Task 52
Solar Heat and Energy Economics
in Urban Environments

SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY

INFLUENCE OF SECTOR COUPLING ON SOLAR THERMAL ENERGY

A scenario analysis of the German energy system

Technical Report Subtask A

Sebastian Herkel

Andreas Palzer

Fraunhofer-Institute for Solar Energy Systems
Freiburg
Germany

With contributions from: Christoph Kost, Hans-Martin Henning and Philip Sterchele

Freiburg, 25th May 2018

IEA Solar Heating and Cooling Programme

The Solar Heating and Cooling Technology Collaboration Programme was founded in 1977 as one of the first multilateral technology initiatives ("Implementing Agreements") of the International Energy Agency. Its mission is

“to enhance collective knowledge and application of solar heating and cooling through international collaboration to reach the goal set in the vision of solar thermal energy meeting 50% of low temperature heating and cooling demand by 2050.”

The members of the IEA SHC collaborate on projects (referred to as “Tasks”) in the field of research, development, demonstration (RD&D), and test methods for solar thermal energy and solar buildings.

A total of 61 projects have been initiated, 53 of which have been completed. Research topics include:

- Solar Space Heating and Water Heating (Tasks 14, 19, 26, 44, 54)
- Solar Cooling (Tasks 25, 38, 48, 53)
- Solar Heat or Industrial or Agricultural Processes (Tasks 29, 33, 49)
- Solar District Heating (Tasks 7, 45, 55)
- Solar Buildings/Architecture/Urban Planning (Tasks 8, 11, 12, 13, 20, 22, 23, 28, 37, 40, 41, 47, 51, 52, 56, 59)
- Solar Thermal & PV (Tasks 16, 35, 60)
- Daylighting/Lighting (Tasks 21, 31, 50, 61)
- Materials/Components for Solar Heating and Cooling (Tasks 2, 3, 6, 10, 18, 27, 39)
- Standards, Certification and Test Methods (Tasks 14, 24, 34, 43, 57)
- Resource Assessment (Tasks 1, 4, 5, 9, 17, 36, 46)
- Storage of Solar Heat (Tasks 7, 32, 42, 58)

In addition to the project work, there are special activities:

- SHC International Conference on Solar Heating and Cooling for Buildings and Industry
- Solar Heat Worldwide – annual statistics publication
- Memorandum of Understanding – working agreement with solar thermal trade organizations
- Workshops and seminars

Country Members

Australia	China	Germany	Norway	South Africa
Austria	Denmark	Italy	Portugal	Sweden
Belgium	European Commission	Mexico	Slovakia	Switzerland
Canada	France	Netherlands	Spain	Turkey
United Kingdom				

Sponsor Members

European Copper Institute
ECREEE
Gulf Organization for Research and Development
International Solar Energy Society
RCREEE

For more information on the IEA SHC work, including many free publications, please visit www.iea-shc.org

Content

1 Objective

This report presents the results of a scenario study on the potential role of solar thermal in future energy systems in Germany. This work is applied in the IEA task 52 Solar Heat and Energy Economics in Urban Environments. In the framework of IEA-SHC Task 52 the (possible future) role of solar thermal energy utilization in urban environments is investigated more deeply. Main focus is on the utilization of solar energy by means of active technologies such as solar thermal collectors. The passive use of solar energy, for instance by means of architectural measures, are not treated in the framework of this project. This report presents the results calculated based on the methodology in Subtask A of the IEA task 52 Solar Heat and Energy Economics in Urban Environments. It contains a description of the purpose of the task, and the boundary conditions that were set to determine scenarios for the development of solar thermal heat in a future energy system.

The Task focuses on the analysis of the future role of solar thermal in energy supply systems in urban environments. Methods for an energy economic analysis - reflecting future changes in the whole energy system – strategies and technical solutions as well as associated chains for energy system analysis will be developed. Subtask A is accompanied by Subtask B focusing on Methodology, tools and case studies for urban concepts and Subtask C focusing on Technology and demonstrators through classification, benchmarking and best practice examples.

Some of the main objectives of Subtask A are:

- Using energy system analyses based data for creating scenarios
- Identifying the role of solar thermal in integrated renewable energy systems
- Identifying balances between building level solar thermal and solar thermal in local district heating networks
- Methods of how to develop integrated renewable energy systems and model solar thermal concepts

These questions are investigated by the substask A partners – Fraunhofer Institute for Solar Energy Systems, Technical University of Vienna and Aalborg University.

