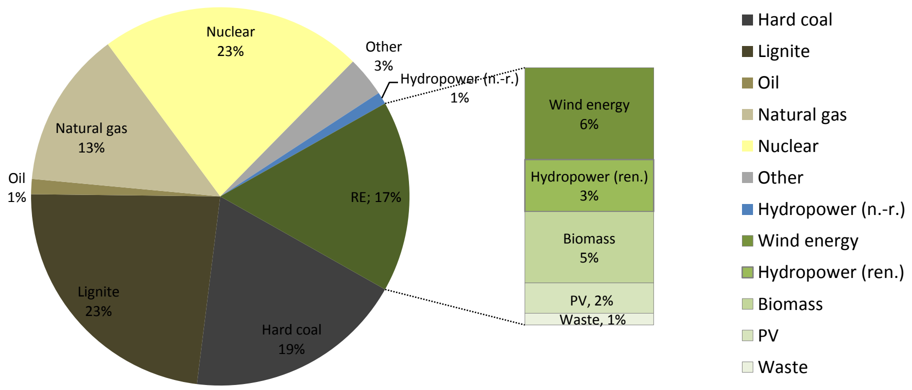


Figure 3 Electricity mix in Germany in 2010 [*BMWi 2011*]

The amount of Renewable Energies in the German electricity mix increased considerably over the last years. In 2010 its share was approximately 17% [*BEE 2011*].

Electricity is necessary to operate heat pumps. This technology allows humankind direct access to another renewable energy source: anergy[4]. That means heat pumps have the ability to convert ambient heat energy to useful heat energy for space heat or domestic hot water. Most building stock models assume that heat pumps will become one of the most important energy source for buildings in the future (*Hofer 2007, Wallbaum et al. 2010, WWF 2009*). The German Association for Heat Pumps (BWP) assumes that until 2025 heat pumps will have a market share of 20% to 40%, according to the respective scenario [*BWP 2009*].

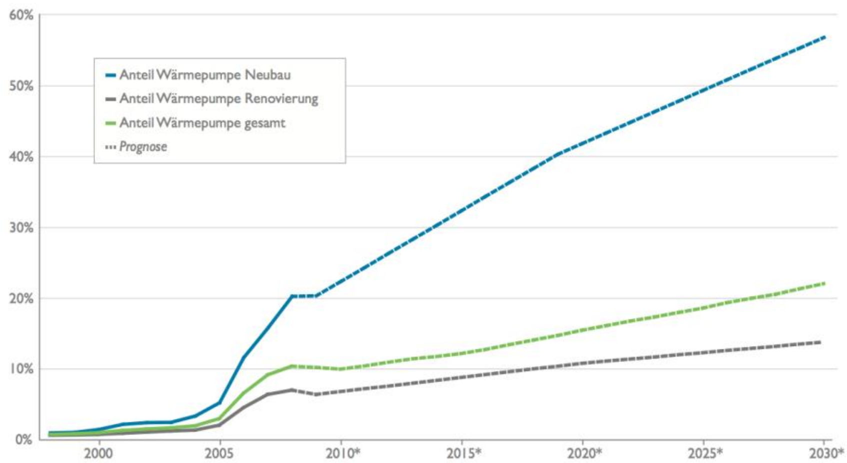


Figure 4 Heat pump diffusion until 2030. Source: *BWP 2009*, Scenario I – constant sales

I-2.1. Annual supply

The example in section I-1 above takes Renewable Energy from solar irradiation on a monthly basis into account. It shows during winter solar collectors supply only very limited energy. As seen in Figure 3 above, solar energy provides only a fraction of total electricity from renewables. Wind energy, biomass and hydroelectricity play a considerable role in German electricity mix.

[4] Anergy is a form of energy that is free from exergy. That means it has no potential to do work or cause change to a system. Cf.: *http://en.wikipedia.org/wiki/Exergy*

Since 2009 the German law on Renewable Energies (EEG) obliges German electricity grid operators to publish data on any installation providing renewable energies. Additionally they must make daily load profiles and predictions public. This data was used to analyse annual renewable energy supply use it as model input in section III. The data available from the grid operators[5] contains several errors and seems to lack consistency. However, the general load profiles seem valid and after some minor corrections prove helpful for the purpose of this analysis. Furthermore data from grid operators may already contain operator controlled throttling / curtailment due to grid overload situations. Therefore, it does not necessarily represent the full renewable energy capacity of the year 2010.

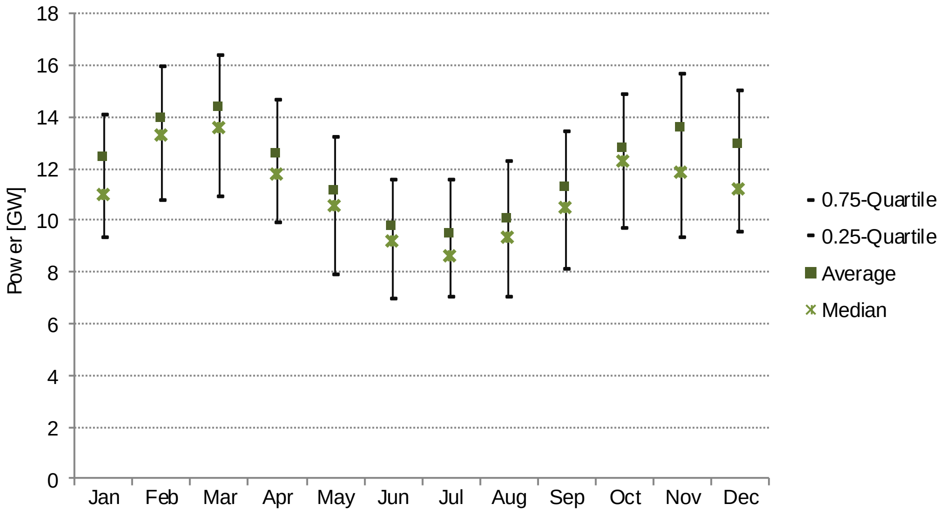


Figure 5 Monthly supply of electricity from Renewable Energies in Germany. Data: *ENTSO-E 2011*

In 2010 approximately 105 TWh of Renewable Energy, with an average power of 12 GW were produced. Figure 5 illustrates the monthly average in RE supply, along with median, lower and upper quartile. The annual standard deviation for RE is 4.3 GW, with wind energy having the largest uncertainty of 3.7 GW. PV has a standard deviation of 2.2 GW.

Figure 6 illustrates the monthly average composition for each energy carrier. According to annual solar path in Germany, electricity from photovoltaics is maximal around July and becomes almost negligible in wintertime (cf. also Figure 2). For meteorological reasons, wind energy supply shows two important trends. On the one hand exists an annual trend, which is almost inverse to solar electricity. Maximal feed-in of almost 6 GW takes place in March and November. During summertime, wind energy supply reduces significantly to 2 GW in July.

No reliable data for electricity supply from biomass is available [*Klobasa et al. 2009, p. 12*]. Therefore a load profile based on *IWES 2009, Fig. 3-5* was used. *IWES 2009* assumes that most biomass power plants consist of thermal systems and they are therefore temperature-controlled. Thus, electricity supply is maximal in the coldest season, whilst during summer approximately 6% of load is provided. Due to a lack of appropriate data, hydroelectricity is assumed being constant throughout the year. Data was partly corrected to fit to energy statistics [*BEE 2011, BMWi 2011*].

[5] Data was extracted from the websites of German transmission system operators (TSOs): 50Hertz Transmission GmbH, Amprion GmbH, EnBW Transportnetze AG, and TenneT TSO GmbH

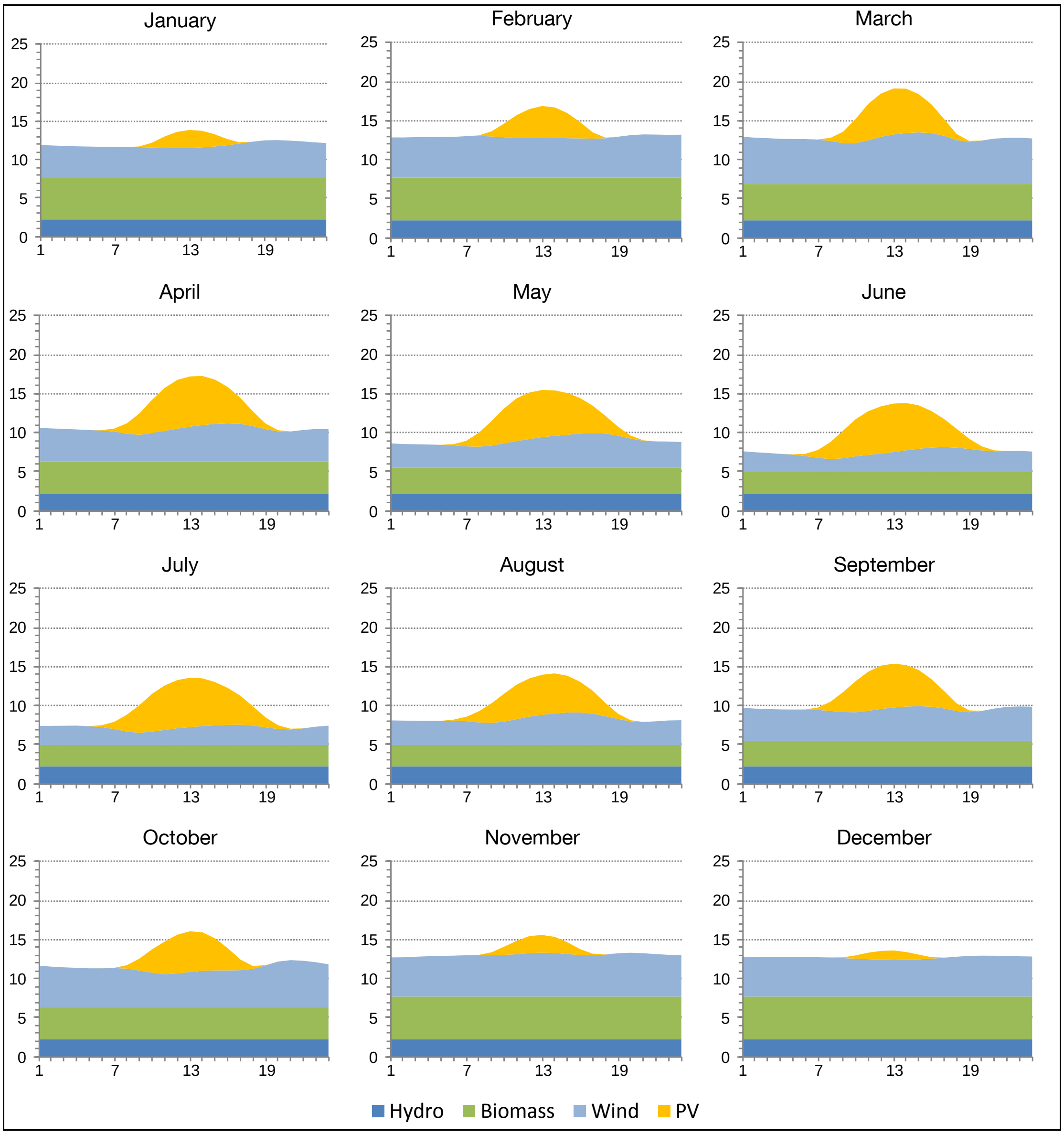


Figure 6 Electricity from Renewable Energy fed to the German grid during an average day from January to December 2010. X-axis: time of day [h]; Y-axis: Power [GW].

On an annual basis RE-electricity corresponds to 76% of household electricity demand [*BMWi 2011*]. Figure 7 illustrates the ratio of electricity from Renewable Energies and typical household demand.[6] That means a figure of 100% would correspond to a month in which the same amount of Renewable Energy was produced, as households consumed in the same period. In wintertime, practically 100% of household electricity demand is covered by renewables. But also volatility of Renewable Energies is highest in wintertime. Standard deviation rises to up to 77% in December. Although electricity from photovoltaics (PV) becomes most important during summertime, the overall ratio of household demand and Renewable Energy supply decreases to approximately 70%.

Households are responsible for 23% of total electricity consumption in Germany [*BMWi 2011*]. The trends in Figure 7 correlate to the ratio of total electricity demand, as provided by *ENTSO-E 2011*, compared to RE supply. That shows the BDEW H0 profile is a good measure for describing household electricity demand.

[6] No factual household electricity demand data is available. Therefore, the BDEW H0 standard load profiles (with differentiation for season and weekday) were used (cf. also section III-1.1).

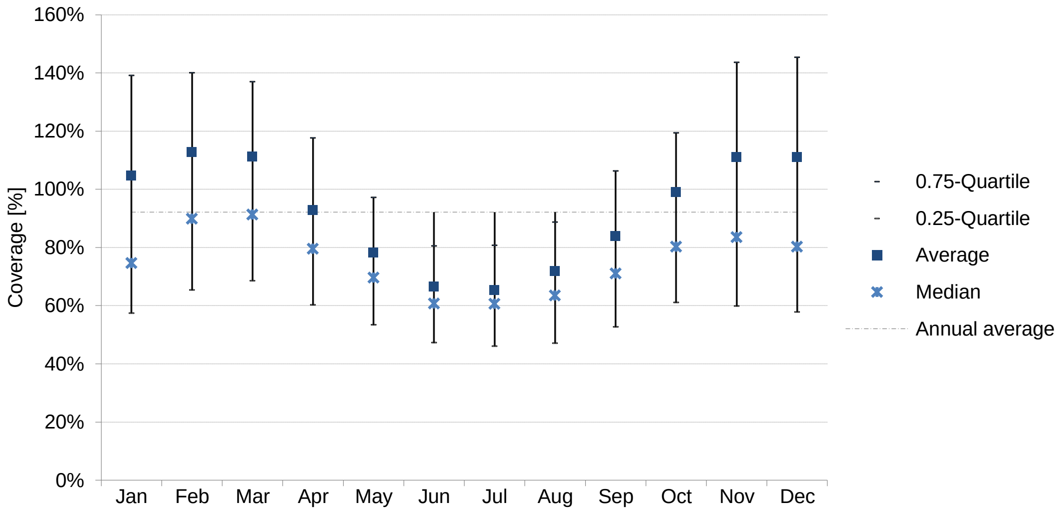


Figure 7 Coverage of household electricity demand by electricity from Renewable Energies. Data: *ENTSO-E 2011*

The elevated supply of RE-electricity during wintertime (Figure 5) suggests that electricity is also an interesting option for space heating (by means of heat pumps). The high variance of RE-electricity coverage during wintertime, as seen in Figure 7, suggests the use of a load management system, in order make optimal use of RE-supply during that season.

I-2.2. Five dilemmas of electricity

Nevertheless, electricity has very specific characteristics that make its exploitation as a carrier for renewable energies very difficult. This section gives some fundamentals on electricity networks, in order to provide some background knowledge for comprehension of the following sections.

Dilemma 1 – Power parity
An electricity grid has no storage capacity on its own. The electrical power drawn from a grid must be fed into it simultaneously. In case of over- or undersupply, the quality of electricity will suffer. That means for example, in the ENTSOE network the alternation frequency will deviate by a gradient of 1Hz per 20GW from the pre-set of 50Hz.[7]

Dilemma 2 – Operating reserves
This is a direct consequence of the previous dilemma. In order to prevent net failure, system / grid operators must hold certain reserves in order to be able to quickly react to electricity shortage or surplus. Additional power can be supplied by a spinning (i.e. already connected power plants increase their output) or non-spinning (i.e. additional power plants are started) reserves. The non-spinning reserve is usually provided by power plants that are able to quickly provide maximum power output, such as hydro or gas power plants. Most types of thermal power plants are only able to react slowly to changes in demand. Therefore operating reserves from those sources cause additional resource consumption and other environmental impact. See also I-2.4.

Dilemma 3 – Fluctuation of renewable energies
In Germany, the share of renewable energies has augmented tremendously in recent years. In the year 2000, 7% of electricity production stemmed from renewable sources – ten years later the share was 17% [*BMU 2011*]. However, traditional electricity grids are mostly unable to cope with this change in supply infrastructure. The results are odd market price situations (e.g. Figure 9), less grid stability and an increased requirement in operating reserve (cf. di-

[7] Source: German article in Wikipedia on Operating reserve
http://de.wikipedia.org/wiki/Regelenergie#Beschaffung_von_Regelleistung (access: 22. Aug. 2011)

lemma above, *Van De Putte et al. 2011*). Renewable energies have very different characteristics than typical combustion power plants, thus prediction of their power supply is characterised by more uncertainty. This uncertainty is usually also compensated by holding additional operating reserves.

Dilemma 4 – Divergence of supply & demand
Since it is impossible to predict perfectly electricity demand, a certain divergence between supply and demand occurs. In addition, electricity supply has certain uncertainties to it (see above). Power plants may be faulty or, in the case of RE, prediction of solar irradiation or wind speed may be incorrect. Furthermore, seasonal and diurnal variations only partly correspond to the demand profile. Another limitation is the time required to power up additional power plants and the resulting delay in power supply (cf. Table 2). Nevertheless, daily predictions of anticipated demand and supply are an important instrument for network operators. Great effort is invested in order to increase the accuracy of those predictions.

Dilemma 5 – Demand can be shifted, not avoided
The idea of demand side management (DSM) sounds intriguing, however loads can only be shifted on in a temporal fashion. For instance, in case of energy shortage the operation of DSM-enabled fridges may be delayed. However, once their thermal capacity is exhausted (i.e. temperature in the fridge rises above a critical temperature), the device will need to draw power again, in order to avoid damage to the goods inside. Furthermore, in thermal processes (e.g. washing machines) energy demand may even increase due to demand shifting (cf. also section III-2).

I-2.3. Renewable Energy vs. Baseload

The current electricity supply network dates back to the age of industrialisation, where energy started being produced by centralized large power stations and distributed to smaller networks to the local consumers. This concept cannot be applied linearly to modern and green electricity production anymore. Renewable electricity power plants have a more volatile profile (i.e. energy is only produced when wind, water or sun is abundant). Furthermore they are increasingly decentralised (e.g. PV-cells on rooftops). Consequently renewable energy producers are perceived by electricity companies and classical electricity grid engineers as problematic for the grid.

The dilemmas, illustrated above, also indicate that a concurrency between “classic” electricity power plants and RE-electricity exists. In the past, differentiation of power plants, thus network management was fairly simple: Inflexible and slow power plants (cf. Table 2) such as coal or nuclear-fired plants provide the baseload. That means they provide a constant power supply, which more or less corresponds to the minimal electricity demand during a typical day (cf. Figure 8). More flexible power plants, such as gas-fired or hydro-plants usually served to provide intermediate load, corresponding approximately to the average daytime demand. Reactive, fast power plants supply electricity that is necessary during peak times (cf. also chapter I-2.4).

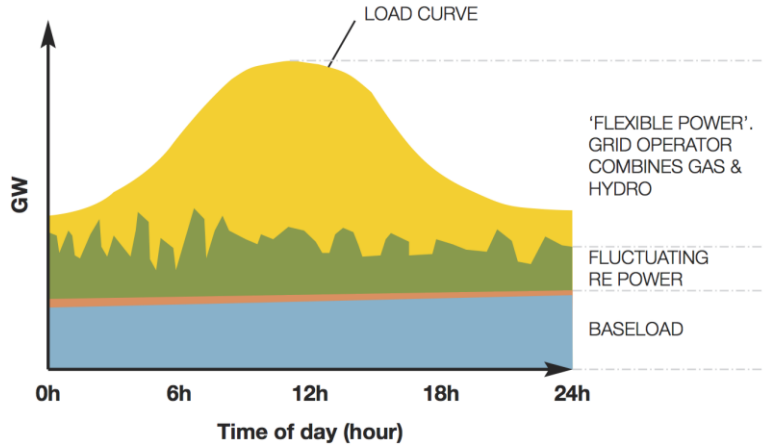


Figure 8 Electricity demand during an average day, according to load type, electricity products respectively [*Van De Putte et al. 2011, p. 11*]

Figure 8 illustrates the conflict between RE power and the conventional electricity network. The Renewable Energies create peaks throughout the day that need to be compensated by the grid operator. In case RE power plus the baseload exceed electricity demand, power plant need to be curtailed, which results in technical difficulties and wasting of energy. Thus, the concurrency between baseload and (volatile) RE can be considered a sixth dilemma.

Such a situation of oversupply has actually occurred in the past and proves to be problematic also from an economical point of view. For instance in 2009 the price for electricity on the European Energy Exchange (EEX) became negative several times (cf. Figure 9). That means network operators were facing hours with oversupply from wind energy and very little energy demand. Therefore potential consumers were offered money in order reduce the grid's load.

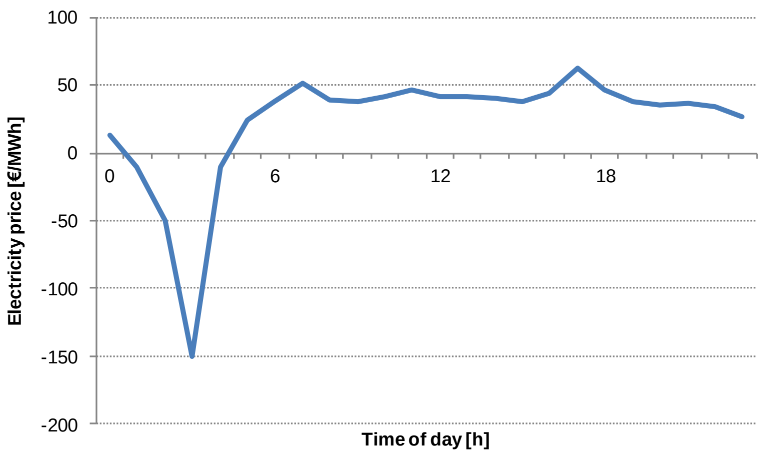


Figure 9 Electricity price [€/MWh] on 24th November 2009, Data source: EEX[8], Physical Electricity Index

Such extreme situations are problematic for network operators. In order to guarantee network stability, they are obliged to find load consumers at short notice. That means prices may augment considerably high. In the example of 24th November 2009 (Figure 9) price was -150 €/MWh at 4 a.m. That is approximately three times higher than the average price for providing one MWh the same day. Hence, a load management system that helps to avoid such peak situations is presumably also an interesting option for electricity suppliers.

[8] EEX PHELIX spot trading on 24.Nov.2009, Source: *http://www.eex.com/en/Market Data/Trading Data/Power* (accessed 11.Aug.2011).

I-2.4. Operating reserve

In Europe, billions of small and large electrical appliances are connected to the European Network of Transmission System Operators for Electricity (ENTSOE). In order to assure smooth operation of all devices, the electricity network needs to 'speak a common language'. This language is the 50 Hz alternating current. Appliances are designed to work for this specific current and are sensitive to any divergence. In the case of a faulty frequency they can be damaged. Hence, the maintenance of a stable current has high priority in electricity networks (Table 1).

Table 1 Network frequency and measures (*Oeding and Oswald 2011*)

Stage	Frequency	Measure
1	49.8 Hz	Alert of personnel; Activate idle power
2	49.0 Hz	Immediate load shedding of 10-15% of network load
3	48.7 Hz	Immediate load shedding of another 10-15% of network load
4	48.4 Hz	Immediate load shedding of another 15-20% of network load
5	47.5 Hz	Disconnect power plants from the network

However, the network's frequency is also an indicator for the system status, quality of electricity respectively. When supply exceeds electricity demand, the frequency will increase and in case of demand excess vice versa (cf. dilemma 2 in I-2.2). Thus the management of the electricity network is a delicate task with little fault tolerance [*Kamper 2010*].