The methodologies applied by the different partners all involve creating energy system models of national energy systems, but differ in terms of geographical scope and the tools utilized. The partners therefore carry out different roles, as the Fraunhofer ISE is responsible for creating a national model of the German system while the Technical University of Vienna provides background data for other partners focusing on energy demand in buildings and the overall Austrian energy system. Finally, Aalborg University develops models of four national energy systems; Germany, Austria, Denmark and Italy. A more detailed description of the development of these models, methods applied can be found in [12]. The purpose of developing these models is to identify the role of solar thermal technologies in urban environments analyzing different options such as:

- Solar assisted heating of individual buildings
- Solar assisted heating of multiple buildings – with long-term central storage and central solar thermal collector field
- Solar assisted heating of multiple buildings – with short-term central storage and central solar thermal collector field
- Solar assisted heating of multiple buildings – with central storage and distributed solar thermal collector field
- Solar assisted heating of multiple buildings – with distributed storage and distributed solar thermal collector field

These systems are defined and presented in further details in IEA SHC Task 52 Subtask C reports C1 “Classification and benchmarking of solar thermal systems in urban environments” and C2 “Analysis of best practice examples”.

2 Methodology

2.1 Energy Economies background

During the past decade, Germany has taken a leading position in the market introduction of renewable energy technologies that was instrumental in bringing down their cost dramatically. The driving force of the energy transformation in Germany is the political goal of drastically reduced greenhouse gas emissions in order to limit the anthropogenic climate change and thus the danger of drastic influences on nature and the conditions of human life and economy. The declared goal of the German Government is to decrease the greenhouse gas (GHG) emissions of Germany by 2050 by at least 80 % [1] and wherever possible by 95 %, below 1990 levels [2, 3]. This objective is supported by a wide social consensus in Germany. The total amount of GHG emissions in the reference year 1990 amounted to 1,215 million tons of CO2 equivalent (for this purpose, all greenhouse-relevant effects are converted into the climate-changing effect of CO2). This value includes the CO2 lowering in agriculture and forestry. For the years prior to 2050, reduction target values are defined as well: a reduction by 40 % by 2020, by 55 % by 2030, and by 70 % by 2040

The largest share of GHG emissions is provoked by energy-related CO2 emissions with close to 990 million tons in 1990 and 793 million tons in 2013 (see green bars in Figure 1). Thus, energy-related CO2 emission is allowed to be at maximum 198 million tons in 2050 in order to achieve the reduction goal of 80 % compared to the reference year 1990. Here it is assumed that energy-related CO2 emissions are reduced to the same extent as all other greenhouse gas emissions.

In 2013 the largest individual portion of energy-related CO2 emissions with close to 45 % is caused by electricity generation. Although electricity amounts to around 20 % of the final energy, its portion in CO2 emissions is significantly larger due to high losses and own consumption in the power plant sector. Mobility is responsible for around 20 % of the energy-related CO2 emissions with street traffic representing the largest portion. Around 18 % are caused by business, public sector, and households. Here, fuels for space heating and hot water play the largest role. Additional 16 % are caused by the manufacturing and construction industry. With these numbers in mind and under the assumption that climate protection targets will be met it becomes clear that the investigation of national energy systems needs to be done considering all sectors together.

2.2 Model overview

To investigate how a national energy system in line with the mentioned political goals could look like in 2050 and for the specific analysis of potential design options of sector coupling in the context of the transformation of the German energy system an energy system model called Regenerative Energy Model: REMod-D was developed to carry out a model-based analysis [3–8]. As far as known, among all existent energy system models, no other model considers all relevant consumption sectors and conversion techniques in the energy system and simultaneously optimizes the transformation path on an hourly resolution from today to the year 2050. With Germany as example, in this report we focus on the relevance and the influence of heating technologies – particularly solar thermal systems – in the context of decarbonizing the German energy system. In order to evaluate the energetic and economic correlations of sector coupling measures in different design options (including high electrification, hydrogen economy or use of regenerative fuels) temporal and operational constraints were taken into account

The basic idea of the model REMod-D is based on a cost-based structural optimization of the transformation of the model German energy supply system for all consumption sectors – i.e. the sectors electricity, heat (space heating and hot water), process heat (industry) and traffic. The purpose of these calculations is to determine a cost-effective transformation path from the current system to an energy system in 2050, with an overall upper limit on annual allowable CO_2 emissions as the sum of all sectors. The model calculations describe technically possible development paths of the energy system and optimize these in terms of minimizing the energy system costs on the basis of the assumptions made and the analysis framework. The aim of the calculations is not to describe what the future will look like, but rather to answer the question of how from a systemic perspective the development of complete systems can be based on the lowest possible total systemic costs and at the same time the desired reduction of energy-related CO_2 emissions. Emissions are reached and the energy supply is ensured. The input data required to calculate the hourly energy balances includes, among other things, cost assumptions, weather data and load and producer profiles. Although the model takes into account geographically resolved weather information, energy demand, generation and distribution are not spatially resolved. Costs for needed infrastructure (e.g. grids) are therefore taken into account by means of a mark-up for each application technology proportional to their expansion. This can create distortions in terms of necessary investment volume, as this - in the comparison with reality - delayed in time. The aim of the optimization is to determine the most cost-effective temporal evolution of the composition of all relevant producers, converters and consumers. At the same time, the energy balance of the system as a whole must be met every hour - so all energy needs must be met - and the politically desired annual CO_2 emissions must not be exceeded.

Conventional power plants with lignite and hard coal as fuel, nuclear power plants, oil-fired power plants, gas turbines, combined heat and power plants and CCGTs have been implemented as power generators. Renewable electricity can be obtained in the model of wind turbines (onshore and offshore), photovoltaic systems and run-of-river power plants. Biomass can be utilized in different usage paths either directly or after conversion to another energy carrier. For example, wood can be used in boilers in order to provide process heat for industrial applications and for the generation of low-temperature heat in the building sector. Biogas systems, gasification systems with subsequent synthetisation into hydrogen, methane, or liquid fuels and biodiesel systems are implemented as systems for the conversion of biomass. Electrical energy storage systems in the form of stationary and mobile (in vehicles) batteries or pumped-storage power plants are used as storage systems. Hydrogen storage systems and thermal hot water storage systems in different orders of magnitudes are considered in addition. With respect to methane storage system, the simplified assumption is made that currently already existing storage capacities in Germany will also be available to the system in the future. Thus, they are not considered in the optimisation. [1]

The energy-efficient refurbishment of the building stock is also optimized as a model and is represented by three energy standards. Figure 2 shows the schematic structure of the depicted energy system. The energy demand side (right) is divided into four groups: traffic, electricity, low temperature heat and process energy for industrial processes. In traffic, the demand of road traffic (based on the driving behavior of cars and trucks) is resolved in time and mapped taking into account different optional drive concepts.

The energy demand side is divided into four groups: Mobility, intrinsic electricity applications, heat for buildings (residential buildings, as well as non-residential buildings and industrial buildings), and fuel-based process heat in the industry. The mobility sector is mapped in detail through passenger cars and trucks with seven vehicle concepts each. Electricity demand for heat and road traffic is calculated as a model and is therefore not part of the base load. The operational management of the power system is specified exogenously within the model. There is thus no hourly optimization of the order of use of the power plants, but a fixed predetermined order of use for a merit order regarding the specific CO2 emissions. In addition, the so-called "single-node or copper plate model" is adopted, in which the distribution of electricity is not subject to any restrictions, that is, every unit generated and each unit demanded current in the time step considered is in whole Germany available. The necessary costs for the expansion or operation of the power grid are included in the cost accounting.

The building sector is implemented with 18 possible heat supply technologies. Each of these heating technologies can be optionally supplemented with a heat storage device or solar thermal energy system. Figure 1 shows an example of the »electrical brine heat pump« system, hence, a brine-water heat pump with ground as heat source. The possible energy flows between the individual system components are shown. Thermal storage devices can be charged through solar thermal energy, as well as through heat from excess power (directly or via the heat pump). The latter option allows the flexible use of power in the case of a negative residual load. Vice versa, the heat pump can be switched off and the heat storage discharged in the case of a positive residual load and simultaneous heat requirement [1]

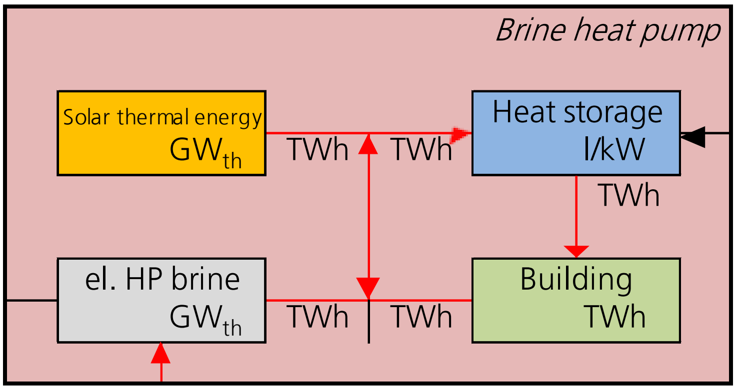

Figure 1: Schematic design of the heating systems on the example of a ground-coupled, electrical heat pump (red lines = heat, black line = power, HP: heat pump)