Especially during peak times (Figure 8), electricity demand can be particularly volatile and unpredictable. Therefore, grid managers (Transmission System Operator, TSO) provide a certain amount of operating reserve (OR). This power can be either positive or negative and serves to balance network failures or other unforeseen events.

Three types of operating reserve exist. In case the network frequency deviates 10-20 mHz, primary control is activated. It consists mostly of the power generators already connected to the network. To a certain degree power generators have the ability of automatically levelling out minor disturbances. The kinetic energy stored in the turbines' rotor compensates small variations. In case the energy shortage reduces turbine speed, additional power must be supplied to the generator in order to maintain the correct frequency. Therefore, network operators must reserve 2% of their respective feed-in. In Europe 3'000 MW of primary control is reserved in average [*Braun 2007, Kamper 2010*].

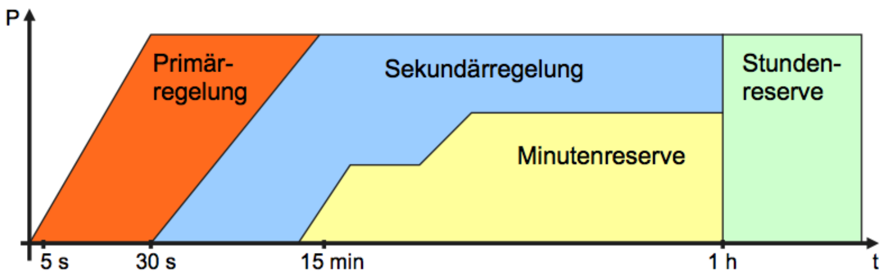


Figure 10 Source: *Kamper 2010, p. 14*

After 30 seconds of active primary control, secondary control is activated. It consists of power plants that are able to quickly provide a large amount of energy (2% of nominal power per minute). After 15 minutes tertiary control ("Minutenreserve") is manually requested by TSOs.

Coal and nuclear driven power plants require long periods to be activated and for obtaining maximum power output. Furthermore, due to thermal stress on the turbines' material, operation cycles are restricted to certain minimum times for start-up, operation, and power-off (Table 2). Requests for additional power must be issued several hours in advance [*Kamper 2010*].

Table 2 Typical duration of power plant operation cycles [*VDE 2009, Weindorf 2011*]

Power plant	Starting time	Minimum power-off	Minimum operation
Nuclear	24-48 h	15-24 h	15
Hard coal	2-5 h	4-15 h	4-15 h
Lignite	2-5 h	4-8 h	4-8 h
Gas (other)	1-5 h	1-6 h	1-6h
Gas turbine	5-8 min	0 h	1 h
Pump storage hydro	1-2 min	-	-
Air pressure	6-15 min	-	-

That means supply of secondary (and partly primary) control power is usually limited to air pressure, pump storage hydro and gas turbine power plants. The former two technologies represent electricity storage systems with good overall efficiency (approx. η=0.77). However, efficient storage does not necessarily mean, that "clean" energy has been stored in the reservoirs. Mostly this kind of power plants serve to cover peak demand during day time and charge their reservoirs during night [*Giesecke and Mosonyi 2009*]. Thus, the stored energy in the reservoir represents the typical nighttime mix of an electricity network. Gas turbines are an efficient option, but involve relatively high emissions. This type of load shifting by means of energy storage is discussed in more detail in sections II-5 and III-3.1.

Hence, peak load power plants are possibly energy providers with particularly elevated environmental impact. An electricity network with focus on "clean energy" would try to avoid excessive use of operating reserve and prioritize electricity from Renewable Energies.

I-3. Résumé section I

The example from section I-1 and the Renewable Energy supply analysis above (I-2) illustrates the plentiful availability of Renewable Energies in Germany. However, exploitation of this potentials is only rudimental today. Excess supply energy storage and demand shifting would be an attractive option to use Renewable Energies efficiently. The question is furthermore, what role intelligent load management systems could play in order to bridge the supply gap. Could they play an equally important role in future buildings, just as the strategies of energy-efficiency and fuel-switch do already today?

Section I of this paper outlines the motivation and, why load management is beneficial from environmental point of view. Important findings are:

- Renewable Energies are abundant in moderate climates
- Theoretical potential of on-site annual solar energy supply in Germany exceeds residential final energy demand by a factor 3 to 4
- Due to a lack of energy storage or load shift, surplus energy is usually lost
- Annual electricity supply from RE corresponds to 75% of household demand
- Seasonal occurrence of Renewable Energies corresponds only partly to residential energy demand
- Coverage of electricity by RE is highest in wintertime – opposed to seasonal solar irradiation
- Due to high variance in RE supply, seasonal and diurnal load shifting could optimise exploitation of Renewable Energies
- Load management is also economically profitable
- Integration of Renewable energies into the electricity network is difficult
- Operating reserve implies environmental impact

II. LOAD MANAGEMENT STRATEGIES

The previous section points out several arguments on why load management can be environmentally and economically beneficial. Section II gives a short overview of potential strategies and their implications. The following section (III), quantifies the load shift potential in Germany for selected measures. As the title suggests, this work focuses on broader structures (i.e. German building stock), instead of considering specific solutions. Thus, electricity is an important focus in this and the following section.

II-1. Overview

Figure 11 represents a non-exhaustive overview of different techniques shifting energy supply and demand loads.

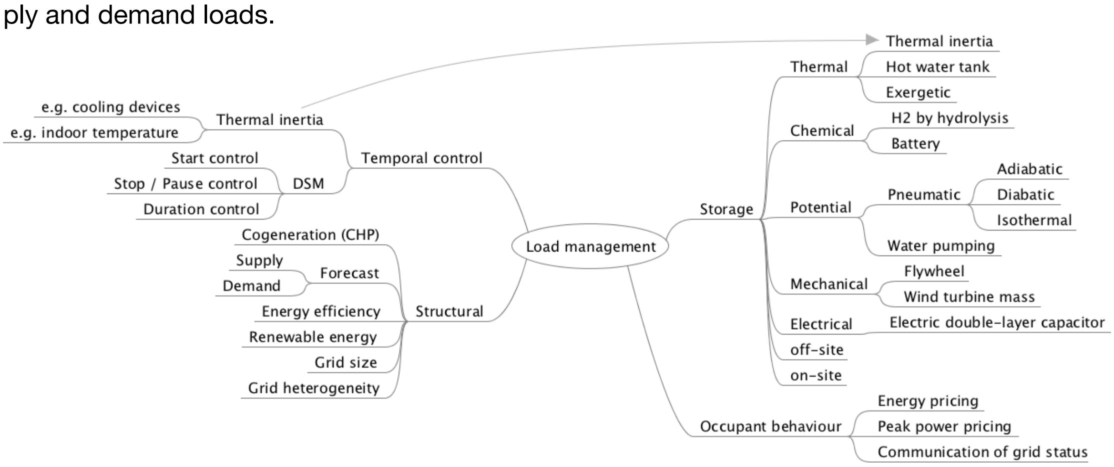


Figure 11 Different possibilities of load management

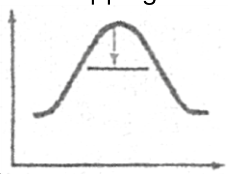
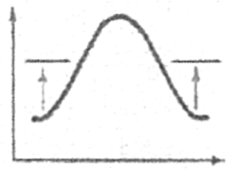
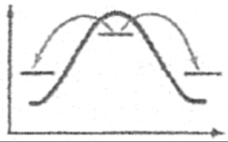
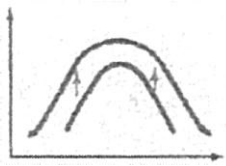
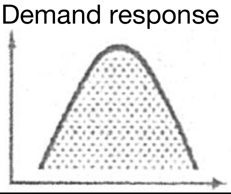
The different measures can be classified into the following

a. Structural measures
b. Occupant behaviour
c. Temporal control of services
d. Energy storage technologies

All of these have capability to shift energy load in time, either on supply or demand side. Some of the measures are closely related to one another and a clear distinction is not always possible. For instance, several Demand Side Management (DSM) techniques rely on the thermal inertia of devices (such as refrigerators, etc.), which can also be considered a form of energy storage.

The possibilities and requirements of load management differ for thermal and electrical systems. That is due to the nature of the two different forms of energy. Thermal energy can be conserved and therefore stored in different media. Transport is difficult. On the contrary, electricity is extremely reactive and therefore difficult to conserve. Yet, it can be transported over large distances with acceptable losses. Nevertheless, some laws of classical load management also apply to thermal systems. Table 3 gives an overview of typical measures in electricity networks. For instance 'load shifting' is a technique that can be realised in buildings by means of thermal mass.

Table 3 Load management strategies according to *Clark and Gellings 2009*

Peak clipping 	Peak load situations are mitigated by means of peak clipping. This represents a typical load management strategy. For instance, energy providers charge large consumers by annual peak load, rather than annual electricity demand. Thus, consumers will try to minimize peak load situations throughout the year.
Valley filling 	Powering up and down of power plants involves several technical difficulties, wear, and costs (cf. section I). This is especially the case for nuclear or coal-fired power plants. Therefore electricity providers favour a high baseload, i.e. no supply gaps (e.g. at night). Thus, most suppliers offer lower prices in off-peak seasons. That provides consumers an incentive to either shift energy-intensive tasks (e.g. hot water generation) or consume additional energy in these periods.
Load shifting 	In recent years, thermal systems (in buildings) are increasingly designed to profit from cheaper off-peak electricity. For instance, ice-storage systems help to shift high electricity demand for air-conditioning to off-peak hours.
Energy efficiency 	Overall electricity demand can be reduced by increasing appliances' efficiency. I.e. the same service is provided with lower energy input. An important example is the immense saving potential of hot water circulation pumps in Europe (cf. *Jardine and Lane 2005*).
New, efficient uses 	*Clark and Gellings 2009* refer to an increasing electrification of end-uses. For instance, the number of electric space heat systems (i.e. heat pumps) is increasing. Therefore household demand for oil or gas decreases while electricity demand increases. Since electricity represents a good carrier for renewable energies this trend may actually help decarbonising society.
Demand response 	According to *Clark and Gellings 2009*, this term involves the active participation of the users and appliances in order manage loads.

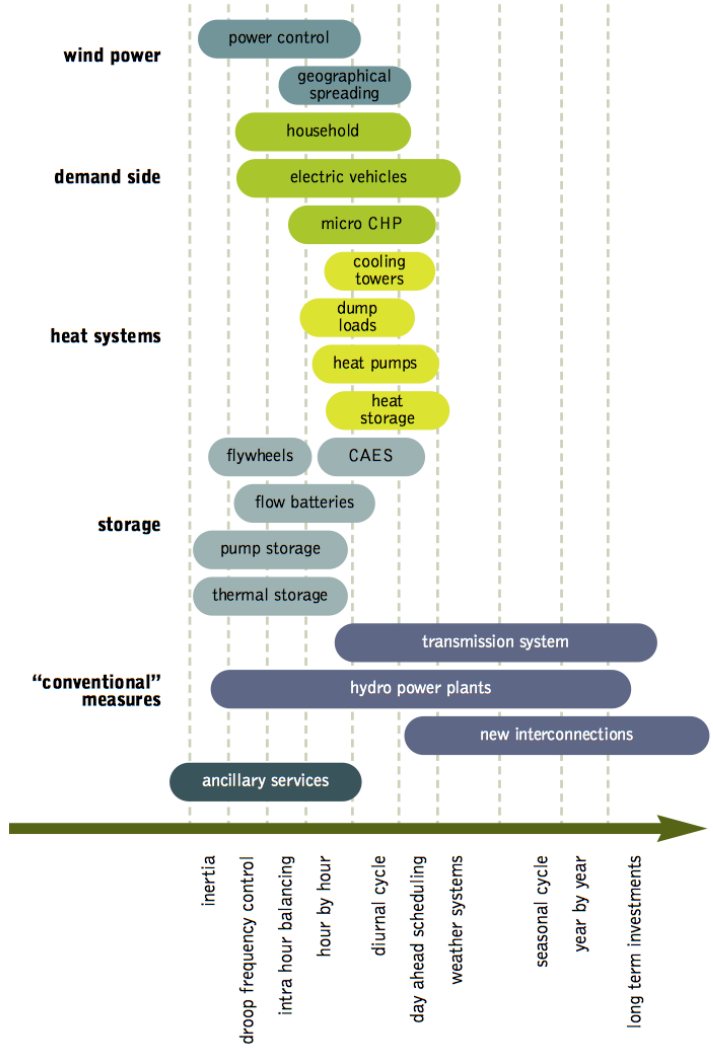


Figure 12 Classification of load management techniques according to *Ackermann et al. 2009, p. 31*

Load management techniques can also be categorized by capacity and time horizon of load shift. Figure 12 illustrates the balancing capabilities of different systems. Most of them facilitate short-term compensation of imbalances (e.g. wind power control) on a daily horizon. However, it is difficult to displace loads for longer periods. Alone hydropower and network infrastructure (cf. next chapter) allow balancing of loads across seasons.

II-2. Structural

For successful load management not only active control of devices is necessary. By changing systems' structure, such as design, a positive effect on load profiles can be achieved.

II-2.1. Electricity

The grid's properties and design play an important role in its performance. Accurate forecast and efficient control of energy consumers and suppliers are important quality criteria of an electricity grid. Renewable Energies represent an energy supply that is more difficult to predict than traditional power plants. The latest increase in their production presents new challenges to grid operators.

II-2.1.1. Prioritizing Renewable Energies

Section I-2.4 illustrates that use of operating reserve should be minimized and Renewable Energies prioritized in electricity networks as a means to reduce environmental impact of electricity generation. However, this relationship is a matter for discussions in recent years. Critics claim that energy supply by Renewable Energies is unreliable and therefore difficult to integrate in the current network regimes (cf. section I-2.3, Renewable Energy vs. Baseload). Recently Greenpeace International commissioned and published a number of studies investigating this issue (*Ackermann et al. 2009, Tröster et al. 2011, Van De Putte et al. 2011*). The authors postulate a paradigm change in electricity generation regimes and sketch a pathway towards 68% RE share in 2030 and 100% in 2050 respectively. Figure 13 compares the current situation with an ideal scenario, as proposed by the authors.

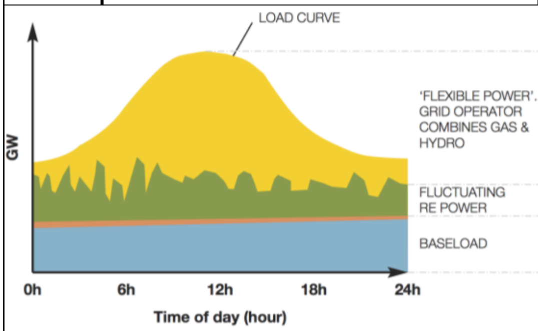
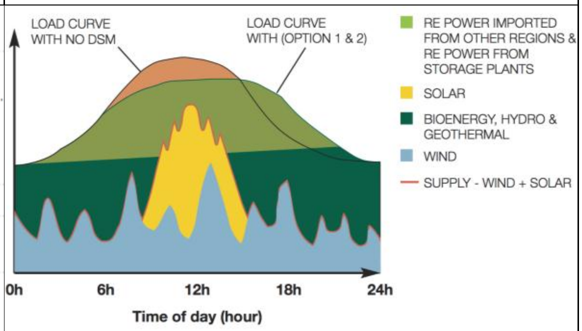
Status quo	RE scenario
	
– Baseload generated by coal and nuclear power plants, – Peak load by hydro and gas power – Maximum RE share of ca. 25% possible – Baseload conflicting with RE, provoking 'waste' energy	– Less volatility in demand and lower overall peak – Demand management for peak hours – Operating reserve fills supply gaps until sufficient storage capacity is available – More renewable power – More constant renewable supply curve

Figure 13 Current electricity supply (left) and an ideal electricity profile, with 90% supply from Renewable Energies (right) [*Van De Putte et al. 2011, p. 11ff*]

The methods to achieve such a scenario are[9]

a. Reduce demand side / increase energy efficiency
b. Establish storage capacity (sinks) in the grid
c. Expand network size in order to increase statistical security
d. Provide network overcapacities to enable European transmission
e. Abandon inflexible non-renewable power plants (i.e. coal and nuclear)
f. Optimize mix of Renewable Energy generation
g. Foster geographical spread of RE suppliers

An effective means to approach energy demand and RE supply is to reduce overall energy demand, for example by increasing energy efficiency. By establishing a common multinational transmission network, volatility in demand and supply can be decreased, resulting in a more predictable and stable electricity network (see next chapter, resp. Figure 16, Figure 14). Enlargement of the network requires the supply of overcapacities in the transmission

[9] *Tröster et al. 2011, Van De Putte et al. 2011* also investigate the economic consequences of the scenario, which will not be further reflected here.

network. This is necessary to ensure transmission of large amounts of electricity across European countries at any time. To further flatten demand and supply curves different load management techniques are established. Possible measures are e.g. installation of storage capacity, DSM, VPP, etc.

Furthermore, the future electricity mix plays a crucial role. Electricity from Non-Renewable energy (NRE) will still be indispensable for the next years, until sufficient supply from Renewables is available. However, the mix of NRE is optimized so that no conflict with RE sources occurs. That means nuclear and coal-fired power plants are abandoned since they are only able to provide inflexible baseload (cf. Table 2), which is conflicting with variable supply by wind power and photovoltaics. Oil and especially gas-fired power plants ensure the necessary flexible supply for operating reserve. In the future biomass, hydropower and geothermal power plants substitute those NRE power plants. Furthermore, also Renewable Energy mix is optimised in order to mutually complement the different supply profiles of Renewable Energies. This can mostly be achieved by diversifying the generation mix and distributing it across Europe (cf. Figure 14, next section respectively).

II-2.1.2. Grid size

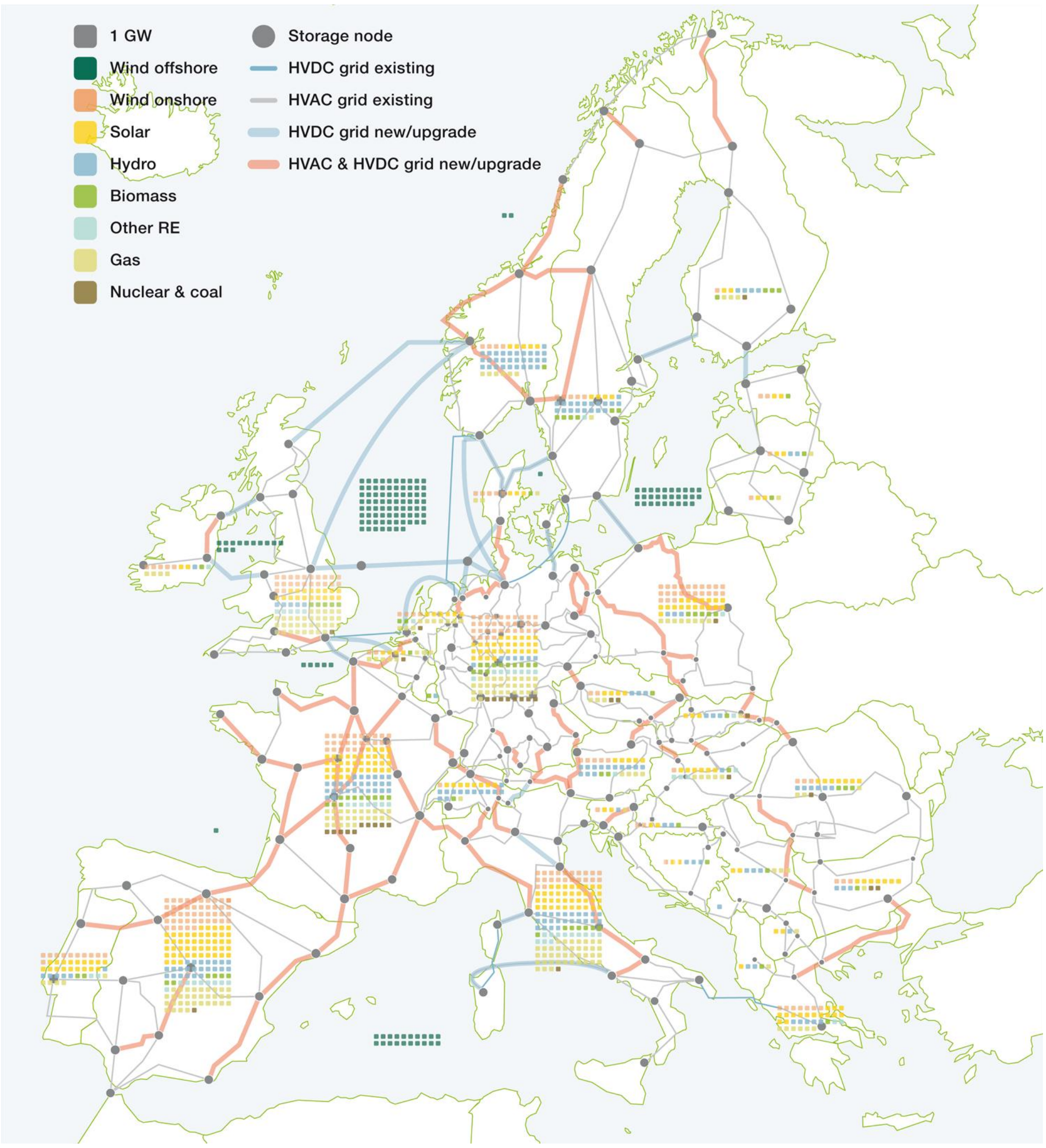


Figure 14 A future RE power generation network according to *Van De Putte et al. 2011, p. 17f*

As illustrated in the previous chapter, *Tröster et al. 2011, Van De Putte et al. 2011* postulate a pan-European electricity network that is able to transmit large amounts of energies across the countries. Figure 14 illustrates the map for such a network. It would have three major advantages.

Firstly, each region has a specific potential for Renewable Energy production. For instance Southern European countries receive more annual solar radiation than others, while wind potential is highest on Northern European coastlines. A pan-European electricity network would be able to connect the regions and provide also regions with less favourable conditions an access to RE.

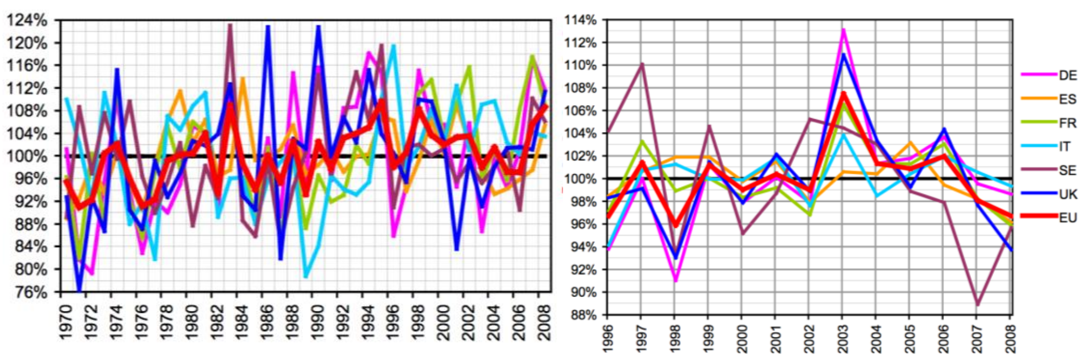


Figure 15 Annual variation of wind power (left) and solar energy supply for different European countries [*Popp 2010, p. 24, 33*]

Secondly, a pan-European network is able to level out discrepancies in RE supply between the different regions. Figure 15 shows the annual mean of wind and solar energy supply roe the last 38 years, 12 years respectively. Although the annual deviation for the respective counties is significant, the European average (red line) shows a far lower standard deviation for both forms of energy. Moreover, deviation in wind and solar energy appear to complement each other. However, statistical significance and magnitude of the complementation have not been tested here.

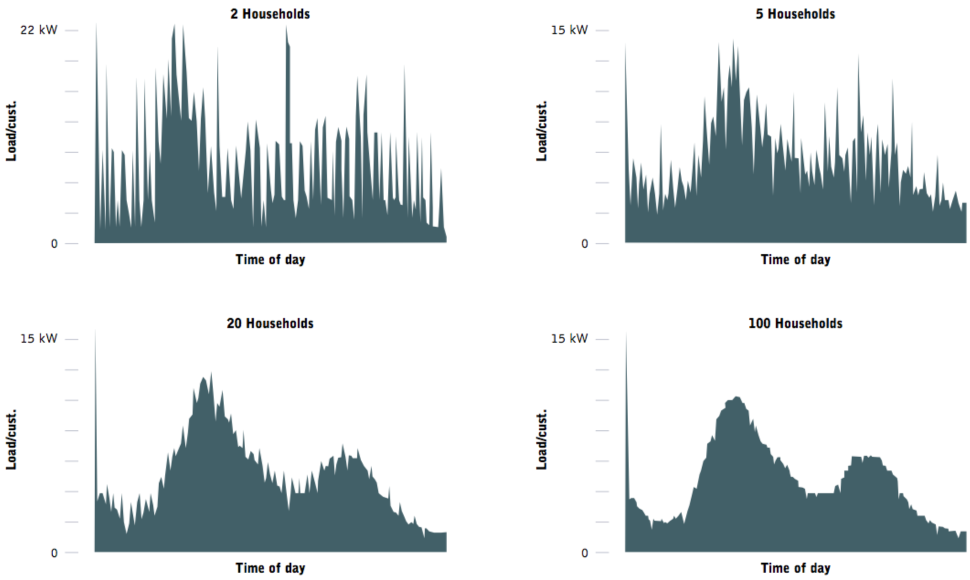


Figure 16 Flattening demand curves by combining systems, exemplary household electricity demand [*Ackermann et al. 2009, p. 41*]

Thirdly, levelling out of imbalances in energy demand can be realised more efficiently by means of a larger electricity network. Figure 16 illustrates the principle. The larger the network the less volatility becomes its energy demand profile. Statistically peaks do not occur simultaneously and therefore the large number of consumers will give a uniform demand curve. Furthermore, peak power demand does not linearly increase with the number of consumers. Each one has its own peak power demand at slightly different points in time.

II-2.2. Architectural

The energy demand profile of buildings can also be affected by different measures. Building orientation, for instance, allows influencing the energy demand characteristics. Buildings that are oriented towards a south orientation receive large amounts of solar irradiation throughout the year. However, the monthly supply profile shows that especially in the cold seasons a relatively large amount of solar energy is received. During summertime, supply is, compared to the other orientations, relatively low (cf. lime green line in Figure 17).

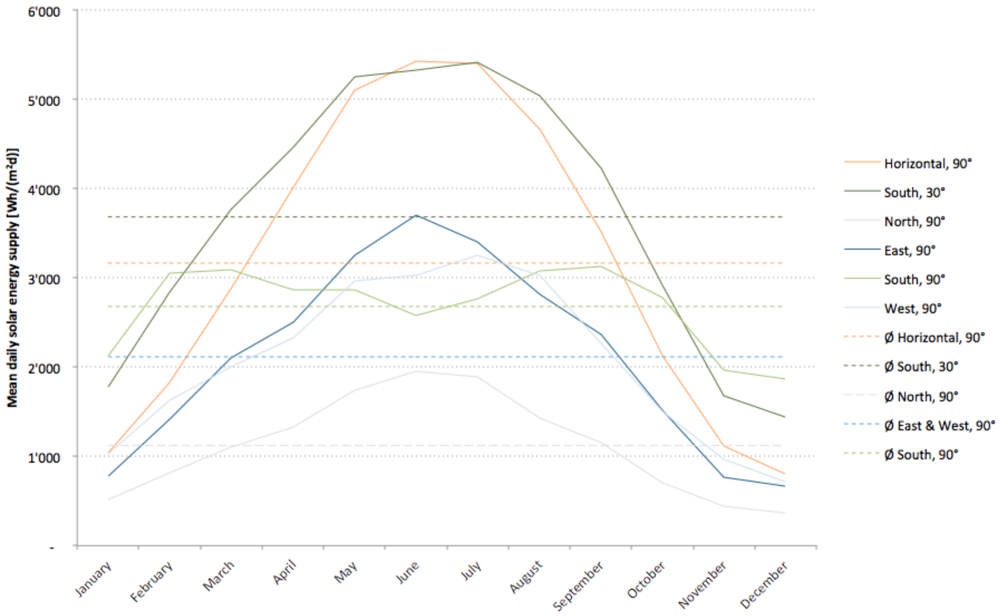


Figure 17 Annual mean daily energy supply for different orientations and inclinations in Wh/m^{2}d. Dashed line corresponds annual mean. Site: Munich, Germany. [*Meteotest 2010*]

Eastern and Western facades receive the better part of their solar irradiation during morning hours, evening hours respectively (cf. dark and light blue lines in Figure 18).

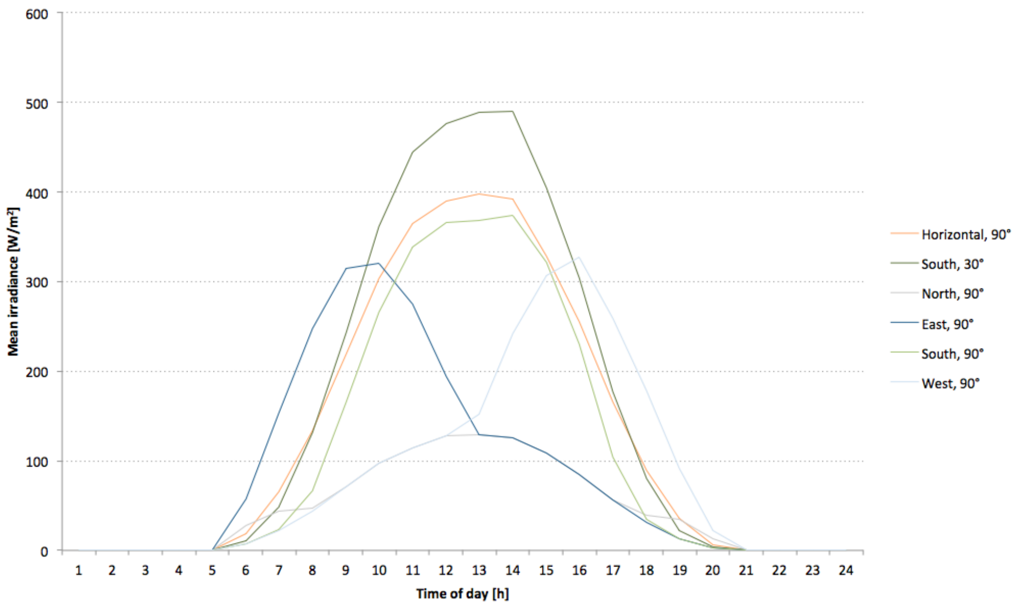


Figure 18 Mean annual solar irradiance for different orientations in W/m². Site: Munich, Germany [*Meteotest 2010*]

Hence, the space heat demand curve can be influenced by orienting window surfaces toward either of those orientations. The demand profile in Figure 46 suggest that Eastern and Southern orientations are favourable. Usually space heat demand is highest during wintertime and morning hours. Buildings with Western facades often show susceptibility for overheating *Hausladen 2005*.

Furthermore, building insulation and thermal mass have a considerable effect on building autonomy from space heat supply. *Bukvić-Schäfer 2008* shows that the time a building with thermal mass and high U-value can remain significantly longer without space heat energy supply, before user comfort is affected (Figure 19 and Figure 43).

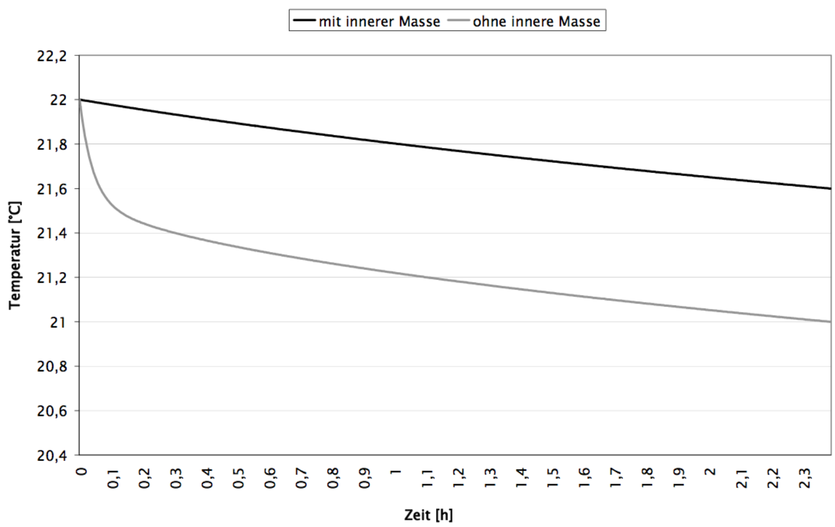


Figure 19 Influence of thermal mass on temperature decrease of a building without heat energy supply [*Bukvić-Schäfer 2008, p. 57*]

II-2.3. Supply side

Except for nuclear power,[10] energy supply from non-renewable energy sources is mostly time independent and available at any time. Renewable Energies however are less flexible. Hydro pump storage plants are an exception. However, these plants are often charged with electricity from non-renewable baseload power plants.

Figure 20 Thermo-solar concentrator power plant in Spain[11]

Recent developments in the solar sector show that continuous energy supply from Renewable Energies is feasible. For instance, a thermo-solar concentrator power plant in Southern Spain provides a continuous power of 20 MW_{el}, also for periods without solar irradiation of up to 15 hours. The principle of the plant is to concentrate solar irradiation and store thermal energy in a molten salt storage tank. Thus, thermal energy is at disposal also at night-time. This kind of power plants may one day help to provide baseload electricity from Renewable Energies.

II-3. Occupant behaviour

Occupant behaviour has an important influence on energy demand of buildings. *Steemers and Yun 2009* found that occupant behaviour has the second largest influence on energy consumption of households in the U.S. Thus, the cooperation of occupants holds valuable potential. Therefore, it is important to establish at least the acceptance for load management with building users. Giving users incentives may lead to a participation in an active load management. Ideally, occupants will then shift energy intense activities to hours where grid load is low and / or renewable energies available. For instance, *Räsänen et al. 1995* suggest that dynamic electricity prices can be an efficient stimulus to alter occupant behaviour. The economic incentive for building occupants are considerable. For instance *Ning and Katipamula 2005* show that a modified setpoint control system for domestic hot water systems can help to save 20% in electricity cost.

[10] The chain reaction in nuclear power plants cannot be adequately controlled. Thus, such a power plant is either required to supply power to the grid or waste of large amounts of energy, in order to keep the reactor under control.

[11] Source: *www.torresolenergy.com*

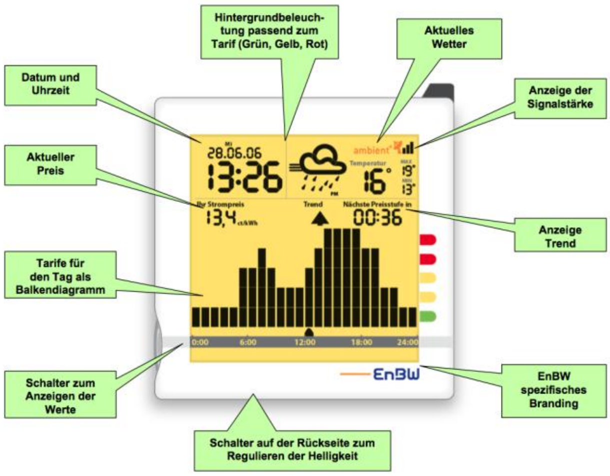


Figure 21 Price information system for building occupants [*Kamper 2010, p. 35*]

Kamper 2010 describes different case studies, carried out in Germany. Figure 21 illustrates one example for a price information system for building occupants. The system provides price information on past, present and future electricity supply. In case such systems are applied on a large scale, energy providers should deliver staggered price information to occupants in order to control the magnitude of load reduction. In a case where all building users respond to a specific price situation, an overshoot in response could be the consequence. That means demand might exceed or fall short of the anticipated response. *Roozbehani et al. 2011* developed a model that shows that network stability may be threatened in such situations.

User can be considered a type of Demand Side Management strategy. Users can adapt energy demand of appliances according to a certain stimulus (e.g. electricity price). Similarly, demand is mostly shifted to a later point in time and demand will be recuperated then.

II-4. Control

A number of services do not require a specific time to be performed or finalized. Therefore, either occupants or ‘smart’ devices may exert active control on the process and determine its start, end and duration. Possible applications are start and pause control of washing machines, dish washer, etc.

II-4.1. Virtual power plants

Braun 2007 looks at the feasibility of integrating cogeneration plants (combined heat & power, CHP) into the electricity network. The aim is to provide operating energy (cf. I-2.4 Operating reserve) by collectively controlling cogeneration plants in buildings. The resulting network is often referred to as Virtual Power Plants (VPP). Prerequisite for such a system are power plants, which can be controlled by the TSO (Figure 22). In case of CHPs, additionally a thermal sink of sufficient capacity is necessary.

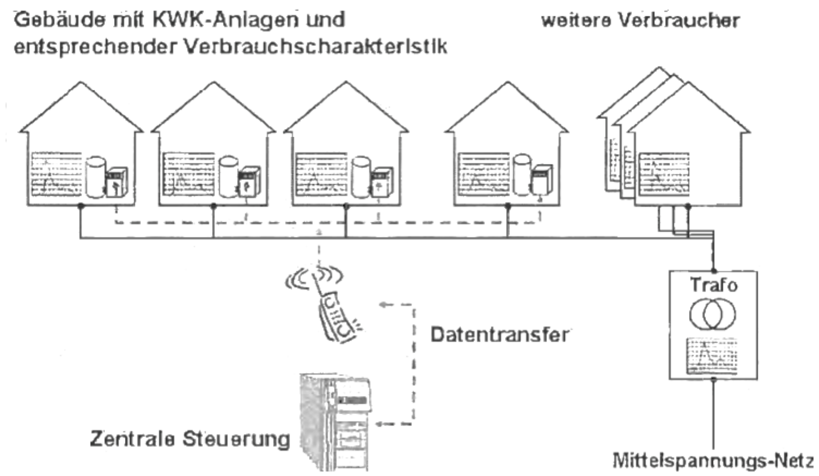


Figure 22 Collective control of cogeneration plants [*Braun 2007, p. 4*]

The simulation of CHP plants in residential buildings yields that supply of negative and positive operating reserve is feasible by means of virtual power plants. However, variance in thermal sink capacity, due to climatic conditions, restricts temporal availability. The author suggests that intelligent control systems, which are capable to include forecast of heat demand, might resolve this issue. Furthermore the author finds that the investigated VPP is probably economically of little interest for its operators.

II-4.2. Demand side Management

Quaschning and Hanitsch 1999 quantify the shift potential of households with 40%. Other authors (e.g. *dena 2010*) and also the DSM-model, described in section III-2.2, find similar figures.

II-4.2.1. Appliances

dena 2010, p. 410ff conducted a study of the DSM potential in household appliances. Some of the assumptions used there were adapted for the analysis. The left-hand side of Figure 23 provides a breakdown of the annual electricity demand of Germany's household appliances. The pie chart differentiates between appliances having a DSM potential (green) and appliances without or little shifting potential (red). According to the figure, 60% of household appliances possess DSM potential.

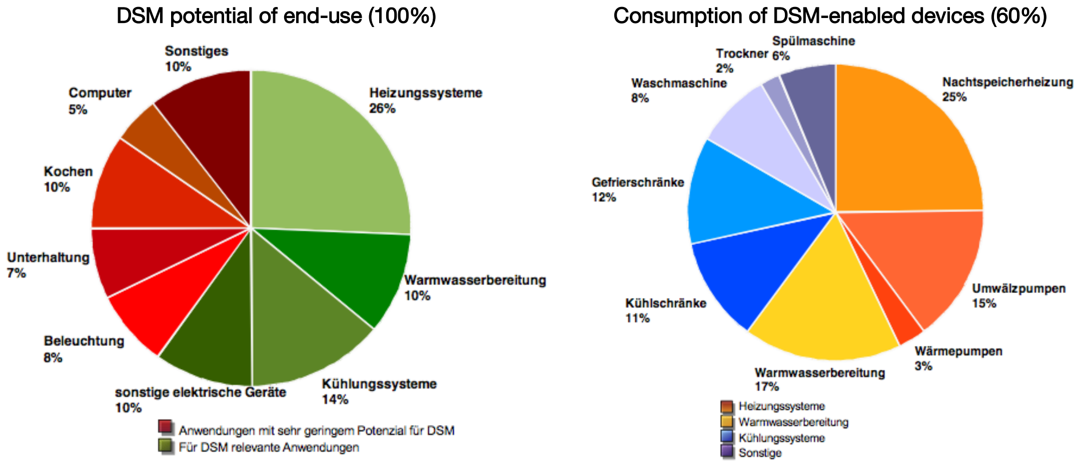


Figure 23 German electricity consumption of households in 2007 and DSM potential of appliances. The right pie chart is a subset (60%) of the left one. [*dena 2010, p. 411*]

On the right-hand side of Figure 23, a breakdown of the appliances that possess DSM potential is illustrated according to the respective end-use. Orange corresponds to space heating, yellow to domestic hot water supply, blue to cooling devices, and purple to miscellaneous respectively. It shows that the majority of devices are appliances using thermal processes (i.e. heating or cooling).

Table 4 Duration of cut-off according to user comfort loss [*Tanner 2007, p. 5*]

Appliance	Little to no loss in comfort	Effects may be noticed	Device not usable
Cooking / oven	30 s	1 min	10 min
Refrigerator	15 min	45 min	3 h
Freezer	3 h	3 h	6 h
Dish washer	15 min	45 min	2 h
Washing machine	15 min	45 min	2 h
Tumble dryer	15 min	45 min	2 h
Lighting	0 s	0 s	10 min
DHW	2 h	3 h	4 h
Space heat	15 min	45 min	2 h

Different authors try to quantify the possible duration of demand shift*Quaschning and Hanitsch 1999, Stamminger 2008, Tanner 2007*. Although *Tanner 2007, p. 5*. Refers more to load shedding than DSM-potential, a selection of the assumptions are summarized in Table 4.

II-4.2.2. Control strategy

Ideally, an intelligent load management systems shifts demand from periods where there is an energy deficit to a period with energy surplus. Thus, information on the current power supply needs to be transported to the consumers. However, that information exchange may pose a number of problems.

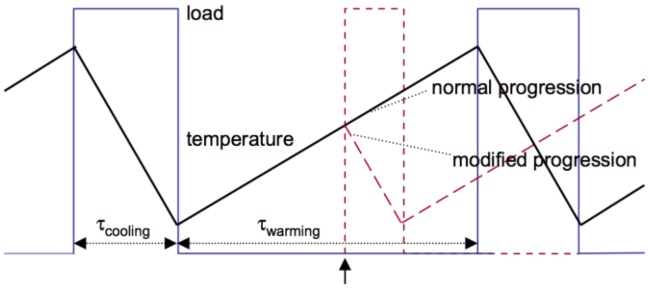


Figure 24 Typical control strategy of thermal systems [*Stadler et al. 2009, p. 287*]

In case the period of deficit outlasts the appliances' capacity to shift energy demand, the supply shortage may even be aggravated. For instance, refrigerators need to respect a certain critical temperature in order to maintain the quality of the goods inside the device. That means a completely charged (i.e. cooled) device may put off compressor operation by approximately 40 minutes at maximum. That means most devices need to draw current after 20 minutes of outage. However if the deficit situation did not improve during that time, a rebound peak occurs and will put the electricity grid under additional stress. This may be especially the case for price-driven DSM control mechanisms. *Roozbehani et al. 2011* show that real-time pricing for consumers possibly results in a closed-loop feedback, affecting network stability and price volatility. Moreover, a potential consequence may also be an overshoot due to a delayed and uncoordinated control response.

This implies that, if market participants react blindly to a control signal (i.e. without exchanging information with their peers or a superordinate unit), DSM may prove harmful to an electricity network.

Figure 24 schematically illustrates typical thermal systems and their control strategy, respectively electrical load over time. This applies to cooling applications, such as space cooling, fridges, etc. When temperature (black line) rises above a predefined threshold, the device's controller will activate the heat pump in order to extract thermal energy from the interior of the insulated container. In 'smart' systems, the electric load of the heat pump (blue line) can be altered by sending a control signal. This could be, for example, a command to prematurely charge the system (red line). This way the electric load can be shifted by a certain time. For heating applications, the temperature curve would be inverted, since the system's purpose is to keep indoor temperature above outdoor temperature.

II-5. Energy storage

Strictly speaking, most forms of energy storage actually are of some type of energy conversion. For instance, only the thermal storage process, illustrated in Figure 11, factually stores the same type of energy, than it is released later on. Most other processes convert electricity into another kind of energy (i.e. mechanical, potential, etc.).

The most effective method of load management, in terms of capacity and duration, is energy storage. Different physical principles, such as chemical, mechanical storage, can be exploited and accordingly the available technologies are ample. Energy can either be stored on-site (i.e. in the building) or off-site (i.e. grid storage capacity). Technologies differ in storage duration (e.g. minutes in supercaps and months in water basins) and efficiency (Figure 25).

- Thermal
- Chemical
- Mechanical
- Potential
- Electrical

II-5.1. Electricity

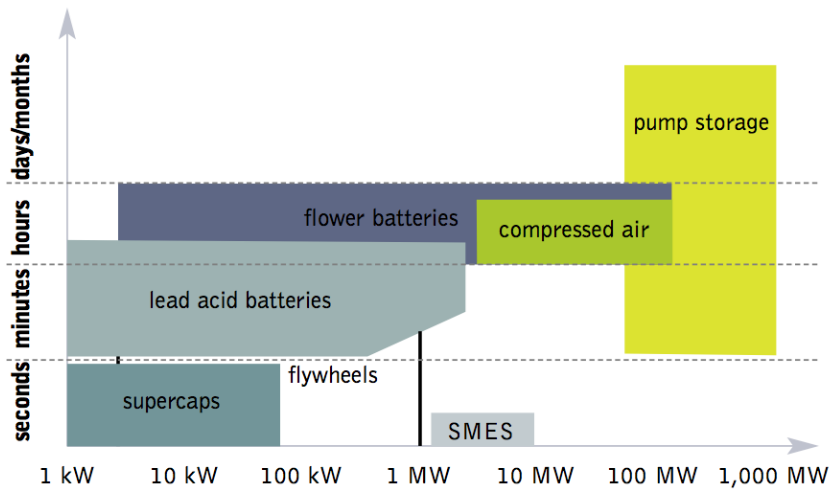


Figure 25 Capacity and dwelling [*Ackermann et al. 2009, p. 75*][12]

Figure 25 illustrates the capacity and dwelling time of selected electricity storage systems. Additionally, Table 5 gives an overview of different electricity storage technologies, along with their prices, efficiency, and capacity.