The energy demand of the industry is derived from the statistical data of the German Federal Ministry of the Economy [2] and refers only to the fuel-based energy supply for process heat. The electricity demand of the industry is included in the base electricity load. Figure 2 shows the schematic presentation of the energy system mapped in the REMod-D model.

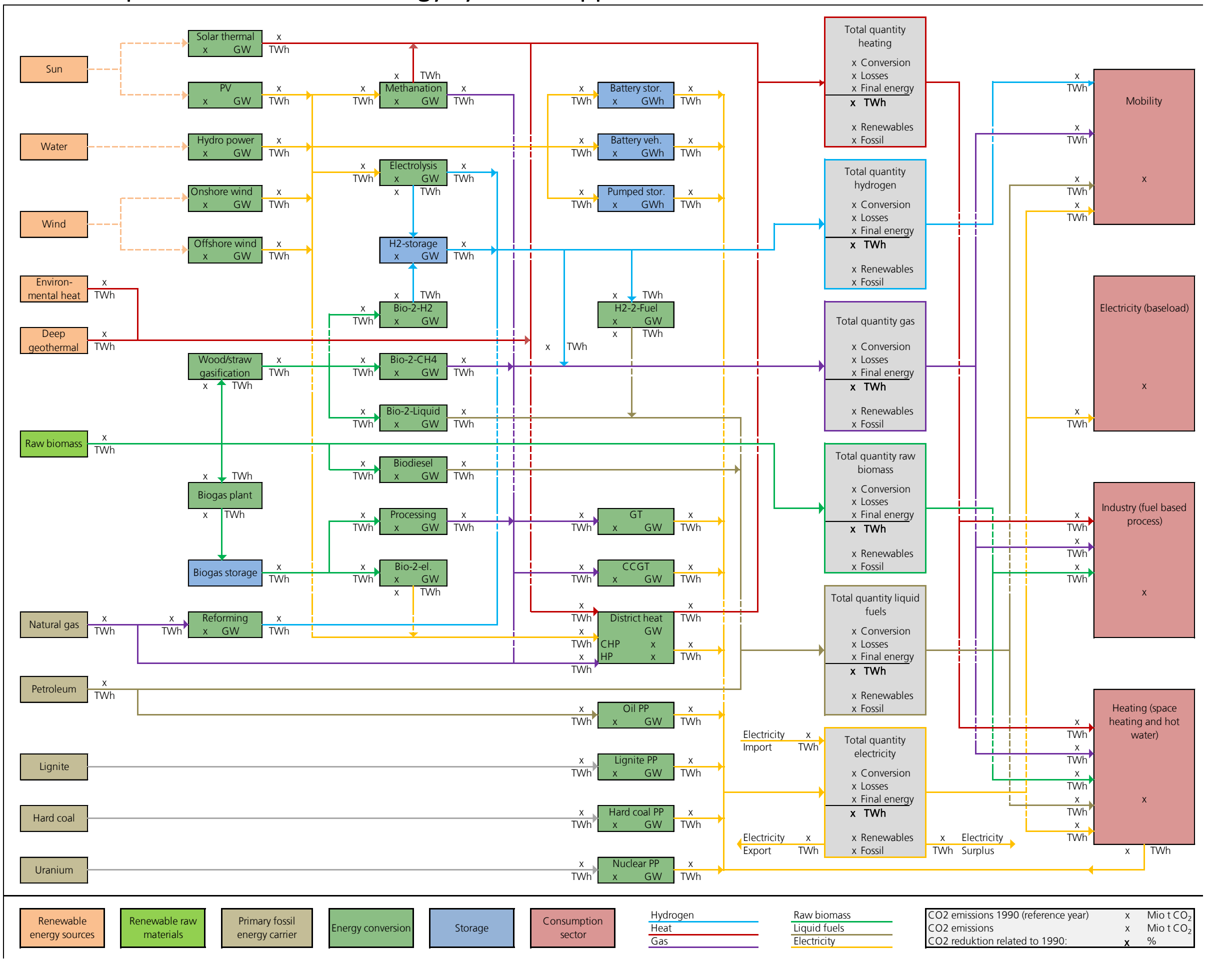

Figure 2: Topology of the model of a national energy system (electricity and heat sector) of the REMod-D model