---

[12] SMES: Superconducting Magnetic Energy Storage

Table 5 Characteristics of different electricity storage systems [EcoGrid 2007*, p. 20*]

Technology	**Power [MW]**	**Energy [kWh]**	**Efficiency [-]**	**Energy cost [€/kWh/a]**	**Power cost [€/kW/a]**
Flywheel	<1.0	<250	≥0.80	77	0.88
Compressed air	5 - 400	≥2'600	0.55 - 0.75	1.5 - 3.0	34.16
Conventional battery	4	40	0.75 - 0.85	24 - 117	73-351
Redox flow battery	0.005 - 500	400	0.65-0.75	9.4-12.5	70-144
Superconducting Magnetic energy Storage (SMES)	2	<5	0.95	300'000	47
Supercapacitors	<20	<5	0.85 - 0.98	570	4.8
Hydrogen	0.2 - 4	n/a	0.75 - 0.80	6.8	128

Depending on the designated use, storage of electrical energy can be extremely costly. The most affordable system in terms of power capacity is the flywheel. These systems can provide relatively large power output for a short time. Thus, their energy costs are considerably higher. The best performing system in terms of energy costs are compressed air systems. In Germany such a power plant with a capacity of 580 MWh is in operation since 1978 [*VDE 2009*]. *Lemofouet and Rufer 2006* show that hydrostatic hybrid compressed air systems may also yield very good efficiency, but with the capacity to store electricity over longer periods of time.

Nieuwenhout et al. 2005 show that an electricity on-site storage system may result in a reduction of electricity costs of 20%.

II-5.2. Thermal inertia

Buildings generally possess a certain thermal inertia. Moreover, several end uses in buildings are based on thermal processes (e.g. oven, fridge). That means a hysteric controller will switch energy supply once an upper or lower limit value is reached. Generally, energy is provided until a limit temperature is obtained and, according to the second law of thermodynamics, the system's temperature will slowly converge back to ambient temperature. Load can be delayed by expanding the boundary temperatures by some extent. Furthermore, energy supply can be prematurely interrupted, even if the system is not fully charged (cf. Figure 24).

a. Indoor temperature

b. Fridge, Freezer

c. Oven

d. Hot water storage tank

For thermal inertia of buildings, refer to chapter II-2.2.

II-5.3. Seasonal thermal energy

In Switzerland, a number of case studies illustrated the feasibility of residential buildings, heated by solar energy yearlong. Therefore, a massive hot water tank is placed inside the building, often spanning over several storeys. That way thermal energy transmission losses remain small. However overheating in summertime may become an issue. Large solar thermal collectors gather the solar irradiation during summertime and the storage tank is then slowly discharged during wintertime [*Jenni 2010*]. Recently *Simons and Firth 2011* proved the ecological usefulness of the concept, including the life-cycle environmental impact. Furthermore, a number of sensible heat storage systems exist. *Pinel et al. 2011* provide an overview of different seasonal thermal storage strategies for residential buildings.

II-5.4. Exergy

In recent years, the idea of 'low exergy' buildings has become increasingly popular. The idea is intriguing – by means of heat pumps buildings gather the necessary thermal energy for space heat and domestic hot water from an exergy (i.e. low temperature) reservoir. The higher the temperature of the reservoir, the higher the efficiency of the heat pump will be.

In case the terrain allows drilling geothermal boreholes, the soil can be used as exergetic storage. During summertime, this storage can then be charged with excess heat of solar thermal collectors, industrial processes, but also waste heat from air-conditioning units. Due to the low temperature difference between the surrounding soil and the drilling, storage efficiency is high. Additionally the earth's core continually provides heat energy to the storage.

In I-1 "Supply & demand gap", it is shown that theoretically a storage efficiency of only 14% needs to be obtained in order to supply a well-insulated building with sufficient thermal energy throughout the year. When considering exergy as a storage medium, such storage efficiencies seem obtainable.

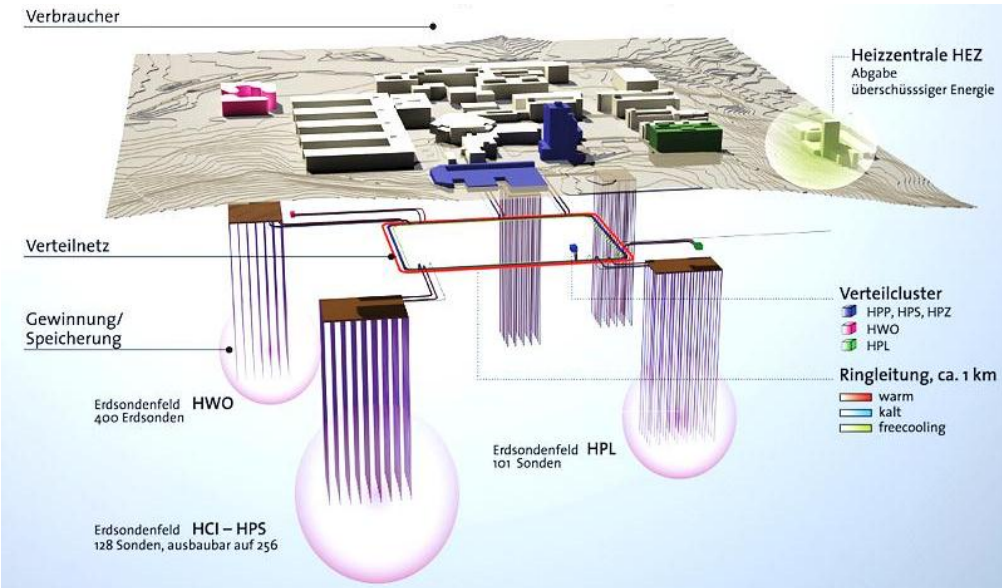


Figure 26 Exergy storage network on the ETH Zürich campus Hönggerberg[13]

Although, especially in Switzerland, there are a number of projects, that apply these principles, are on the way, little long-term experiences exist. One crucial question is, if the soil can store the fed energy in practice. Figure 26 illustrates the low-temperature storage network currently being established on the campus of the Swiss Federal Institute of Technology (ETH Zürich).

[13] Source: *http://www.ethlife.ethz.ch/archive_articles/110902_Energiepraxis_ETH/index* (access: 26. Aug. 2011)

III. BUILDING STOCK POTENTIALS

The previous sections illustrated the ecological usefulness of load management in general (I) and provided an overview how load management in buildings could be realized (II). Section III gives an indication about the ecological potentials of selected load management measures. The objective is to compare analyse the exploitation potential of Renewable Energies. As seen in the first section, operating energy is difficult to supply and involves usually environmental impacts. Therefore, a number of scenarios are tested for their potential to harmonise household load to the prevailing Renewable Energy supply. The performance of a scenario is evaluated, by comparing the residual load, respectively the estimated greenhouse gas emissions.

III-1. Methodology

In order to test the potential of energy efficiency, storage, and DSM scenarios in the following sections, a dynamic model for German electricity supply & demand was developed and used.

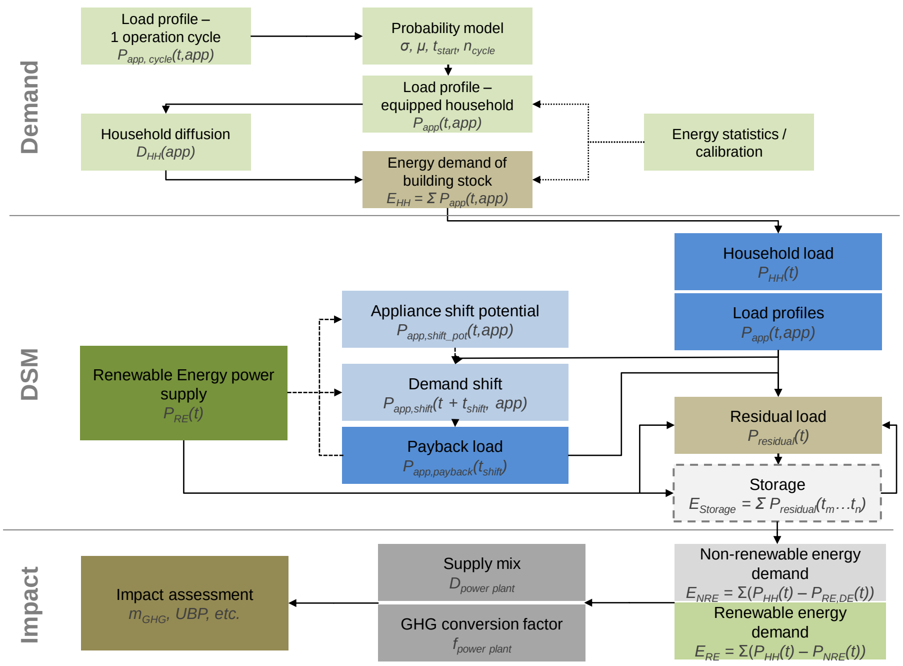


Figure 27 Model structure, consisting of demand, DSM and impact assessment module

The model is generally divided into three parts. The first part determines appliance electricity demand (top part in Figure 27), taking into account their diffusion, power demand profiles, etc. (cf. section III-2.2.1). The second part of model, analyses DSM, respectively storage potential by using the disposal of Renewable Energy as decision criterion (cf. section III-2.2 and III-2.1). The last module determines residual electricity, in order to estimate environmental impacts. The respective modules will be explained in more detail in the respective sections of this chapter. In order to account for the rapid fluctuations of energy supply and demand curves, the model uses 15-minute resolution for input and output. The algorithms are programmed as Visual Basic scripts.

III-1.1. Electricity demand

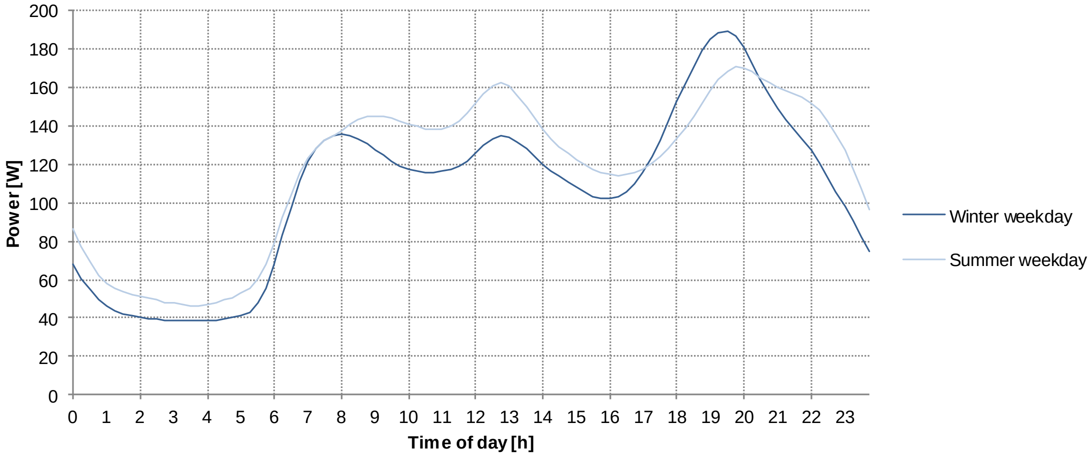


Figure 28 BDEW H0 household profile for a weekday in summer and winter

European electricity load profiles are available from the website of the European Network of Transmission System Operators for Electricity (ENTSOE).[14] For this study, 2010 data was used. The electricity demand of German households was generated synthetically by means of an appliance demand model. The household (H0) load profile of the BDEW[15] serves as a basis in order to characterize and calibrate electricity demand of selected appliances (cf. section III-2.2.1).

In order to investigate the potential of Demand Side Management for German households, a number of appliances were selected. The choice of appliances corresponds mostly to *dena 2010*, as illustrated in chapter II-4.2.1 and Figure 23 on pages 32f. That means approximately 60% of household electricity demand is covered by the model. The appliances, that are used, are the following (cf. also III-2.2):

- Washing machine
- Tumble dryer
- Dish washer
- Cooking (aggregate)
- Refrigerator
- Fridge
- Electrical space heating
- Circulation pumps
- Domestic hot water

Furthermore, an air-conditioning and a heat pump appliance exists in the model. Both were not used, because annual electricity demand of these categories is low.[16] Energy demand of each appliance is modelled by means of the demand module. Figure 29 illustrates the procedure.

---

[14] The ENTSOE website provides a large number of electricity network data for recent years: *www.entsoe.eu* The ENTSOE website provides a large number of electricity network data for recent years: *www.entsoe.eu*

[15] Bundesverband der Energie- und Wasserwirtschaft e.V., formerly known as VDEW

[16] Existing heat pumps are comprised in the 'electrical space heating' appliance. A separate study on heat pumps is carried out in III-2.3.1.

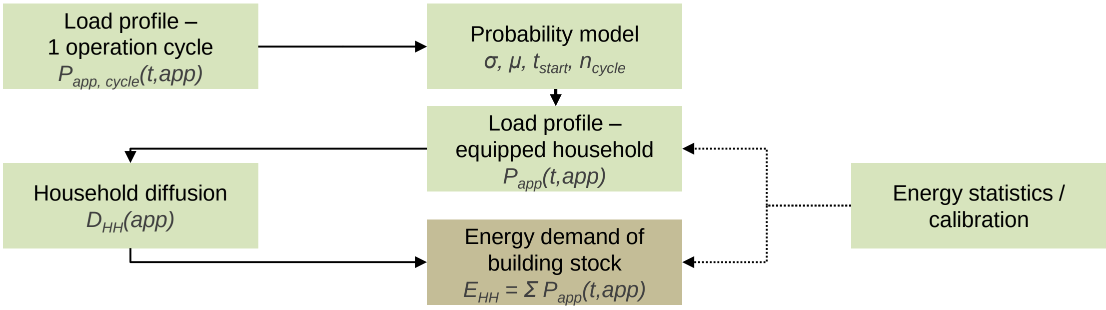


Figure 29 Probability model determining load profile of appliances, households, and building stock (cf. demand module in Figure 27)

Based on a typical load profile of each appliance (category) and a probability of appliance start, a load profile for an equipped household is determined. In the next step, typical diffusion rates of the appliances are multiplied with the number of German households and annual electricity demand of the appliance. The resulting electricity demand is compared with other sources, such as *Stamminger 2008*, *Enerdata 2011*, and *dena 2010*. In case of a deviation, another iteration is necessary. Adaptations may be necessary for the respective load profile (esp. duration), number of cycles, and household diffusion.

NB: Influencing these figures appears justified, since various uncertainties prevail in the field of households appliances. Knowledge seems to be rather limited. Independent statistics and reports, such as the above, are often contradictory. Moreover, this appears to be a common shortcoming. Also Swiss sources on electricity demand provide deviating figures (cf. *Bush et al. 2007, Hofer 2007*, etc.).

The specifics on the respective appliances are provided in section III-2.2.

III-1.2. Demand Side Management

In the following chapter (III-2, Scenarios), different scenarios of load management are tested. Therefore, the model contains a module determining demand shift potential for each appliance. Figure 30 illustrates the procedure of this module.

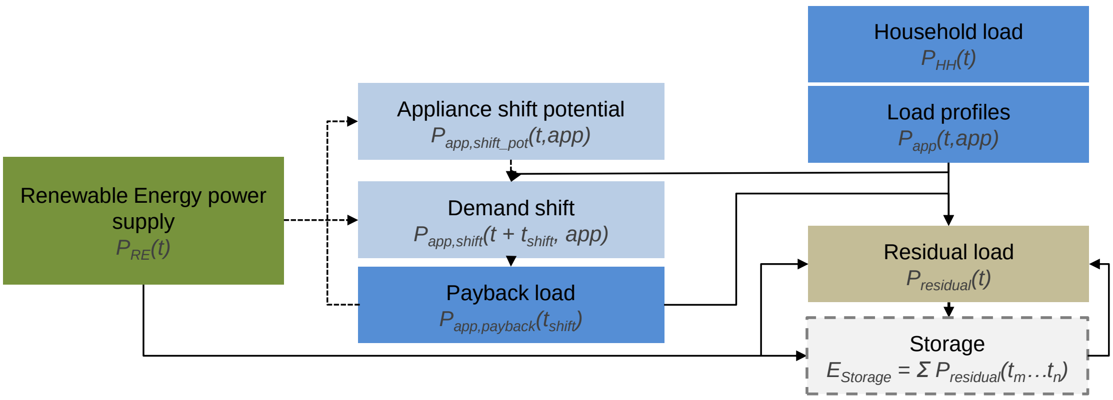


Figure 30 DSM module determining energy demand after demand shift and energy storage (cf. Figure 27)

As a decision rule, household demand is compared with the prevailing supply in Renewable energies. When more electricity from renewables is available than consumed by the household, the model proceeds to the next time-step. However, in case household demand exceeds the Renewable energy supply, the model decides to activate the demand shift of the respective appliance. As a first priority, the model activates appliances, where only little loss in the building occupant's comfort is anticipated. If the measure is not sufficient (i.e. reduced household demand still exceeds RE supply), DSM of further appliances is activated. This routine is repeated for all appliances. An appliance has the possibility to shift its demand during a certain time period (cf. t_{shift} in Table 6). When this period is expired, the appliance is forced to recuperate the energy it displaced earlier. Since the appliances have no means of predicting the future supply situation, it is simply assumed appliances will use the maximum time of demand shift regardless of the network state.

Furthermore, this module holds an optional storage algorithm. It is capable to displace over-capacities of RE and release them either when supply is necessary or after a given time $t_{storage}$. Finally, the module delivers the remaining appliance load curve after DSM and storage. It is assumed that all appliances of a kind are able to shift their load (P_{app}) during the entire shift time (t_{shift}). This is a rough simplification, since appliance operation cycle stat is not taken into account. A fraction of the appliances in the building stock may be at the end of a demand shift and therefore not able to displace power consumption any longer.

III-1.3. Electricity supply

Feed-in electricity 2010 from biomass, hydropower, photovoltaics and wind power are considered as input data for Renewable Energy supply. Data for PV and wind power was extracted from the homepages of German TSOs. For all other RE sources a synthetic profile was created. The data is documented and discussed in more detail in section I-2.1 on pages 14ff. Data was either available in 15-minute time-steps or converted to such. The Renewable Energy supply profile is taken "as is", i.e. no changes are made to it. It is only the demand side adapting to the current (at time t) supply situation.

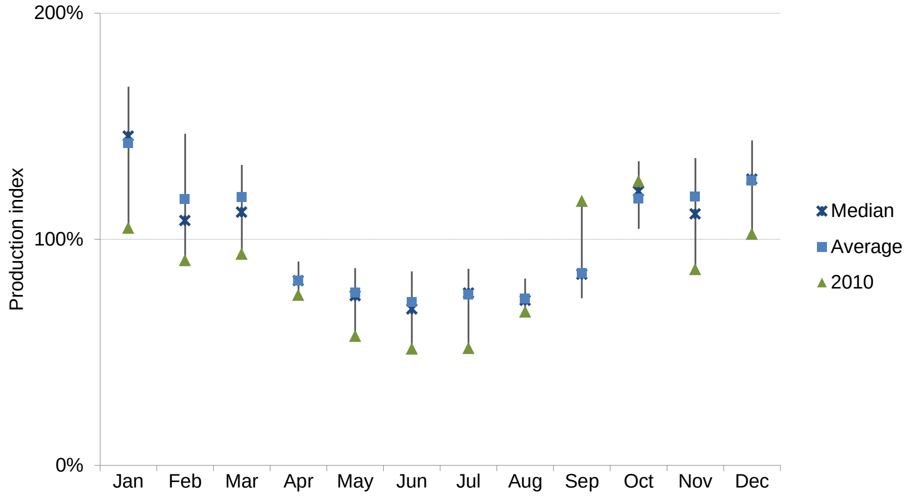


Figure 31 Wind energy production index for Aurich, Northern Germany. 2010 data and average, median with lower and upper quartiles for data from 1990 to 2010[17]

Supply of solar and wind energy fluctuates only slightly in between different years. Figure 15 shows that annual deviation is only about ±8% in relation to the 40, resp. 10 year average (given as 100%). Seasonal variation however is much more pronounced. While wind power supply increases in autumn and winter time, solar energy supply is maximum in summer.

Although 2010 was in Germany the year with the highest amount of RE supply so far, this specific year seems not necessarily representative. Figure 31 illustrates wind power data for one site in Northern Germany in 2010. Annual average lies 15% below the 10-year average. This observation is confirmed by other sources, such as the IWR. They state data for 2010 is approx. 15% to 25% below average.[18] According to the German meteorological service

[17] Data: *http://www.anemos.de/2/?pg=212&lg=1* (Dataset WEA P=2 MW, h=100m)

[18] Internationale Wirtschaftsforum Regenerative Energien (IWR): *http://www.iwr.de/wind/wind/windindex/index10_10jahre.htm*, Access: 9. Aug. 2011

(DWD), global solar irradiation was 3% above average (cf. Figure 32).[19] For the other RE sources, no long-term data was accessible.

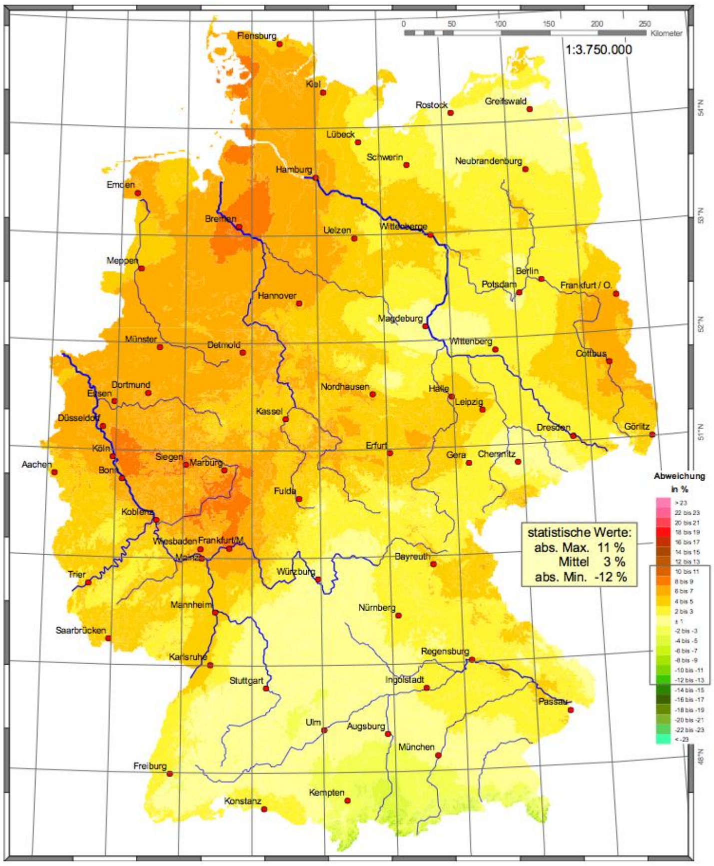


Figure 32 Deviation in global irradiation, 2010 compared to perennial mean.

The supply profile of Renewable Energies is taken

III-1.4. Impact assessment

The previous module (cf. III-1.2 on page 39) calculates the effect of DSM and storage, providing a modified load profile. Figure 33 illustrates the third module of the model (cf. Figure 27), which calculates the annual household consumption of renewable and non-renewable final energy. The effectiveness of a scenario can then be evaluated, by comparing those figures with the original state (i.e. no DSM or storage applied).

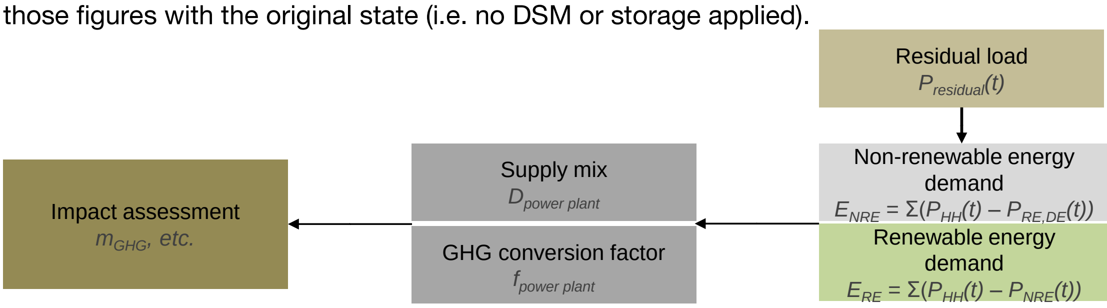


Figure 33 Impact assessment module, determining greenhouse gas emissions, etc. (cf. Figure 27)

Furthermore, a more sophisticated criterion is provided. The module calculates greenhouse gas (GHG) emissions for renewable energy carriers on an hourly basis. Feed-in data for non-renewable is unavailable. Instead annual energy statistics [*BMWi 2011*] serve as a basis to

[19] Source: Deutscher Wetterdienst, *http://www.sonnewindwaerme.de/sww/content/strahlungsdaten/pdf/pdf-jahresmittel/12.pdf*, Access: 9. Aug. 2011

calculate an approximate annual greenhouse gas emission factor. For Renewable Energy supply hourly load profiles exist (see previous section).

The data for calculating greenhouse gas emissions is extracted from the Life Cycle Inventory (LCI) database ecoinvent [*ecoinvent Centre 2007, Frischknecht et al. 2005*].[20] The lifecycle approach includes environmental impacts over the entire lifecycle of a process. That includes impacts due to fabrication, transport, disposal, etc. Emissions are given in CO_2-equivalent (CO_2-eq.) as described by the IPCC (*Forster et al. 2007*).That means greenhouse gas emitted during combustion is weighed with its respective climate forcing potential. For instance, nitrous oxide (N_2O) has 298 times the climate forcing effect than carbon dioxide (CO_2). For those reasons, also Renewable Energy carriers cause greenhouse gas emissions. Figure 34 lists GHG emission factors for each energy carrier.

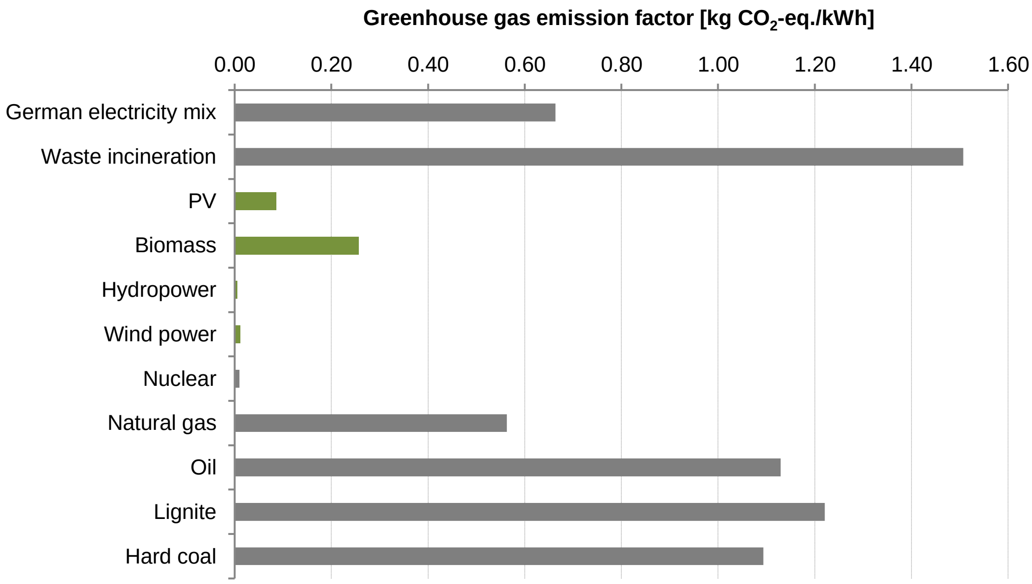


Figure 34 Greenhouse gas emission factors for electricity [*ecoinvent Centre 2007*]

The result is a dynamic emission factor on an hourly basis. Hourly power demand is then multiplied with its corresponding emission factor (i.e. same time-step *t*). The sum of all 35’040 results corresponds to the annual greenhouse gas emissions of the scenario.

III-2. Scenarios

This section investigates the potentials of load management, by means of storage and demand shift in residential buildings. A section on energy efficiency allows comparing the results with other measures. Additionally a sensitivity scenario facilitates the evaluation of results.

III-2.1. Storage

This section looks into the usefulness of electricity storage over different periods, with different control mechanisms. For this analysis a variant of the model, as described in III-1, was used. The storage model investigates a theoretical dedicated storage over the entire electricity network. That means the location of the storage plays no role for the model. It is simply assumed that a certain storage capacity is available. Charge control acts autonomously, taking only into account if Renewable Energy supply exceeds household demand. That

[20] The used datasets are listed in the Annex, Table 8.

means also demand of single appliances has no influence. Therefore, the probability module (Figure 27, respectively Figure 29) is omitted here.

The following scenarios are tested in chapter III-3.1:

Ideal storage – No losses due to charge, discharge, and storage are taken into account. This facilitates understanding of storage principle and total capacity.

Storage losses –Storage loses 5%/h of its charge.

Charge losses – Charging process takes place with an efficiency of 90%.

Storage flushing – Storage needs to be flushed (i.e. emptied) after 5 hours.

Since storage capacity plays the most important role, each scenario is run repeatedly with increasing storage capacity. The calculation algorithm stops when the improvement, compared to the previous scenario run is smaller than 0.0001%.

III-2.2. Demand Side Management

The demand side management assumes an autonomous control system that will delay power demand in case Renewable Energy supply is limited.

III-2.2.1. Characterisation of Appliances

All scenarios base on a household appliance model, which was introduced specifically for the purpose of this survey. The typical load profiles of a number of appliances serves

In the following, the different appliances used for the model are characterised. The application's power profile (green line in the following figures) denotes the application's power demand for a single cycle, e.g. one washing procedure of a washing machine. A number of variables, as given in Table 6, describe the characteristics of the appliance and its distribution in German households. The distribution model, described in III-1.1, calculates the probability of cycle start during the day. The blue line in the following respective figures (e.g. Figure 36 for washing machines) illustrates this start probability of an application. The variable t_{start} describes the point in time where a cycle start is most probable. The red line in the figures signifies the cumulated probability during one day.

Table 6 Variables used to describe DSM appliance power demand, distribution and potentials

Appliance	
P_{peak}	Peak power demand of appliance [W]
P_{mean}	Continuous power demand in Germany (i.e. all households) during one year [W]
t_{cycle}	Duration of one operation cycle [h]
t_{start}	Highest probability of cycle start [time of day]
n_{cycle}	Number of cycles (per year or day) [-]
E_{app}	Energy demand of one device during one year [kWh/a]
D_{HH}	Household diffusion – households equipped with the appliance [%]
Demand Shift	
P^{-}_{shift}	Potential to negatively buffer electricity, i.e. reduce power demand [% of $P(t)$]
t_{shift}	Maximum duration of load shifting [h]
η_{shift}	Efficiency of load shift; i.e. energy demand surplus due to increased losses [-]
η_{shift}	Efficiency potential when replacing with a 'best in class' device [% of E_{app}]

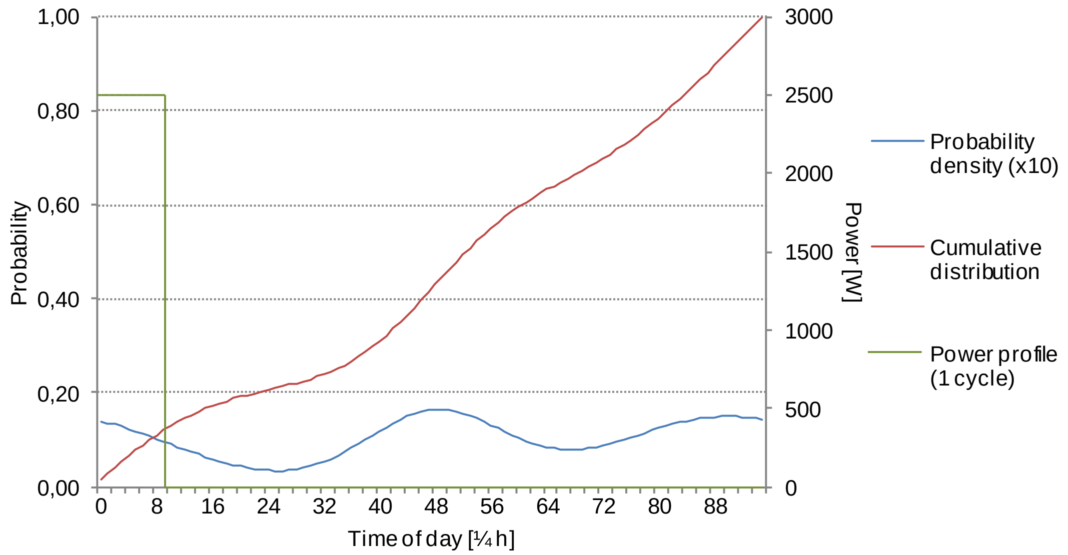
For certain appliances it is assumed that they require additional power for the load shifting cycle. This was introduced in order to account for processes, such as thermal losses during a pause phase. For instance, a washing machine heats water to a certain temperature in order to facilitate the chemical cleansing process. In case, the water is heated to a certain temperature level, e.g. 60° C, and the machine then pauses the washing cycle for a certain time, water will rapidly cool down, since machines are generally not thermally insulated. I.e. it water must be heated anew to the desired temperature level (which would have not been necessary without the intermission of the washing cycle (cf. also dilemma 5 in section I-2.2). The variable η_{shift} describes the effect, while 0.00 would signify a total loss in energy during demand shift, resulting in a twofold demand at the end of the shifting process.

Data for the appliances and DSM scenario was mostly derived from *Ackermann et al. 2009, Bukvić-Schäfer 2008, Bush et al. 2007, dena 2010, Hofer 2007, Quaschning and Hanitsch 1999, Stamminger 2008, Tanner 2007, WWF 2009*. Since sources are often divergent, the parameters were set in a way that electricity demand quantitatively corresponds to energy statistics from *BMWi 2011, Enerdata 2011*.

III-2.2.2. Domestic hot water

Information on diffusion and annual electricity demand of electrical hot water systems is contradictory. For instance, sources mention diffusion of 26% to 45% for German households (*Stamminger 2008, WWF 2009*). Moreover, a number of smaller secondary hot water units are installed.

Domestic hot water (DHW)

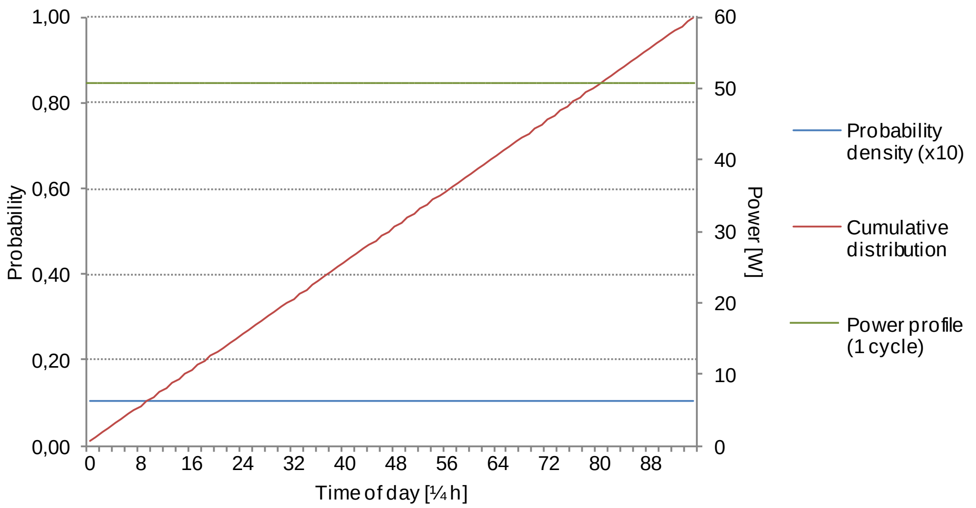


Characteristics	Probability	Potentials
P_{peak} = 2500 W	D_{HH} = 45%	P'_{shift} = 100%
P_{mean} = 40 W	t_{start} = 22.5h	t_{shift} = 6h
t_{cycle} = 2.5 h	n_{cycle} = constant	η_{shift} = 1.00
E_{app} = 787 kWh/a		η_{eff} = 0.95

III-2.2.3. Circulation pumps

Centralized heating systems are usually equipped with circulation pumps to distribute the hot water to the heat radiators in the building. Moreover, domestic hot water systems of large buildings often have circulation pumps to reduce waiting times for hot water on tap water extraction points.

Circulation pump (CP)



Characteristics	Probability	Potentials
P_{peak} = 51 W	D_{HH} = 70%	P_{shift} = 100%
P_{mean} = 36 W	t_{start} = continuous	t_{shift} = 3h
t_{cycle} = 24 h	n_{cycle} = continuous	η_{shift} = 0.95
E_{app} = 447 kWh/a		η_{eff} = 0.40

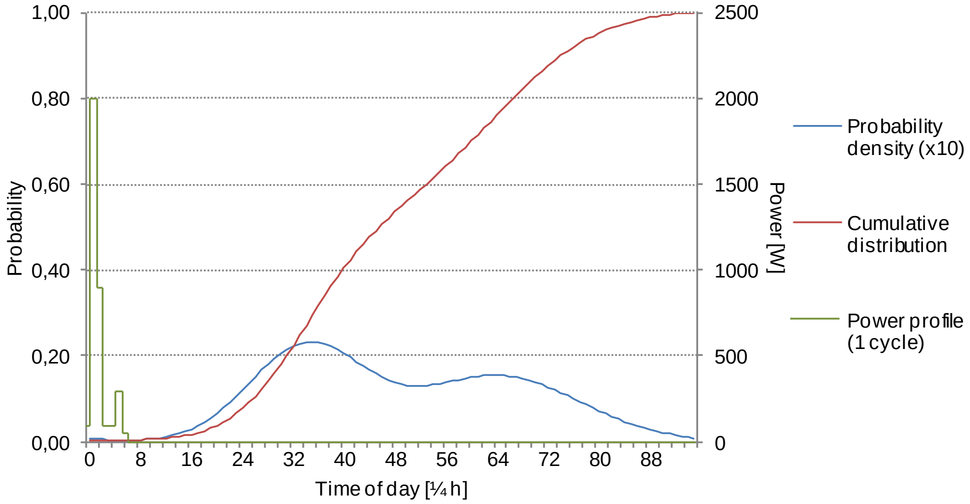
Figure 35 Circulation pump parameters

The annual energy demand of circulation pumps is surprisingly high. In Germany annually approximately 13 TWh, are consumed by circulation pumps. That corresponds to 9% of Germany's total electricity demand. According to *Bukvić-Schäfer 2008* and *Jardine and Lane 2005* the main reason is that pumps are usually oversized and operate during the entire heating season or even the whole year. Furthermore, manufacturers developed more efficient pumps with adapting rotation speed in recent years. *Jardine and Lane 2005* estimates that system optimization could yield in an electricity demand reduction by 60%.

III-2.2.4. Washing machine

Washing machines consume approximately 7 TWh/a in Germany. The shift potential of this appliance lies partly in the start delay. I.e. the user sets a delay of machine start, so that night-time electricity can be used. Another possibility is that the user lets the machine chose the optimal start time. A demand shift of a running washing program results in energy loss, since water must be reheated after an interruption.

Washing machine (WM)



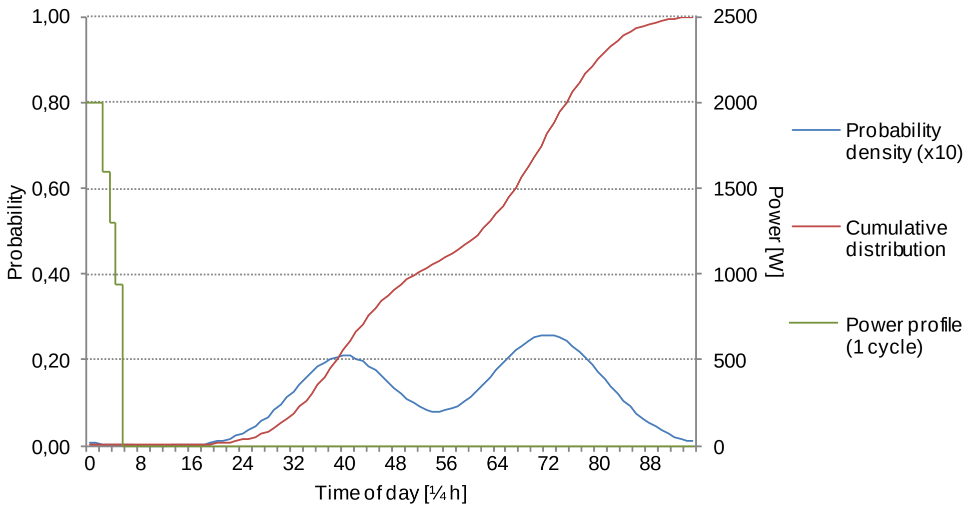
Characteristics	Probability	Potentials
P_{peak} = 2000 W	D_{HH} = 95%	P'_{shift} = 100%
P_{mean} = 19 W	t_{start} = 8.5h	t_{shift} = 4h
t_{cycle} = 1.75 h	n_{cycle} = 197 a^{-1}	η_{shift} = 0.95
E_{app} = 176 kWh/a		η_{eff} = 0.66

Figure 36 Washing machines parameters

III-2.2.5. Tumble dryer

Tumble dryer characteristics resemble the ones of washing machines. Therefore, similar assumptions are made. Since most tumble dryers are used after washing clothes, its operation probability is highest 1-2 hours after washing machine peaks. Modern tumble dryers are equipped with heat pumps and far more energy efficient, compared to typical devices.

Tumble dryer (TD)



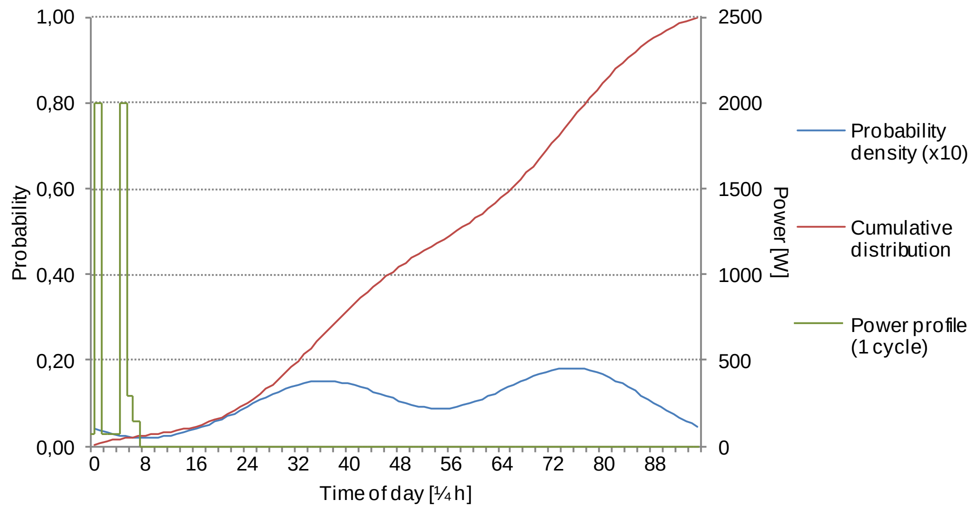
Characteristics	Probability	Potentials
P_{peak} = 2000 W	D_{HH} = 42%	P'_{shift} = 100%
P_{mean} = 5 W	t_{start} = 18 h	t_{shift} = 2h
t_{cycle} = 1.5 h	n_{cycle} = 37 a^{-1}	η_{shift} = 95%
E_{app} = 100 kWh/a		η_{eff} = 0.40

Figure 37 Tumble dryer parameters

III-2.2.6. Dish washer

Similar to washing machines modern dishwasher possess a timer functionality, which lets users displace machine start into night hours and therefore profit from lower electricity tariffs.

Dish washer (DW)



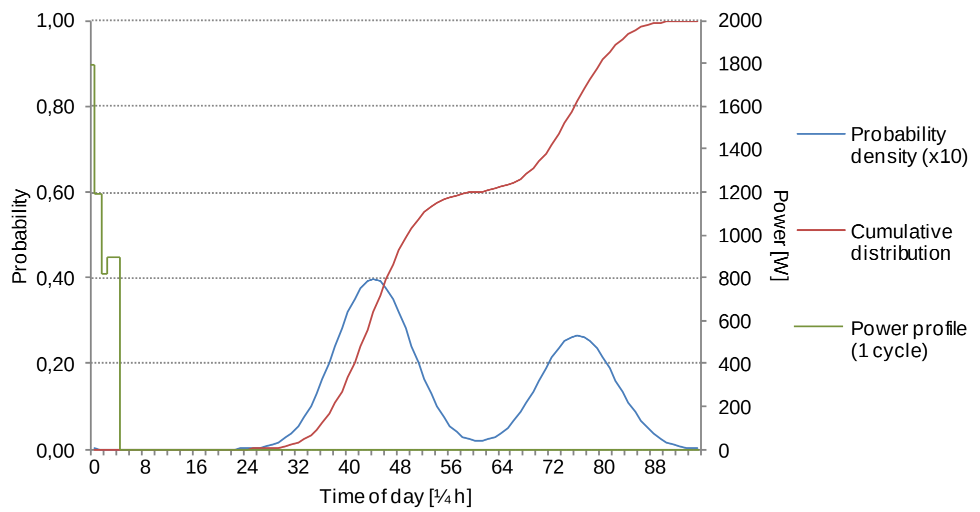
Characteristics	Probability	Potentials
P_{peak} = 2000 W	D_{HH} = 62%	P_{shift} = 100%
P_{mean} = 14 W	t_{start} = 19 h	t_{shift} = 3h
t_{cycle} = 2.00 h	n_{cycle} = 153 a^{-1}	η_{shift} = 95%
E_{app} = 203 kWh/a		η_{eff} = 0.60

Figure 38 Dish washer parameters

III-2.2.7. Cooking

This appliance actually describes the aggregate of electrical thermal cooking devices, i.e. ovens and hobs. The household diffusion of 90% accounts for the fact that a small percentage of households disposes also of gas or wood stoves for cooking.