2.3 Cost functions and solver

From 1990 to 2013, all plants or units of all implemented conversion and utilization technologies are counted in number or installed capacity to take account of the historical investment stock. Based on the inventory data of the technologies, the optimization algorithm is used to determine the future plant park and simulate the system every hour for the entire observation period. After this run, it checks that the given amount of CO2 has been met every year and calculates the costs of the system (investment, maintenance and operation, fuel costs, etc.). At the beginning of the calculations, in addition to the input data required for the annual accounts, additional information on the existing plant stock and the amount of the specific investment of the respective technologies is read in as a function of the respective year. The optimization algorithm targets the minimum total cumulative cost (new acquisition costs including capital costs and all operating costs including maintenance and fuel costs) of the system over the period considered. In order to carry out model calculations in which specific external influences are specifically examined for their effects, certain model assumptions or external dependencies can be specified. Which technology is chosen and to what extent is the result of the optimization, i.e. the minimization of the systemic total costs under observance of the set maximum CO2 emissions.

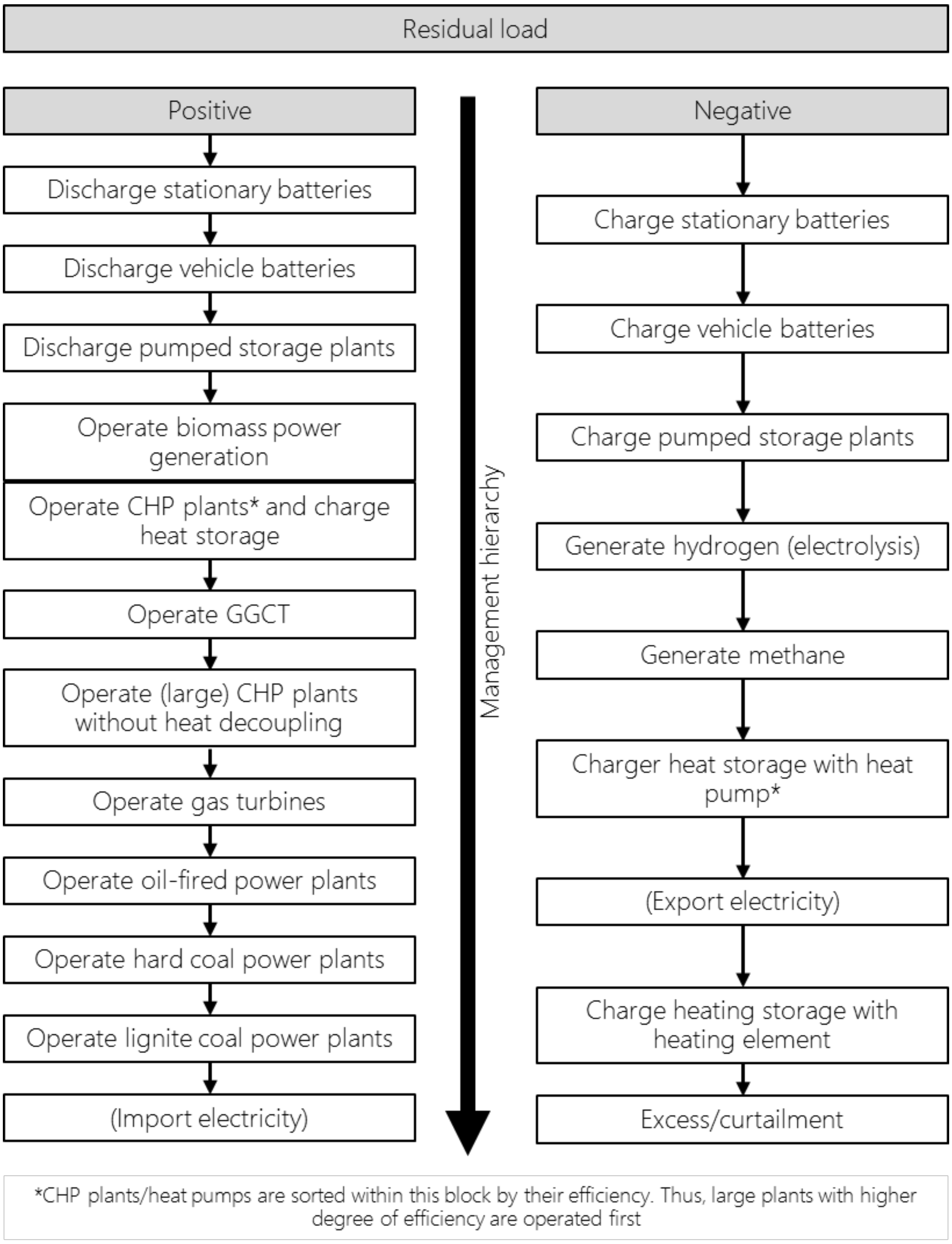

Figure 3: Operation management in the case of positive (left) and negative (right) residual load. Source: [1]

The REMod-D model is based on simple physical models of all components contained. The central component is the energy exchange across the electricity system. A load still to be covered after feed-in of renewable energy is compensated by the generation of electricity from systems of different sectors. Excess electricity, on the other hand, can be stored and/or converted into different electricity forms (chemical and thermal) and is thus accessible for all sectors. The operation of electricity-generating and electricity-using systems in the case of positive and/or negative residual load follows a defined management strategy. The component usage sequence in this management strategy follows the path of highest energy efficiency at simultaneously lowest CO_2 emissions. Figure 3 shows the different stages for the generation and usage of electricity in the case of a positive and/or negative residual load in the system.