Cooking (CO)



Characteristics	Probability	Potentials
P_{peak} = 1800 W	D_{HH} = 90%	P_{shift} = 10%
P_{mean} = 40 W	t_{start} = 11.5 h	t_{shift} = 15 min
t_{cycle} = 1.25 h	n_{cycle} = 274 a^{-1}	η_{shift} = 100%
E_{app} = 388 kWh/a		η_{eff} = 0.80

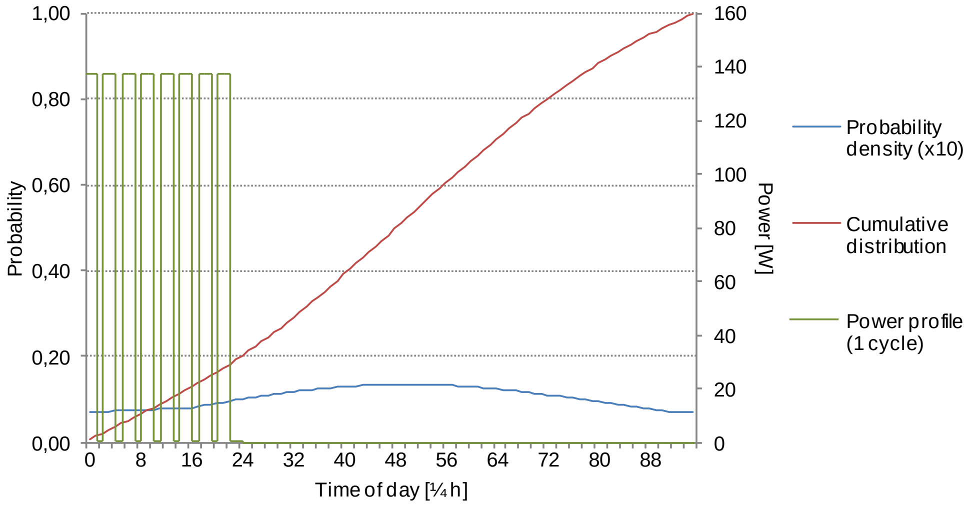
Figure 39 Cooking appliances parameters

III-2.2.8. Refrigerator

Refrigerators operate 24 hours a day and usually have an on/off mechanism, switched by a hysteresis thermostat controller. It is assumed the devices run approx. 2.6 cycles per day. In Germany all households are equipped with at least one refrigerator.

Since refrigerators are thermal devices, they have a certain capacity for demand shift. *Koch et al. 2009b* investigate the storage capacity and show that refrigerators may cut their power consumption for approximately 15 minutes.

Refrigerator (RE)

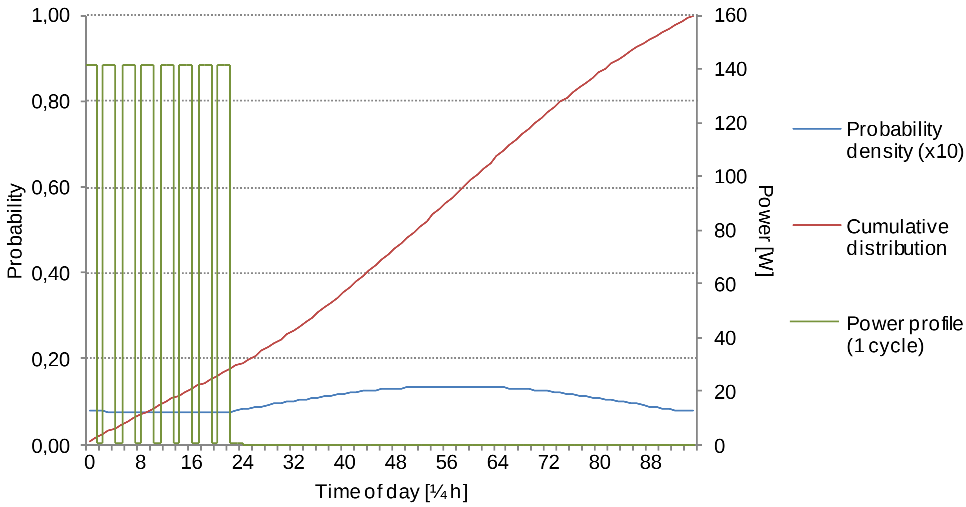


Characteristics	Probability	Potentials
P_{peak} = 138 W	D_{HH} = 106%	P_{shift} = 100%
P_{mean} = 26 W	t_{start} = 16h	t_{shift} = 45 min
t_{cycle} = 6.5 h	n_{cycle} = 1.4 d^{-1}	η_{shift} = 1.00
E_{app} = 216 kWh/a		η_{eff} = 0.50

Figure 40 Refrigerator parameters

III-2.2.9. Fridge

Fridge (FR)



Characteristics	Probability	Potentials
P_{peak} = 142 W	D_{HH} = 52%	P_{shift} = 100%
P_{mean} = 29 W	t_{start} = 17.5 h	t_{shift} = 2h
t_{cycle} = 6.5 h	n_{cycle} = 1.4 d^{-1}	η_{shift} = 1.00
E_{app} = 480 kWh/a		η_{eff} = 0.75

Figure 41 Fridge parameters

III-2.2.10. Space Heating

Since German residential buildings are very heterogeneous in shape, fabric and energy demand it is difficult to determine load profiles and shift potential for space heat demand. If thermal energy supply to a building is interrupted in wintertime, a building will normally slowly cool down (cf. Figure 42). At a certain temperature, thermal comfort in the building is impaired.

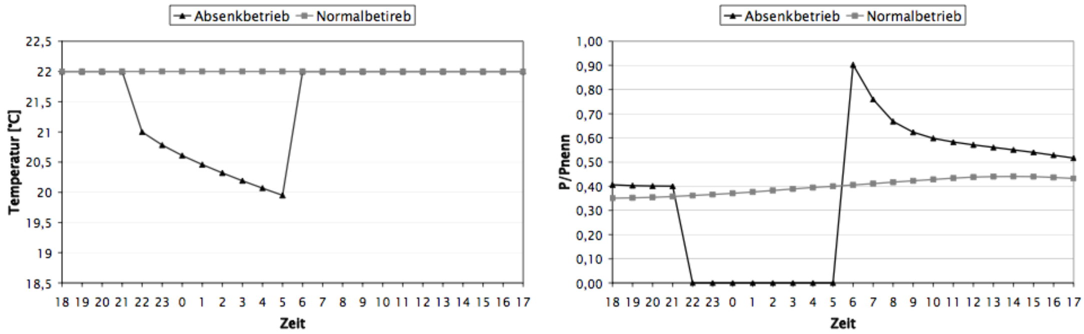


Figure 42 Indoor temperature and heating power according to heating control [*Bukvić-Schäfer 2008*]

Bukvić-Schäfer 2008 carries out a comprehensive study of a building's thermal inertia and corresponding potential of load delay. By means of dynamic simulation, he determines the influence of the building envelope's thermal transmittance (U-value) and mass. Therefore, Bukvic-Schäfer investigates the composition of typical German building fabric.

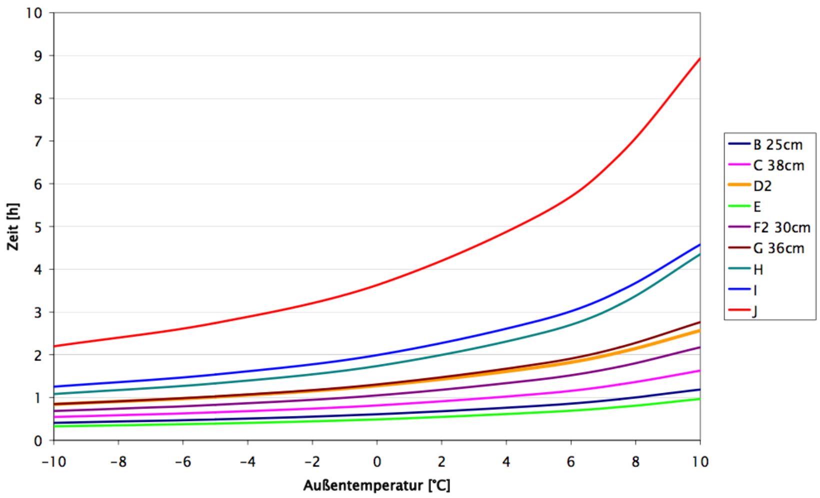


Figure 43 1 K cool-down of a building for different building envelopes [*Bukvić-Schäfer 2008*]

Figure 43 illustrates cool-down of 1 K for different building envelopes. A rough estimation of wall compositions of the German building stock shows, that approximately 70% of buildings were constructed between 1919 and 1986 (cf. Figure 44). That means the graphs C to G are most relevant to the German building stock.

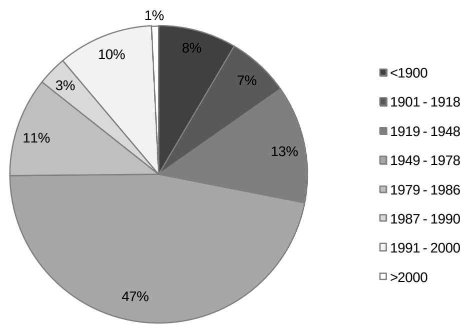


Figure 44 German building stock by construction period

In order to derive load shift duration for space heating, also outdoor temperature must be known. The German reference climate data (according to DIN 4108-6) shows that average outdoor temperature during the heating season is approximately 4° C (cf. Figure 45).

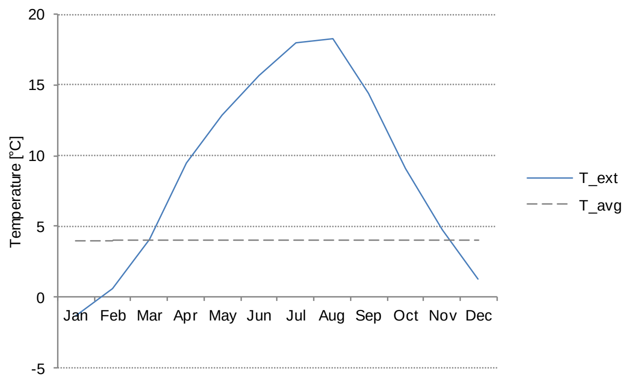


Figure 45 Monthly and average outdoor temperature in Germany according to DIN 4108-6

These figures allow estimating a shift potential for space heating in Germany. A temperature decrease of 1 K within the building allows interrupting thermal energy supply for 1 to 2 hours.

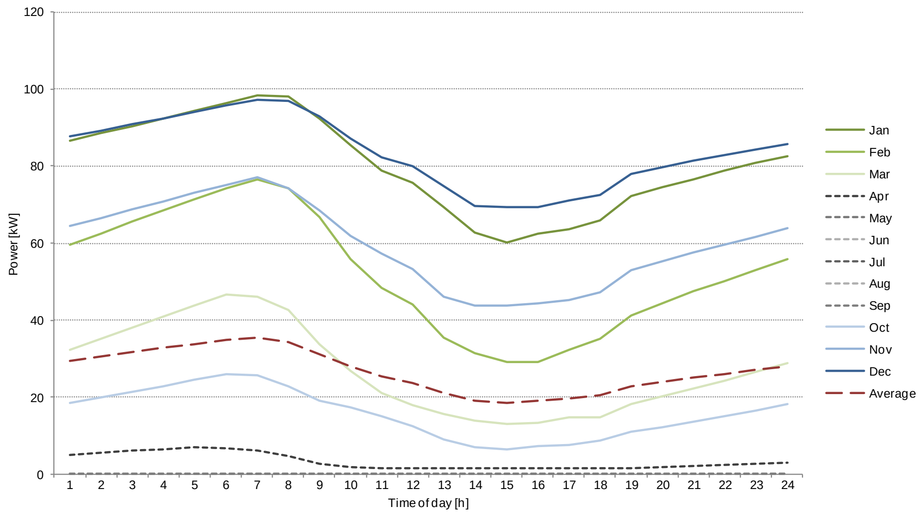


Figure 46 Average monthly thermal power demand of a residential building

Figure 46 illustrates the power demand of a reference building during one year. The building has similar glazing ratios towards eastern, southern and western facades. The northern facade has half the glazing surface. The power demand curves illustrate the typical annual thermal power demand of a building. At midnight, the residential building cannot profit from any solar, nor internal gains. Therefore power demand increases until sunrise, 7 a.m. respectively. Power demand decreases during the day, having a minimum at around 3 p.m. The building's thermal mass mitigates its cooling after sunset.

According to the Odyssee database (*Enerdata 2011*) space heat demand in Germany is around 14 MWh per household. Furthermore, 3.6% of space heat was provided by means of electricity in 2009.

III-2.2.11.Appliances load profile

The ten appliances, processed by the model, represent approximately 54% of the total German household electricity demand [*Destatis 2011*]. Figure 47 illustrates the resulting average demand for the appliances characterised above. For reasons of comparability, an average BDEW H0 household profile is also is depicted (dotted grey line).

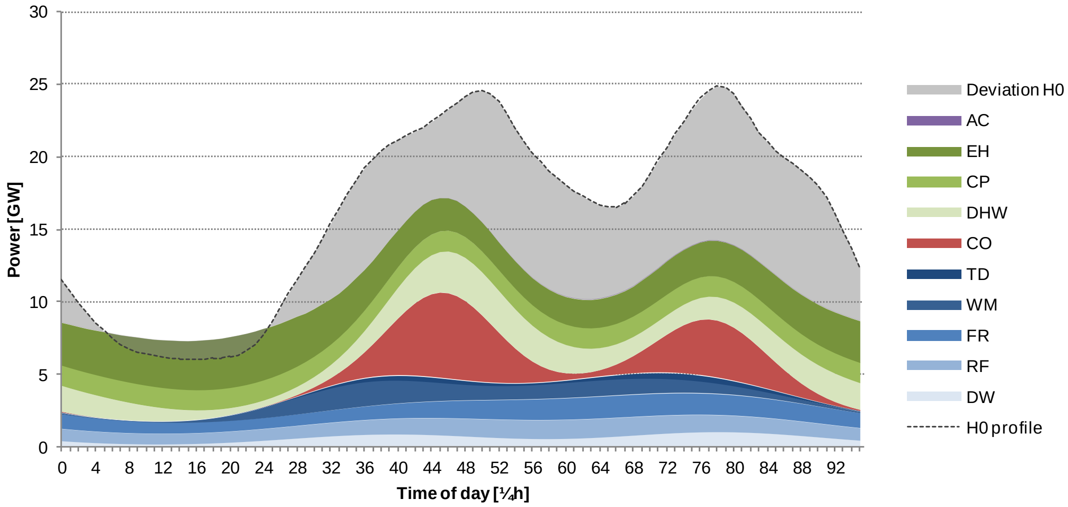


Figure 47 Average annual appliance load profile compared to VDEW German standard profile H0

The resulting demand profile resembles the standard profile for German households. Around noon and in the late evening a peak in electricity demand is observed. These are mostly dominated by occupant-related behaviour, such as washing, cooking and dishwashing. The space heat appliances operate mostly at night, while electricity is cheap and the storage systems allow displacement of loads. At night hours, the demand does not correspond to the H0 profile. However, the H0 profile does not account for electrical heating systems and is therefore not fully representative.

III-2.3. Sensitivity analysis

In order to widen the understanding of the interrelationships between Renewable Energy disposal and load shifting, a number of sub-scenarios will be investigated.

III-2.3.1. Heat pump scenario

The current share of heat pumps in the German residential sector is approximately 0.5% and 5.5% for direct electric heating respectively (*WWF 2009*). Therefore, the scenarios above represent the DSM potential of the buildings' thermal mass only inadequately. In order to investigate the theoretical potential of grid-connected space heating systems, a second DSM scenario is applied to the model.

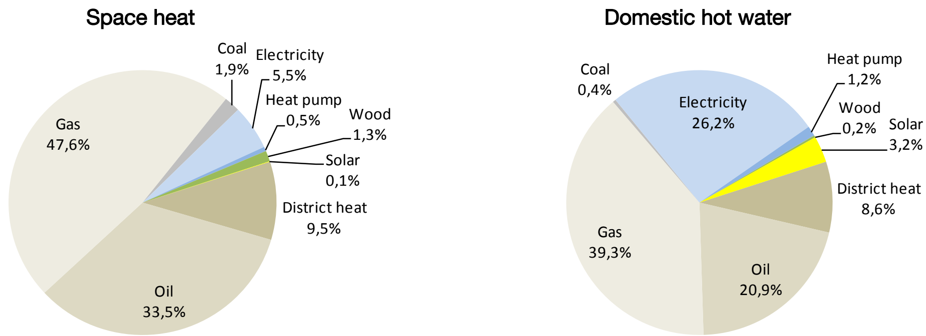


Figure 48 Space heat and hot water production in German households in 2005, Source: *WWF 2009*

It is assumed that 100% of space heating is supplied by heat pump systems with an average annual COP of 3.0. The COP shall represent an average mix of air source and geothermal heat pumps, for retrofitted and newly constructed buildings [*Erb et al. 2004*].

III-2.3.2. Efficiency

The energy efficiency scenario shall provide a comparison to the DSM and storage scenarios. The efficiency factors (Table 7) are applied to the DSM scenario load curve. The factors were calculated and derived from *Bush et al. 2007, WWF 2009* and by considering current 'top ten' devices.[21]

Table 7 Efficiency potentials for appliances

Appliance	Abbreviation	Energy efficiency potential
Space heating	EH	60%
Domestic hot water	DHW	95%
Circulation pump	CP	40%
Washing machine	WM	66%
Tumble dryer	TD	40%
Dish washer	DW	60%
Cooking	CO	80%
Refrigerator	RF	50%
Freezer	FR	75%

III-2.3.3. Demand shift duration

In order to investigate the influence of demand shift duration (t_{shift}), the model is run with ±20% and ±50% of the factors given in III-2.2.

III-2.3.4. Renewable Energy share

The availability of Renewable Energy lets the model decide if an appliance should shift its demand or electricity storage charge or discharged. Thus, it plays an important role for the model behaviour. The more often RE supply exceeds the demand curve, the more appliances have the possibility to recover, respectively storage can be filled. Thus, the current share of Renewable Energy (17.4%) is altered by ±5.0%.

III-3. Results

In the following, the results of the scenarios model runs are documented. The results are given in greenhouse gas emissions, as described in III-1.4.

III-3.1. Energy storage

As given in the scenario descriptions, III-2, the storage module considers a general storage potential for the building stock. That means periods of high Renewable Energy supply can be buffered. The variables having most important influence are storage capacity $E_{storage,max}$, maximal storage duration $t_{storage,max}$, and storage management. Storage capacity at the first time-step ($t = 0$) is zero.

Ideal storage – No losses due to charge, discharge, and storage are taken into account. This facilitates understanding of storage principle and total capacity.

- Storage losses – Storage loses 5%/h of its charge.
- Charge losses – Charging process takes place with an efficiency of 90%.
- Storage purge – Storage is forced to discharge after 6, respectively 12 hours of storage.

[21] Top ten appliances: *www.stromeffizienz.de* and *www.topten.ch* (Access: 23. Aug. 2011)

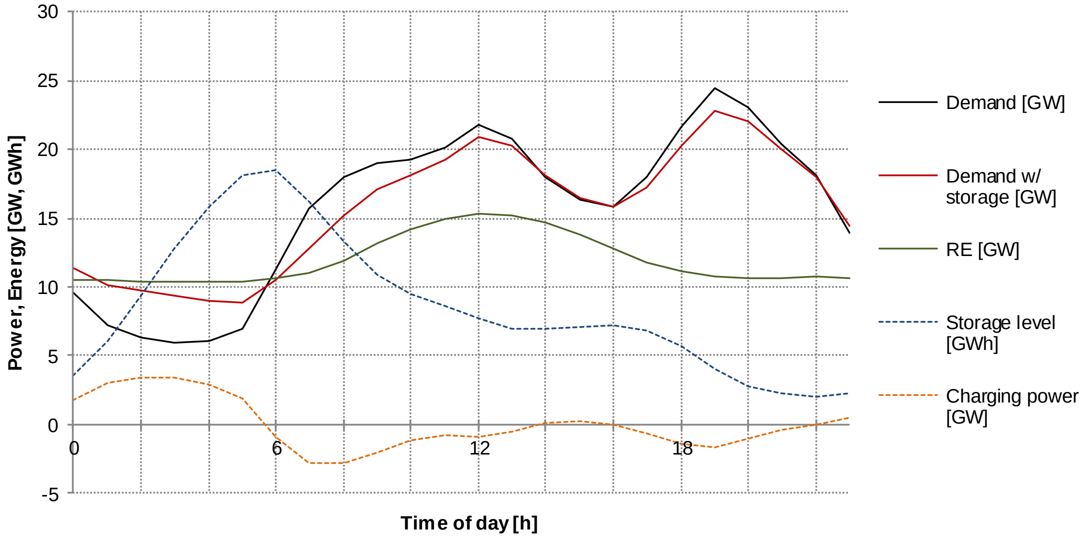


Figure 49 Annual average power demand curve with and without storage and storage level and charging power (scenario: ‘ideal storage’, 1kWh capacity)

Figure 49 shows the principle of the storage system. The original demand curve (black) is modified (red) by means of charging, respectively discharging (orange, dotted) the storage system (blue, dotted). This helps to flatten the demand curve out and approach it towards the current supply situation of Renewable Energies (green).

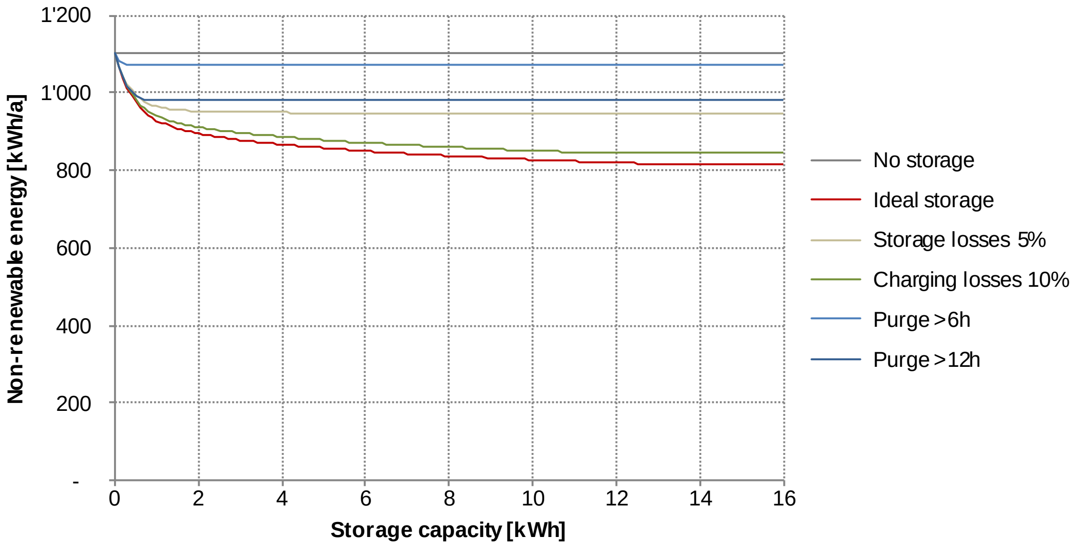


Figure 50 Results for energy storage scenarios

Figure 50 illustrates the results of the different simulation runs. The horizontal axis gives storage capacity in kWh. While 9.4 kWh correspond to approximately the amount of electricity one average household consumes in one day. The vertical axis describes the resulting non-renewable energy demand in kWh per household and year. It shows that with increasing storage capacity the non-renewable energy demand reduces as a logarithmic function, approaching each a certain threshold.

The ‘no storage’ graph illustrates annual non-renewable energy demand of households – in case 100% of Renewable Energy, currently produced in Germany, is allocated to households. 1’100 kWh originate from non-renewable energy sources. That means 2’320 kWh, 68% of German household demand respectively, is already provided by Renewable Energies.

Naturally, the ‘ideal storage’ system yields the highest savings in non-renewable energy demand. At a storage capacity of approximately 14 kWh (150% of average daily demand), the function approaches its threshold of 810 kWh. That corresponds to a reduction of 26%, compared to the ‘no storage’ scenario.

Charging losses have only little influence on the performance of a storage system. The ‘Charging losses’ scenario performs only marginally worse than the ideal storage. The threshold is also at approximately 12 kWh. The reduction potential, compared to the ‘no storage’ scenario is 24%.

Storage losses seem to have a more important effect on the performance of an electricity storage system. The scenario ‘storage losses’ yields 14% reduction, compared to initial status. The threshold lies at 950 kWh. This hints at the fact, that the electrical charges have a high dwelling time.

That insight is also supported, when looking at the two ‘Flush’ scenarios. Both perform significantly lower than the other scenarios. From a storage capacity of 0.5 kWh on, the 6h scenario yields a reduction of approximately 3%, respectively 11% at 1 kWh storage capacity for the 12-hour dwelling time. That suggests that long-term storage systems, with low energy losses, perform presumably best in residential buildings. Figure 51 illustrates the problem.

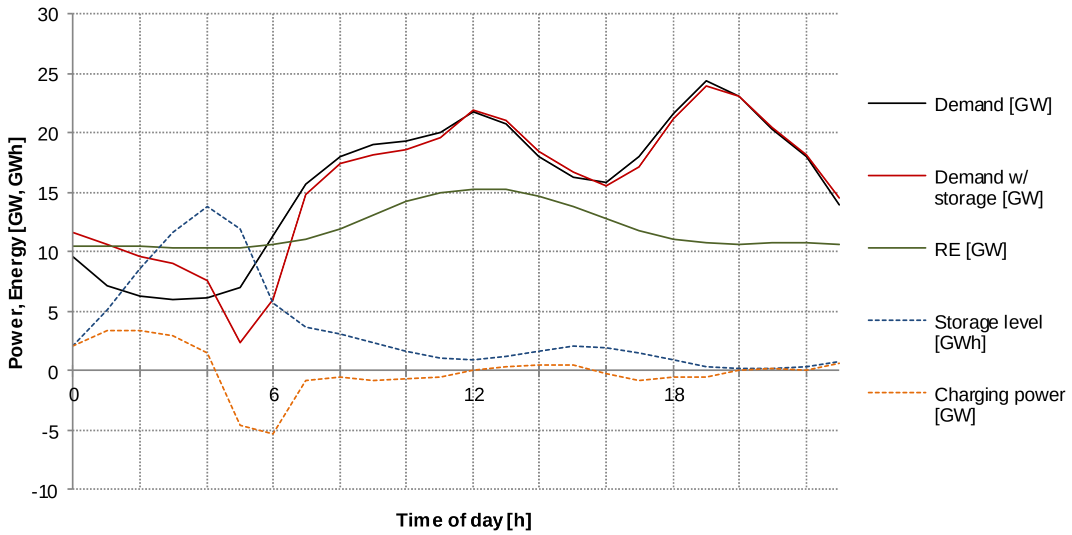


Figure 51 Analysis of the ‘Purge >6h’ scenario

Although the load management scenario that is applied in the purge scenario is a simplified one, it shows the principle. In the morning hours, storage is filled with Renewable Energy. However, it must be emptied again after 6 hours. Since morning hours is the period having most often an excess of Renewable Energy, the storage is not able to recover during the rest of the day (Figure 51). Thus, a successful load electricity storage management system must in particular be able to shift RE supply from morning hours to peak times.

The thresholds in Figure 50 depend mostly on the Renewable Energy supply profile. Electricity storage is charged only when Renewable Energy is available. The longer the period of supply, the higher the performance of the storage system. Compare also the section on sensitivities (III-3.3) for more details.

If all households were equipped with a storage device of 9.4 kWh capacity, the German electricity network would dispose of an theoretical additional sink capacity of 380 GWh. That corresponds to 0.3% of annual electricity demand of German households. Currently about 40 GWh of storage capacity from pump storage plants is installed in Germany.[22]

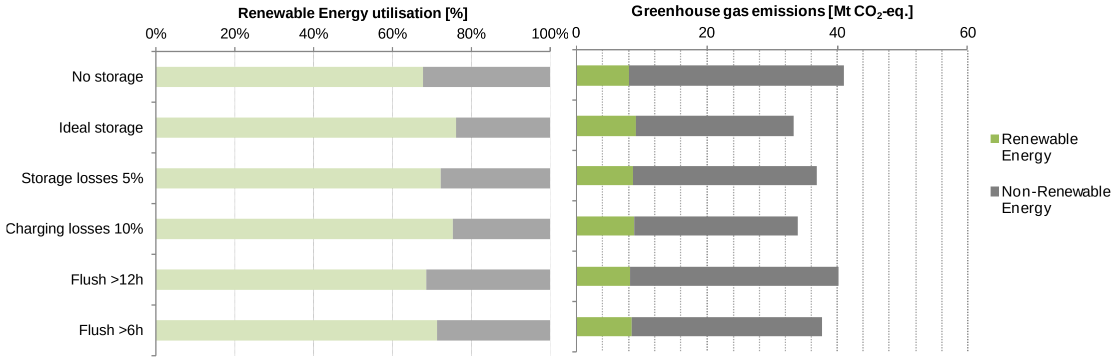


Figure 52 Household utilization of Renewable Energies (left chart) and resulting greenhouse gas emissions (right chart) for all households according to scenario. Storage capacity: 1 day, 9.4 kWh respectively.

Each scenario leads to a different utilisation of available Renewable Energy supply. In the reference scenario 'no storage', already 68% of household demand are supplied from renewables. By means of storage charge and discharge the demand curve can be modified, hence utilization of RE optimised. By means of the 'ideal storage' scenario, additional 10% of Renewable Energies can be used. Relating to the entire German residential building stock, the 'ideal storage' scenario with 9.4 kWh storage capacity (100% daily demand) allows a reduction of greenhouse gas emissions of approximately -19% (Figure 52).

Energy storage systems have the advantage of being flexible systems. As long as storage dwelling time and storage losses are insignificant, they can be charged at any given time before the load occurs.

III-3.2. Demand Side Management

The methodology and assumptions of the DSM model are provided in section III-1.2 on pages 39f and III-2.2 on pages 43f. Figure 53 illustrates the demand shifting process for the annual average. The black graph denotes the original demand curve and the red graph the modified demand curve, respectively. The orange dotted line describes shifting (negative values) and recapture respectively. Around noon and 7 p.m., when electricity demand is highest, the appliances shift their demand to less critical situations, according to their temporal shift potential (t_{shift}). Around 10 p.m. the devices recapture the demand that was delayed previously. The largest negative demand shift takes place at 7 p.m.

[22] Source: *http://de.wikipedia.org/wiki/Pumpspeicherkraftwerk* (Access: 21. Aug. 2011)

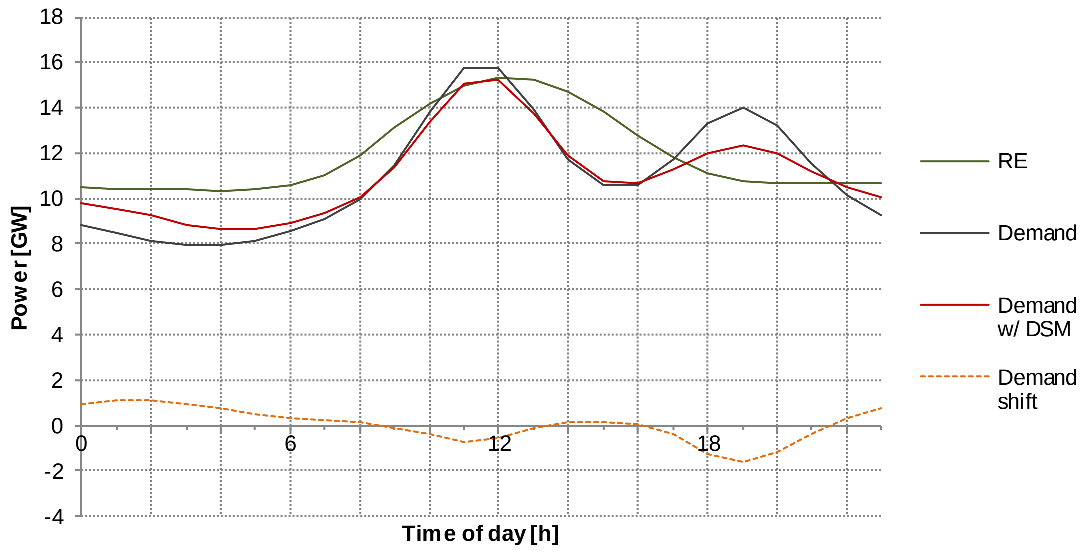


Figure 53 The effect of appliance demand shift

The respective demand shift potential of appliances is illustrated in Figure 54, below. In particular, the domestic hot water system (DHW) offers an important shift potential, since a long shift period is assumed. Despite the large energy demand of electric heating appliances (EH), their shift potential plays a secondary role. In the contrary – they show a problematic profile. Highest recapture time is around the midday peak period.

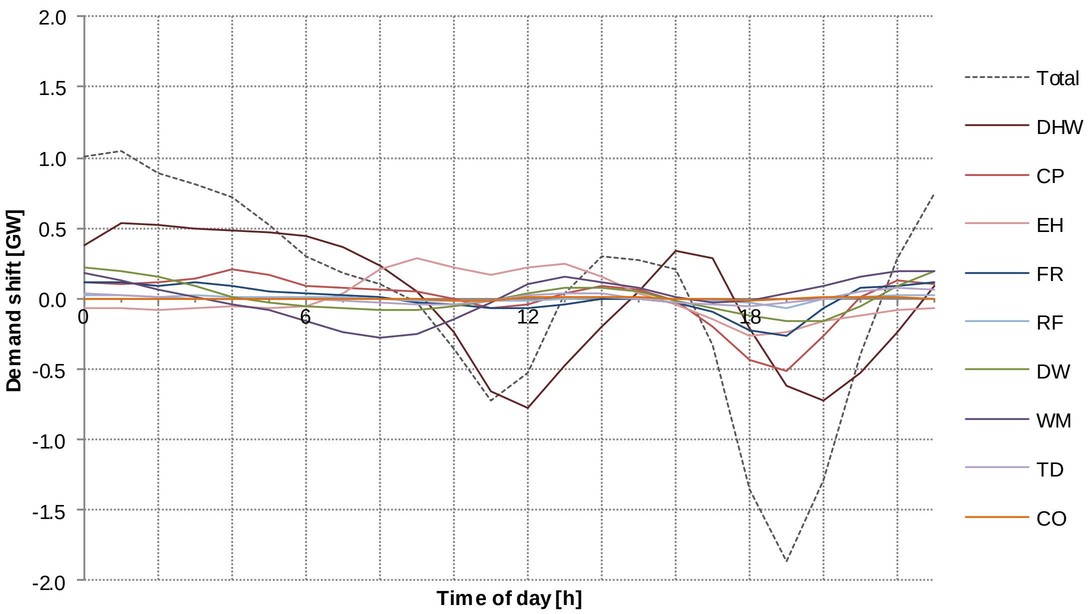


Figure 54 Annual average demand shift of appliances

This is on the one hand due to the DSM control mechanism used in the model (cf. section III-1.2 and III-4).[23] On the other hand, electric heating systems without energy storage show principally already an advantageous load profile. Space heat demand is highest during night hours and decreases from around 8 a.m. on (cf. III-2.2.10, Figure 46). That means if demand is intentionally shifted away from night-hours, the load profile will oppose to the average RE supply profile. The load shift of the cooking appliance is lowest, although it is the second largest energy consumer in the profile. That is due to the small shift potential (P_{shift}) of 5%.

[23] The demand shift takes place without consideration of future demand / supply. It is active for the entire time t_{shift}. A more intelligent control algorithm might be able to avoid elevated space heat demand during peak times.

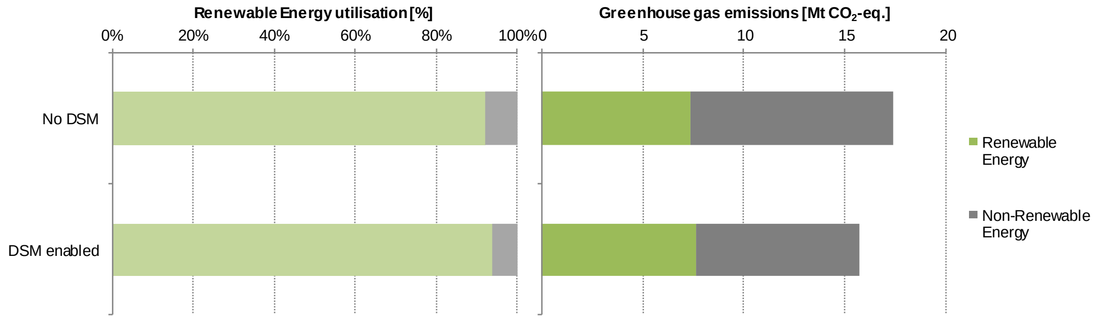


Figure 55 Household utilization of Renewable Energies (left chart) and resulting greenhouse gas emissions (right chart) for all households according to scenario.

Figure 55 illustrates the consequences of the Demand Side Management of appliances. The utilization of Renewable Energies can be increased by the in the DSM enabled scenario by 2 percentage points. Thus, greenhouse gas emissions reduce by 1.1 Mt CO_2-eq. (i.e. -8%).

Overall DSM behaviour resembles the profile in the electricity storage scenario (cf. Figure 49 and Figure 54). During peak hours, an important part of load is displaced and the demand profile is attenuated. However, a comparison of the two scenarios is only justified on a qualitative level. Each scenario bases on different assumptions and control algorithms and is solely intended to illustrate the principles of the two techniques. In contrast to storage systems, the DSM technology is less flexible. In order to leave user comfort unaffected, appliances rely on demand recovery after a given time (cf. *Quaschning and Hanitsch 1999, Tanner 2007*). Hence, the resulting demand peak cannot be avoided.

III-3.3. Sensitivities

The scenarios above investigate specific parameters, which were chosen in order to limit the extent of this work. The model has a large quantity of input parameters that can impossibly investigated in all detail here. Thus, a number of side studies show the model's sensitivity to parameter change.

III-3.3.1. Demand shift duration

The demand shift duration (t_{shift}) of all appliances is altered by ±20%. The resulting in Renewable Energy utilisation is below one per cent and the total greenhouse gas emissions changes by ±1%. The model reacts relatively insensitive to changes in time shift potential. A second run with ±50% variation, yields 2% of change.

III-3.3.2. Energy efficiency

For assessment, the effect of the appliance energy efficiency the same model as in the previous sections was used. However, the storage, respectively DSM-module, had no functionality. The efficiency factors from Table 7 are applied to the load profile of the previous section. Thus, demand reductions between 60% and 70% result. Since Renewable Energy supply exceeds the resulting demand profile frequently, 96% of energy comes from renewable sources.

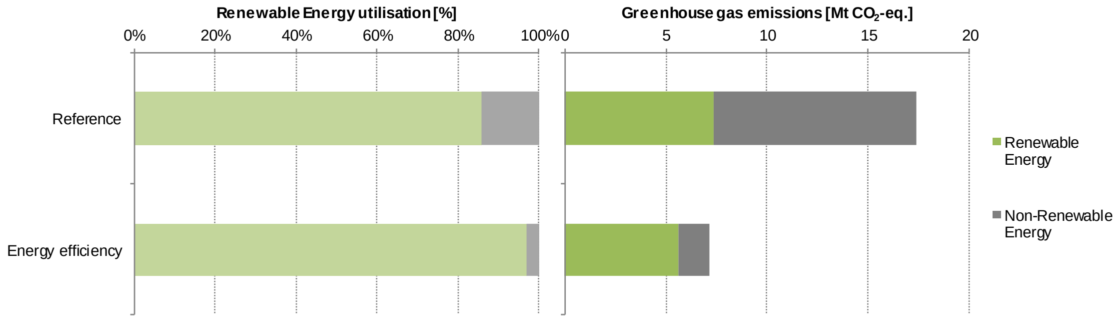


Figure 56 Household utilization of Renewable Energies (left chart) and resulting greenhouse gas emissions (right chart) for all households. Energy Efficiency sensitivity.

As a result, greenhouse gas emissions are 58% below the reference scenario. This findings correspond to *Heeren et al. 2011*, who looked at the building-specific energy-efficiency potentials of the Swiss building stock. They find greenhouse gas potentials of 46% until 2050. This is the only scenario where the GHG emissions due Renewable Energies also reduce. In the other scenarios the share of RE is increased, thus GHG emissions in this category rises.

That result outperforms the GHG reduction of energy storage and DSM by far. This finding must be considered carefully however, since it bases on rather ambitions reduction potentials, as described in III-2.3.2, Table 7.

III-3.3.3. Heat pump scenario

This sensitivity assumes that all German households are supplied with space heat by means of heat pumps. Figure 57 illustrates that the trend, already observed in the DSM scenario, aggravated. The heat pump profile (HP) has its highest demand at approximately 9 a.m. That is 2 hours after the most probable start time t_{start} (cf. Figure 46).

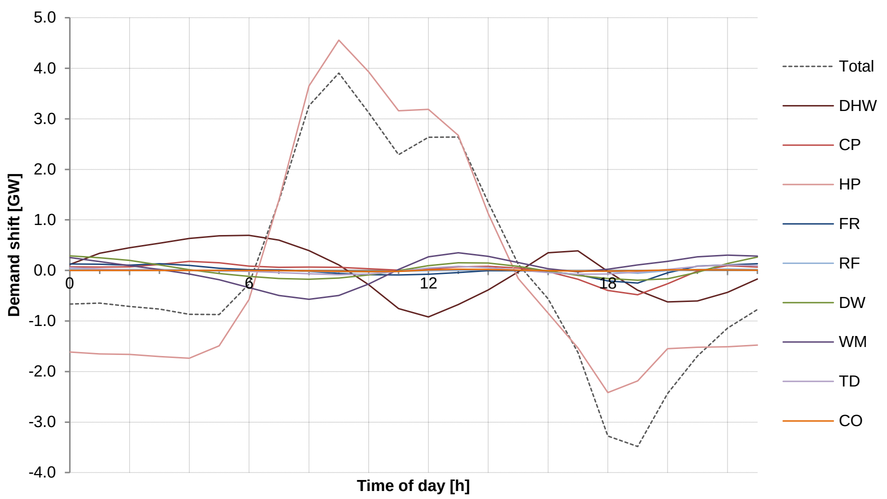


Figure 57 Demand shift - heat pump sensitivity

Instead of mitigating the typical demand profile, this sensitivity actually has a higher electricity demand during peak hours. Such a scenario is not favourable under any conditions, since it would constitute an additional problem to energy providers. However, this issue could be probably resolved by assuming a smart predictive control mechanism for demand prediction.

III-3.3.4. Renewable Energy share

An increased share in Renewable Energies facilitates the DSM control. The more often periods of RE supply occur, the higher becomes the probability that the devices can recover during such a period. Figure 58 illustrates the effect of increased and decreased supply of Renewable Energies. The first two rows show the original scenarios with a RE share of 17.4% of German electricity supply. The next two rows '+5% RE' depict the scenario with an assumed German RE share of 22.4%. '-5% RE' stands for 12.4% RE share respectively.

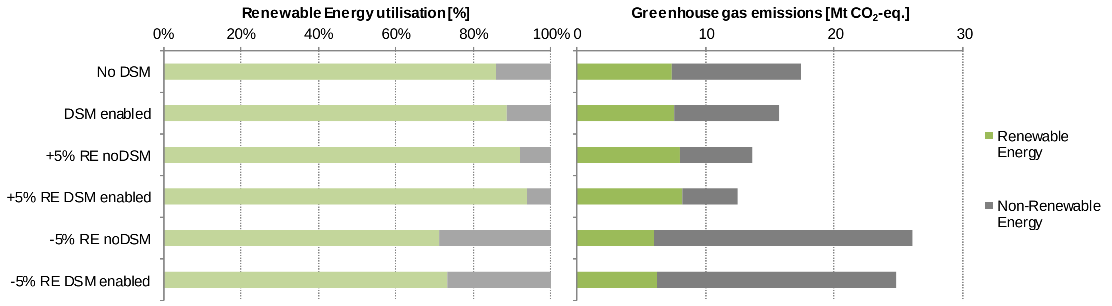


Figure 58 Household utilization of Renewable Energies (left chart) and resulting greenhouse gas emissions (right chart) for all households. RE sensitivity.

On the one hand, the scenario with the higher share in Renewable energy performs better in terms of RE utilisation and Greenhouse gas emissions. The 'DSM enabled' scenario reduces GHG emissions further to a total of 13.3 Mt CO_2-eq.

On the other hand, the scenario with reduced share in Renewable Energy results in significantly higher greenhouse gas emissions. The DSM-enabled appliances find rarely an opportunity to profit from Renewable Energies in the recapture process.

III-4. Discussion

The following section discusses a number of critical issues and possible strategies for future improvement.

III-4.1. Data quality

Due to the German law on Renewable Energies (EEG) data availability in Germany is plentiful. However, data quality is not always plausible and sometimes contradictory. Obviously, energy providers do not fully comply with the stipulated data collection.

Since the current regime in electricity markets and due to the baseload conflict, it is possible, that TSOs curtail wind or PV power from time to time, in order to prevent overcapacities. Curtailment could have falsified energy supply data. Generally, curtailment should be rather low, since legislation obliges TSOs to prioritize Renewable Energies.

III-4.2. Modelling

The model represents a simplified model of the German household electricity demand side and the Renewable Energy suppliers. As a consequence some results must be considered carefully.

For instance, the demand shift potential is determined by cycling through the single applications. In each cycle, remaining demand shift requirement is compared with the supply situation. Interactions between applications or supply situation are not yet properly represented. This is an important aspect to improve model accuracy.

The decision rule, whether demand is shifted or not, used for this model is questionable. Currently the availability of renewable energy (cf. section III-1.2) is compared to household load. This rule is does not account for the entire German electricity network. In order to improve this aspect of the model, the electricity producers should be dynamically modelled in future work. Considering the actual state and composition of energy producers, allows to judge the potential and need for load management correctly. Currently the appliances decide ‘blindly’ to shift their demand and thus provoke problematic situations (III-3.2). For instance, highest recapture time may occur around the midday peak period. In such a situation, a more intelligent control mechanism would disable demand shift in the first place.

The allocation problem of Renewable Energies is also questionable from point of view of impact assessment. The allocation of Renewable Energies to households is questionable. As mentioned in III-1.4, household demand is compared directly with the hourly available RE supply. Both points are not strictly correct from an energy management point of view. Nonetheless, this method was chosen for demonstration purposes.