To cover positive residual loads, CHP plants are operated first after the use of electrical storage systems and biogas CHP. The generated heat is then used to charge heat storage devices and/or to cover thermal loads if these are present at the same time. Any additional demand is covered by the operation of combined cycle gas turbine (CCGT) plants and of CHP plants in »electricity only mode«. The remaining load is covered by highly flexible gas and oil turbines and with the help of the remaining, flexibly usable power of conventional lignite and hard coal power plants. In model calculations that also investigated the electricity import, it can also contribute to covering the electricity demand at the end of the usage cascade with a previously defined maximum power. [1]

The weather influence is decisive for the different residual load states during the simulation. To map this influence adequately, real data records are used within the scope of calculation. The weather data used in the model for the calculation of feed-in and load profiles are based on publicly accessible data of the German Meteorological Service [3, 4]. The weather data from two different reference locations in Germany, Braunschweig for North Germany and Würzburg for South Germany, are processed in the model. Hourly outside temperature values and solar irradiation data are used from both locations. The real profile of the power consumption is also to ensure an adequate correlation between the profile of the basic electricity load and the profile of the power provision from renewable sources, which is defined by the profile of the meteorological variables. [1]

The technology specific system costs are obtained from an exogenously specified cost function depending on the investigated year (here 2050). When determining this cost function, the values of every technology for start year 2015 and target year 2050 were used as start and end value.

The curve profile of the specific costs of photovoltaic systems is presented in Figure 4 as example. The curve profile is based on studies discussing the cost degression behaviour of the respective technologies. As result, a specific cost value in €$_{2013}$/kW is available to the model for every year.

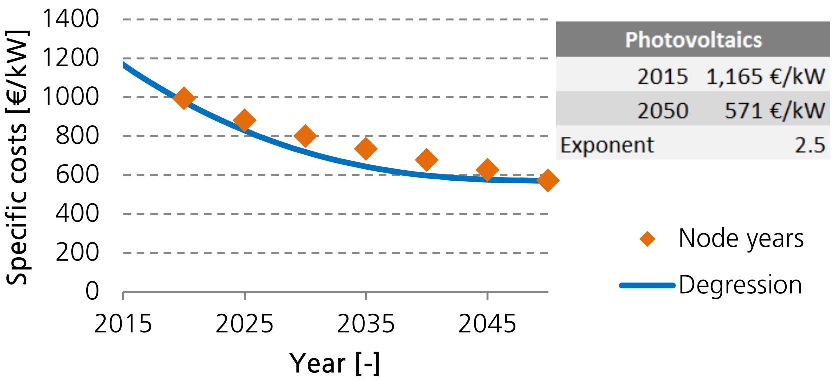

Figure 4: Cost profile of photovoltaic systems up to 2050. Source: [1] based on [12].

In addition to the cost investigations for components, such as converters or storage devices, where the specific costs are used relative to the thermal or electric power and/or capacity of the systems, costs for energy saving measures in the building sector through energy renovations are considered as well in the model. Here, energy-related additional renovation costs are considered only that result from the difference of the full costs and the costs incurred for renovations for standard building preservation. This is based on the so-called coupling principle, which states that an energy renovation of a component is only performed if the component is to be renovated anyway (see [5-7]). Two energetic standards are assumed for energetically renovated buildings in the modelling. These are referred to as »fully renovated« and »highly efficient«. Based on the renovation levels [8] defined in the »Climate-neutral Building Stock 2050« project, »fully renovated« complies with the standards of the Energy Saving Regulation (EnEV) 2009, however, tightened by 25 % (EnEV -25 %), and »highly-efficient« complies with the requirements on a passive house based on [9].

Similar to the approach for energetic building renovations, the coupling principle is also applied in the mobility and heating technology sectors. Here, passenger cars with classic combustion engine and heating technologies with gas condensing boiler are assumed as reference technologies for the costs required for system renovation. Thus, the financial additional effort of the changed energy system relative to the current system is considered in the total costs of the investigated climate protection scenario.

The calculation of the total costs required in the year 2050 (fuel costs, investments and expenditures for maintenance and operation, financing) follows the specification of VDI Directive 2067 and is annualised[1]. The observation period for the annualisation is 20 years. Interests are specified per technology. Here, the interest rates are used consistently: 8 % for investments mainly by private investors (e.g., house owners and motor vehicle owners) and 8 % for investments by institutional investors, hence mainly investments in power plants, wind turbines, and infrastructure facilities.

The annuity of the capital-related costs of a technology i with a service time T_N considering its residual value is due to VDI 2067 calculated based on: the annuity factor a_i (Equation 2.1), the residual value R_{W_i} (Equation 2.2) and the cash values for procured replacements of the n[th] replacement (Equation 2.3).

$$a_i = \frac{q_i^T(q_i-1)}{q_i^T-1} \qquad \text{Equation 2.1}$$

$$R_{W_i} = A_{0_i} \cdot r^{n_i T_{N_i}} \cdot \frac{(n_i+1)\cdot T_{N_i}-T}{T_{N_i}} \cdot \frac{1}{q^T} \qquad \text{Equation 2.2}$$

$$A_{n_i} = A_{0_i} \cdot \frac{r^{n_i T_{N_i}}}{q^{n_i T_{N_i}}} \qquad \text{Equation 2.3}$$

Finally, the annuity of the capital-related costs of a technology i is calculated using Equation 2.4.

$$A_{k_i} = (A_{0_i} + A_{1_i} + A_{2_i} \ldots + A_{n_i} - R_{W_i}) \cdot a_i \qquad \text{Equation 2.4}$$

Costs for operation and maintenance of a technology i are based on VDI 2067 calculated using the price-dynamic cash value factor b_i (Equation 2.5).

$$b_i = \frac{1-\left(\frac{r_{O\&M_i}}{q_i}\right)^T}{q_i - r_{O\&M_i}} \qquad \text{Equation 2.5}$$

The annuity of operation and maintenance costs of a technology i A_{b_i} are calculated using Equation 2.6:

$$A_{b_i} = A_{0_i} \cdot f_{O\&M_i} \cdot a_i \cdot b_i \qquad \text{Equation 2.6}$$

With:

[1] All cost values are converted into $€_{2013}$. Furthermore, it is simplified and assumed that the price-increase rate of maintenance and operating costs is identical to the assumed rate of inflation (here: 1.7 %).

$A_{0_{i,t}}$	Investment amount of a technology i at time t
$A_{i,t}$	Total annuity of a technology i at time t
$A_{k_{i,t}}$	Annuity of capital related costs of a technology i at time t
$A_{b_{i,t}}$	Annuity of operation and maintenance costs of a technology i at time t
$f_{O\&M_i}$	Factor for servicing and inspection effort
q_i	Interest factor (equals 1 + interest rate) of a technology i
T	Observation period (here 20 years)
T_{N_i}	Service time of a technology i
r_i	Price change factor of a technology i
$r_{O\&M_i}$	Price change factor of operation and maintenance of a technology i
B	Fuel costs
P	Penalty function
j	Number of technologies

The total system cost of a system G consisting of all technologies j results from the sum of the costs of all technologies and the fuel costs B of the total system:

$G = \sum_{i=1}^{j}(A_{k_i} + A_{b_i}) + B$ equation 2.7

The final objective function considering all penalty functions P is due to equation 2.8:

$Z = \sum_{i=1}^{j}(A_{k_i} + A_{b_i}) + B + P$ equation 2.8

The underlying equations are solved with a particle swarm optimizer PSO.