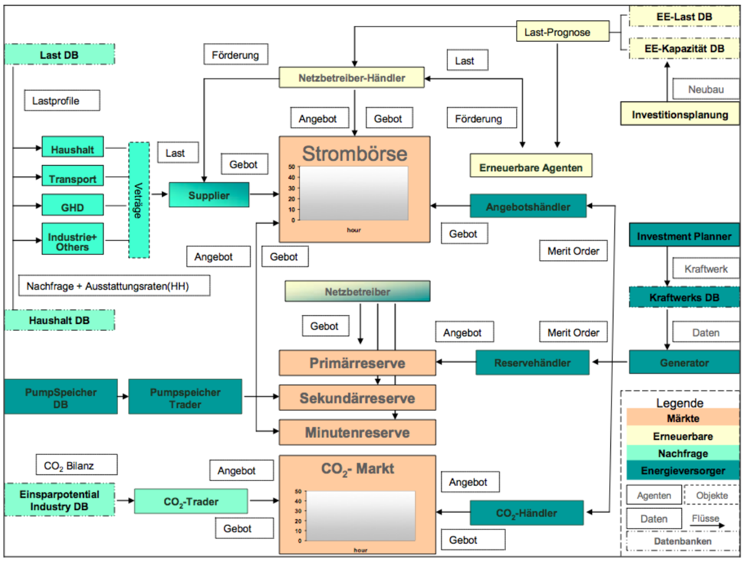


Figure 59 Model structure of *Klobasa et al. 2009*

The method implemented in *Klobasa et al. 2009* shows a possible solution to solve the allocation problem. The energy market is modelled dynamically, whilst taking all important market actors into account. Figure 59 illustrates the findings of the authors. Each RE source has different substitution of conventional fossil-fuelled power plants. This is due to the respective supply profiles. However, establishing such type of model involves considerable work.

For the above reasons, figures that are provided by this model are solely indicative and not necessarily comparable with each other or with other sources. In addition, DSM and storage scenario cannot be compared directly. Nevertheless, the model provides some interesting insights and facilitates high-resolution analysis of household energy demand.

III-4.3. Demand Side Shifting

Load shifting leads to a delayed power demand of appliances. At the time appliances recuperate, they may generate considerable load, which again could provoke an energy supply gap. It is important to control such behaviour by ensuring communication with a control entity or in between appliances.

III-4.4. Storage scenario

Figure 50 describes a logarithmic function for non-renewable energy demand reduction. Looking into the context of this function was no objective of this work. However, further investigation of the patterns could yield interesting insights.

IV. CONCLUSIONS

This section summarizes the finding of this work and discusses their relevance for the building sector.

IV-1. Data

Data on household consumption and appliance diffusion is surprisingly inconsistent (cf. III-1.1, p. 38). This illustrates yet again, that energy demand of households is a “black box” for the energy providers [*Kamper 2010, p. 32*]. They know little about the composition of load profiles in low-voltage networks and mostly have to rely on statistical methods to predict power demand.

In this respect, Smart Homes might improve data quality in the future. So-called smart homes are equipped with electricity meters that are able to measure individual demand with a high resolution and partly for individual appliances. However, this new technologies harbour privacy concerns, which must be dealt with in the future. For instance, scientists were recently able to identify the television program that building occupants were watching by analysis of currency fluctuations of the apartment [*Greveler et al. 2011*].

IV-2. Renewable Energy and environmental impact

The mix in Renewable Energies (RE) in Germany (Figure 6) allows a theoretical supply of households of 92% throughout the year (Figure 7). Interestingly the supply in Renewable energy actually increases during wintertime. Although electricity from photovoltaics reduces during this season, the supply in wind power increases significantly during the intermediate seasons and wintertime. Moreover, many biomass power plants are combined heat & power generators and therefore run mostly during wintertime.

Load management is a very interesting option to foster utilization of Renewable Energies in the electricity network. Demand can be partly adapted to the volatility of Renewable Energy producers. Hydropower, wind power, and photovoltaics are the Renewable Energy sources with lowest emission factors (Figure 34). Thus, it is important to prioritize their utilization accordingly.

Hydropower and biomass are two of the few Renewable Energy technologies that are available on request. This makes them important instruments for balancing the volatile PV and wind energy supply profiles in the future. Energy suppliers are working on new solutions to supply continuous energy supply from solar energy (cf. II-2.3). Such projects could help to further reduce the demand for operating reserve in the future. It should be a priority of European politics, to establish a mix in Renewable Energies that is able to complement each other (cf. II-2.1.1).

In order to reduce the magnitude of environmental impact, other measures, such as energy efficiency (cf. III-3.3.2) or fuel switch (cf. II-2) are probably more effective. Seasonal supply shift of thermal (solar) energy is nevertheless favourable since it allows harmonising the supply / demand gap illustrated in chapter I-1. Diurnal supply shift of thermal energy is useful to bridge periods with less-than-average supply. As seen in III-3.2, demand shift of electrical thermal systems may become problematic, since it can amplify peak demand during the day.

The extensive reports on the German electricity grid, commissioned by the German Energy Agency (dena), show that load management is an increasingly popular topic in discussions electricity [*dena 2010*]. Therefore, it is surprising, that only little work on the environmental effect has been realized. Most authors concentrate on the integration of Renewable Energies into the electricity network. *Erol-Kantarci and Mouftah 2010* carry out a similar study and determine the carbon footprint of households with DSM. However, their model investigates only specific load management aspects and parts of the electricity markets.

IV-3. Load management

In order to provide an environmentally beneficial effect from load management, (regional) Renewable Energy supply in the electricity network must exceed idle demand of consumers. That means periods with RE excess are necessary for appliances or storage systems to recharge. Section III-3.3.4 shows that a low supply in Renewable Energy will significantly reduce the effect of demand side management (DSM).

The effect of energy storage and DSM are basically alike. Nevertheless, an important difference exists in the characteristics of the two techniques: Their displacement characteristics show a different time dependency.

On the one hand, storage systems require knowledge on the future <u>demand</u> situation. In order to supply power at a given time, the storage systems need to charge <u>beforehand</u>.

On the other hand, DSM systems only work effectively if the future <u>supply</u> situation is known. Once demand is displaced by an appliance, it will need to draw additional power <u>afterwards</u>.

This insight allows deduction of a recommendation. Since the daily load profile shows mostly two peak situations (e.g. Figure 28), basically two different situations occur: First peak situation, allows charging beforehand (i.e. at night); second peak situation allows recapture afterwards (i.e. later evening). That means, storage systems should be primarily used to mitigate midday peaks, while DSM should be employed in the afternoon. It is intended to test this hypothesis in future work.

Nonetheless, the practical environmental impact reduction potential of load management measures is limited. Measures, such as energy efficiency (cf. III-3.3.2) or fuel switch (cf. II-2) are probably more effective. Still, load management is a crucial tool that will help establishing electricity networks that make use of a large share in Renewable Energies (II-2.1). Only by reducing volatility of electricity demand, Renewable Energies will be able to supply the large quantities of energy that are needed throughout Europe.

Germany currently holds an average operating reserve of approximately 0.7 GW electrical power [*Kamper 2010, p. 14*]. The scenario in III-3.2 shows that the DSM is able to provide an additional power sink of approximately 1-2 GW. However this figure strongly depends on the time of the day [*Tanner 2007*]. The potential of electricity storage naturally depends on the storage capacity that is installed. With a storage of 1 kWh per household, around 2.5 GW of power can be liberated if necessary III-3.1. Of course, this can only work if devices respond quickly to a centralised control signal.

In terms of performance, Demand Side Management and electricity storage are similarly successful. Storage systems are scalable, whilst DSM has a given total capacity. That is mostly due to the comfort requirements of users. Consumers will, presumably not accept systems that are temporarily unavailable or limited in operation. *Quaschning and Hanitsch 1999, Stamminger 2008, Tanner 2007* estimate the tolerated loss in comfort. However, it seems that so far no scientific basis exists. In future work this aspect should be studied further.Chapters III-3.2 and III-3.3.3 illustrate that a responsive space heat demand profile actually is favourable for Renewable Energy supply. Whilst storage systems help to bridge supply gaps, DSM appears less useful for space heating, than compared to other appliances. Due to limitations in the demand shift module, this hypothesis could not be investigated exhaustively and needs to be further tested in the future.

Temporal awareness is a general issue of load management. As seen in III-3.2 for example, heating systems may shift their demand although it actually leads to an even more critical situation. Therefore, simple control mechanisms, such as consumer pricing, are insufficient for successful load shifting. Demand shift of appliances, for instance, should be controlled by a 'smart', predictive control mechanism. The load prediction should include parameters, like weather forecast, season, day of the week, etc. However, there are limits to the load control of appliance. *Roozbehani et al. 2011* show that response of consumers to a price signal, for example, may result in an overreaction and thus compromise network stability.

IV-3.1. Demand Side Management

Figure 23 illustrates that mostly thermal appliances have DSM potential. That is because their thermal inertia and insulation allow bridging temporary electricity cut-off. Thus, deactivation will go unnoticed until critical service parameters are reached (e.g. temperature inside a freezer; cf. II-4.2.2). In order to facilitate DSM penetration in the future, those parameters of devices should be optimised.

Since most current appliances do not have the capability to act in a DSM system, it is necessary to establish an infrastructure on future markets. That means common protocols and characterisation methodologies should be implemented. For instance, the DSM potential (duration and magnitude of demand shift) are not standardised yet. Moreover, retrofit of systems may become an important market.[24]

IV-3.2. Storage

The findings in III-3.1 suggest that long-term storage systems, with low energy losses, perform best in residential buildings. However, such systems are expensive and usually represent a trade-off between storage power and capacity (cf. II-5.1).

Analysis of the average storage profile in Figure 49 yields that a successful storage system must in particular be able to shift energy supply from morning hours to peak times. That is because excess in Renewable Energy supply is usually greatest in morning hours. As it is explained in I-2.4, storing electricity from baseload power plants may be economically appealing, but has no environmental advantage.

The issue of load management is not only a crucial task for integrating renewable energies in electricity grids in the future. The historic strategy of load management in grids bases on the broadcast of electricity from producers to consumers. So far, the most important unknown variable in the equation was the demand side. Due to the high share of renewable energies, today also the supply side has high levels of uncertainties to it. That calls for more intelligent and probabilistic-based management of grid resources (cf. *Koch et al. 2009a*).

---

[24] Different vendors, such as *www.myesmart.com* or *www.digitalstrom.org* are developing retrofit solutions.

Resources

Ackermann, T., Tröster, E., Short, R. and Teske, S. 2009. "[r]enewables 24/7"Greenpeace International and European Renewable Energy Council. Amsterdam.

BEE. 2011. "Jahreszahlen Erneuerbare Energien 2010". Bundesverband Erneuerbare Energien e.V. Accessible at: *http://www.bee-ev.de/Erneuerbare-Energien/Erneuerbare-Energien.php*.

BMU. 2011. "Erneuerbare Energien 2010"Federal Ministry for the Environment Nature Conservation and Nuclear Safety.

BMWi. 2011. "Energiedaten - nationale und internationale Entwicklung". German Federal Ministry of Economics and Technology. Accessible at: *http://www.bmwi.de/BMWi/Navigation/Energie/Statistik-und-Prognosen/energiedaten.html*.

Braun, M. 2007. "Virtuelle Kraftwerke aus KWK-Anlagen zur Bereitstellung von Regelleistung Technische und wirtschaftliche Potenzialanalyse". VDM Verlag Dr. Müller. Saarbrücken. pp. 83.

Bukvić-Schäfer, A.S.a. 2008. PhD thesis, "Lastmanagement – Nutzung der Thermischen Kapazität von Gebäuden als nichtelektrischer Energiespeicher in elektrischen Versorgungsnetzen". Elektrotechnik / Informatik Universität Kassel. Kassel, Germany.

Bush, E., Josephy, B. and Nipkow, J. 2007. "Energetisches Einsparpotenzial von Fördermassnahmen für energieeffiziente Haushaltgeräte". Bush Energie GmbH. Elektrizitätswerke der Stadt Zürich (ewz). Zurich.

BWP. 2009. "BWP-Branchenstudie 2009"e.V., B.W.r. Berlin.

Clark, W. and Gellings, P.E. 2009. "The Smart Grid: Enabling energy efficiency and demand response". Fairmont Press : Taylor & Francis distribution. Lilburn, GA. pp. xv, 300 p.

dena. 2010. "Integration erneuerbarer Energien in die deutsche Stromversorgung im Zeitraum 2015 – 2020 mit Ausblick auf 2025 (dena-Netzstudie II)". dena-NetzstudieDeutsche Energie-Agentur GmbH (dena) and Energiewirtschaftliches Institut an der Universität zu Köln (EWI).

Destatis. 2011. "Gemeinsames Neues Statistisches Informations-System - ". Federal Statistical Office Germany. Online database accessible at: *www-genesis.destatis.de.*

EcoGrid. 2007. "EcoGrid phase 1 - Steps toward a Danish power system with 50% wind energy". Sørensen, P., Togeby, M. and Ackermann, T. (Eds.). WP4: New measures for integration of large scale renewable energyTechnical University of Denmark. Århus, Denmark.

ecoinvent Centre. 2007. "ecoinvent data v2.01". Swiss Centre for Life Cycle Inventories. Online database accessible at: *www.ecoinvent.org.*

Enerdata. 2011. "Odyssee – European energy efficiency database". Online database accessible at: *www.enerdata.net.*

ENTSO-E. 2011. "ENTSO-E Statistical Database". ENTSO-E - European Network of Transmission System Operators for Electricity. Online database accessible at: *https://www.entsoe.eu/resources/data-portal/.*

Erb, M., Hubacher, P. and Ehrbar, M. 2004. "Feldanalyse von Wärmepumpenanlagen". FAWA (Ed.)Bundesamtes für Energie. Bern, Switzerland.

Erol-Kantarci, M. and Mouftah, H.T. 2010. "The impact of smart grid residential energy management schemes on the carbon footprint of the household electricity consumption". Electric Power and Energy Conference (EPEC), 2010 IEEE. 25-27 Aug. 2010.

Eurostat. 2011. "Eurostat Statistics Database". Statistical Office of the European Communities. Online database accessible at: *http://epp.eurostat.ec.europa.eu/portal/page/portal/statistics/search_database.*

Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D.W., Haywood, J., Lean, J., Lowe, D.C., Myhre, G., Nganga, J., Prinn, R., Raga, G., Schulz, M. and Van Dorland, R. 2007. "Changes in Atmospheric Constituents and in Radiative Forcing.". Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate ChangePress, C.U. Cambridge, United Kingdom and New York, USA.

Frischknecht, R., Jungbluth, N., Althaus, H.-J., Doka, G., Dones, R., Heck, T., Hellweg, S., Hischier, R., Nemecek, T., Rebitzer, G. and Spielmann, M. 2005. "The ecoinvent Database: Overview and Methodological Framework". *The International Journal of Life Cycle Assessment*. 10 (1). pp. 3-9.

Giesecke, J. and Mosonyi, E. 2009. "Wasserkraftanlagen Planung, Bau und Betrieb". Springer. Heidelberg. pp. 897 S.

Greveler, U., Justus, B. and Löhr, D. 2011. "Hintergrund und experimentelle Ergebnisse zum Thema „Smart Meter und Datenschutz“". Data Privacy Management DaPriM. Fachhochschule Münster. Münster, Germany.

Gutschner, M. and Nowak, S. 1998. "Das Photovoltaik-Potential im Gebäudepark der Stadt Zürich"Ltd., N.N.E.T. Zurich, Switzerland.

Hausladen, G. 2005. "Climate design solutions for buildings that can do more with less technology". Birkhäuser. Basel. pp. 200 S.

Heeren, N., Wallbaum, H. and Jakob, M. 2011. "Towards a 2000 Watt society – assessing building-specific saving potentials of the Swiss residential building stock". World Sustainable Building Conference SB11. Helsinki, Finland. 18-21. October 2011.

Hofer, P. 2007. "Der Energieverbrauch der Privaten Haushalte, 1990 - 2035. Ergebnisse der Szenarien I bis IV und der zugehörigen Sensitivitäten BIP hoch, Preise hoch und Klima wärmer". Prognos AG. BFE, B.f.E. Bern.

IEA. 2002. "Potential for Building-Integrated Photovoltaics"International Energy Agency. St. Ursen, Switzerland.

IWES. 2009. "Dynamische Simulation der Stromversorgung in Deutschland nach dem Ausbauszenario der Erneuerbaren-Energien-Branche". Saint-Drenan, Y.-M., von Oehsen, A., Gerhardt, N., Sterner, M., Bofinger, S. and Rohrig, K. (Eds.). Fraunhofer-Institut für Windenergie und Energiesystemtechnik (IWES). Bundesverband Erneuerbare Energie e.V. (BEE). Kassel.

Jardine, C.N. and Lane, K. 2005. "Characterisation and reduction of the electrical consumption of central heating systems and components (WP4 - Impact Evaluation)". EU SAVE - SAVELECOxford.

Jenni, J. 2010. "Das Sonnenhaus mit hohem solarem Deckungsgrad für Warmwasser und Heizung eine Möglichkeit, dank Eigenversorgung in Zukunft nicht zu frieren". Jenni Energietechnik AG. Burgdorf, Switzerland. pp. 88 S.

Kamper, A. 2010. PhD thesis, "Dezentrales Lastmanagement zum Ausgleich kurzfristiger Abweichungen im Stromnetz". Fakultät für Wirtschaftswissenschaften. Karlsruher Institut für Technologie (KIT). Karlsruhe, Germany.

Klobasa, M., Sensfuß, F. and Ragwitz, M. 2009. "CO2-Minderung im Stromsektor durch den Einsatz erneuerbarer Energien im Jahr 2006 und 2007". Innovationsforschung, F.-I.f.r.S.-u. (Ed.). Fraunhofer-Institut für System- und Innovationsforschung. (ZSW), Z.f.r.S.-u.W.-F.B.-W.r. Karlsruhe.

Koch, S., Meier, D., Zima, M., Wiederkehr, M. and Andersson, G. 2009a. "An active coordination approach for thermal household appliances – Local communication and calculation tasks in the household". PowerTech, 2009 IEEE Bucharest. June 28 2009-July 2 2009.

Koch, S., Zima, M. and Andersson, G. 2009b. "Potentials and applications of coordinated groups of thermal household appliances for power system control purposes". 2009 IEEE PES/IAS Conference on Sustainable Alternative Energy (SAE). 28-30 Sept. 2009.

Lemofouet, S. and Rufer, A. 2006. "A Hybrid Energy Storage System Based on Compressed Air and Supercapacitors With Maximum Efficiency Point Tracking (MEPT)". *Industrial Electronics, IEEE Transactions on*. 53 (4). pp. 1105-1115.

Meteotest. 2010. "Meteonorm 6.0". Meteotest. Bern, Switzerland.

Nieuwenhout, F., Dogger, J. and Kamphuis, R. 2005. "Electricity storage for distributed generation in the built environment". International Conference on Future Power Systems. 18. Nov. 2005.

Ning, L. and Katipamula, S. 2005. "Control strategies of thermostatically controlled appliances in a competitive electricity market". Power Engineering Society General Meeting, 2005. IEEE. 12-16 June 2005.

Oeding, D. and Oswald, B.R. 2011. "Elektrische Kraftwerke und Netze". Springer. Berlin. pp. 968.

Pinel, P., Cruickshank, C.A., Beausoleil-Morrison, I. and Wills, A. 2011. "A review of available methods for seasonal storage of solar thermal energy in residential applications". *Renewable and Sustainable Energy Reviews*. 15 (7). pp. 3341-3359.

Popp, M. 2010. PhD thesis, "Speicherbedarf bei einer Stromversorgung mit erneuerbaren Energien". Technical University of Braunschweig. Berlin. pp. 159.

Quaschning, V. and Hanitsch, R. 1999. "Lastmanagement einer zukünftigen Energieversorgung - Integration regenerativer Energien in die Elektrizitätsversorgung". *BWK – Brennstoff Wärme Kraft*(10). pp. 64-67.

Räsänen, M., Ruusunen, J. and Hamalainen, R.P. 1995. "Identification of consumers' price responses in the dynamic pricing of electricity". Systems, Man and Cybernetics, 1995. Intelligent Systems for the 21st Century., IEEE International Conference on. 22-25 Oct 1995.

Roozbehani, M., Dahleh, M.A. and Mitter, S.K. 2011. "Volatility of Power Grids under Real-Time Pricing"

Simons, A. and Firth, S.K. 2011. "Life-cycle assessment of a 100% solar fraction thermal supply to a European apartment building using water-based sensible heat storage". *Energy and Buildings*. 43 (6). pp. 1231-1240.

Stadler, M., Krause, W., Sonnenschein, M. and Vogel, U. 2009. "Modelling and evaluation of control schemes for enhancing load shift of electricity demand for cooling devices". *Environmental Modelling & Software*. 24 (2). pp. 285-295.

Stamminger, R. 2008. "Synergy Potential of Smart Appliances". Smart Domestic Appliances in Sustainable Energy Systems (Smart-A)Commission, E. Bonn.

Steemers, K. and Yun, G.Y. 2009. "Household energy consumption: a study of the role of occupants". *Building Research and Information*. 37 (5-6). pp. 625-637.

Tanner, L. 2007. "Das Lastabwurfpotential in Haushalten und dessen Abhängigkeit von der Tageszeit". Wiederkehr, M. (Ed.). Fachhochschule Nordwestschweiz. Fachhochschule Nordwestschweiz.

Tröster, E., Kuwahata, R. and Ackermann, T. 2011. "European Grid Study 2030/2050". energynautics GmbH. International, G. Langen, Germany.

Van De Putte, J., Short, R., Beranek, J., Thies, F. and Teske, S. 2011. "Battle of the Grids"Greenpeace International. Amsterdam.

VDE. 2009. "Energiespeicher in Stromversorgungssystemen mit hohem Anteil erneuerbarer Energieträger Elektronische Daten Bedeutung, Stand der Technik, Handlungsbedarf Vorträge der ETG-Fachtagung vom 22. bis 23. September 2009 in Erfurt". ETG-Fachbericht. Berlin

Wallbaum, H., Jakob, M., Heeren, N. and Martius, G. 2010. "Gebäudeparkmodell Zürich – Büro-, Schul- und Wohngebäude – Vorstudie zur Erreichbarkeit der Ziele der 2000-Watt-Gesellschaft für den Gebäudepark der Stadt Zürich "Stadt Zürich.

Weindorf, W. 2011. "Warum Atomkraftwerke nicht zu erneuerbaren Energien passen". Munich, Germany.

WWF. 2009. "Modell Deutschland". Öko-Institut e.V., Prognos AG. WWF Germany.

Annex

Ecoinvent datasets

Table 8 Datasets used for determination of environmental impact from *ecoinvent Centre 2007*

Energy carrier	Dataset name
Hard coal	*electricity, hard coal, at power plant*
Lignite	*electricity, lignite, at power plant*
Oil	*electricity, oil, at power plant*
Gas	*electricity, natural gas, at power plant*
Nuclear power	*electricity, nuclear, at power plant*
Wind power	*electricity, at wind power plant*
Hydro power	*electricity, hydropower, at power plant*
Biomass	*electricity, at cogen with biogas engine, allocation exergy*
PV	*electricity, production mix photovoltaic, at plant*
Waste incineration	*electricity, industrial gas, at power plant*
Other	*electricity, production mix DE*

Declaration of originality

Hereby I declare that this thesis “Potentials of load management in buildings” is my own work. Information derived directly or indirectly from others has been acknowledged in the text and a list of references is given in the bibliography.

Eidesstattliche Erklärung

Ich versichere, dass ich die vorliegende Master-Thesis „Potentiale des Lastmanagements in Gebäuden“ selbständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel verwendet habe. Alle Stellen der Arbeit, die anderen Werken wörtlich oder sinngemäß entnommen sind, sind unter Angabe der Quelle als Entlehnung kenntlich gemacht.

Zürich, 28.09.2011

Niko Heeren