2.4 Boundary conditions

The following boundary conditions were defined in all transformation model calculations:

1. A cost burden of CO_2 emissions was not accepted in the calculations. The permitted amounts of CO_2 were, however, specified for the year and the calculation model ensures that these quantities are complied.[2]
2. The interest rate for the annuity invoice is uniformly 8 percent.
3. Energy prices for oil / gas and coal imports are assumed to be constant over time (2016 value). Cost assumptions for energy sources are: natural gas 33.1 €/MWh, oil 52.0 €/MWh, hard coal € 16.0 €/MWh, lignite € 1.5 €/MWh, biomass (wood) € 50.0 €/MWh, biomass (cultivation) 50.0 € €/MWh), biomass (damp) 10.0 €/MWh.
4. Conventional power plants cannot be dismantled before the end of their imputed life. However, the duration cannot be extended beyond (nuclear phase-out is taken into account, CCS technology does not apply).

[2] 1.This corresponds to the approach of a trading system with a fixed upper limit for permissible CO2 emissions. An exogenous specification of prices, on the other hand, would rather correspond to a taxation of emissions.

5. Coal-fired power plants are subject to a partial must-run condition (for cogeneration and to avoid cold starts).
6. The annual sum of the base load is assumed to be constant over time (481 TWh, today's values corrected for traffic and heat).
7. Performance and capacity of the pumped storage power plants remain current.
8. Maximum electricity import and export remains constant at around 15.5 GW.
9. The expansion of heating grids can only increase by about 1 per cent annually.
10. Solar thermal energy is not considered for the provision of process heat.
11. The supply of biomass remains constant at the current level of about 300 TWh.
    Other CO2 emissions due to non-energy use of carbonaceous fossil fuels (for example in steel, chemicals) are not taken into account.
12. The number of vehicles in circulation has been updated and is slightly lower for cars (-5 percent) and slightly higher for trucks (+5 percent) until 2050.
13. Power-to-gas and power-to-liquid applications have considered being options for the electrolytic production of hydrogen, the production of synthetic liquid fuels and methanation.

3 Scenario description

The aim of the calculations made with the energy system model REMod is to investigate different scenarios that have a special influence on the role solar thermal heat in a future energy system of an industrial country. Several factors were identified that have a particular effect on the amount of installed capacity of solar thermal collectors. These factors are:

- Overall CO2-emission reduction target
- Overall available renewable resources for biomass
- PV modules and wind for electricity generation
- Specific cost of solar thermal collectors
- Composition of the drive concepts in the transport sector

In a first step, the development of the total energy system and in particular the implications for the sector coupling depending on the CO reduction target value are presented. For this purpose, CO reduction values of -60%, -75%, -85% and -90% in the year 2050 compared to the reference value in 1990 are given in the model calculations (details on the different assumptions in the model calculations can be found in Table 1). These scenarios were noted in the following as “open” as not restraints are given in the optimization beside the before mentioned in chapter 2.4.

Five other scenarios were considered to be specific design options for the reduction of energy-related CO emissions by 85%. In order to understand the impact of different system layouts and transformation paths the first sensitivity is done on the cost development of solar thermal. In this scenario, the cost for small, building mounted solar thermal and for large scale central solar thermal remain on the a higher cost level as of today – 1500 EUR/m² (instead of 1200 EUR/m²) for small systems, 1200 EUR/m² (instead of 890 EUR/m²) for large systems (“85% ST exp.”). The second scenario (“85% Bio&Mob”) addresses the availability of biomass and enables the comparability to the scenario analysis performed by Mathisen et al.[3]. This scenario differs from the “85% open” scenario by a much higher availability of biomass resources and a fixed share of electric vehicles of 65% in 2050% (cars 75%, trucks 0%).

For further analysis one of these design options is characterized by a development in which hydrogen plays a particularly important role as a future source of energy, especially as fuel in transport (scenario “85% H2”). In another model calculation, an energy system is considered in which other regeneratively produced fuels (methane, liquid fuels) play a dominant role in the transport, electricity and heat sectors (scenario “85% PtL/PtG”). The results - as explained below - show that all model calculations with at least 85% reductions in CO_2 emissions lead to very large necessary installed power values of the converters of fluctuating renewable energies (sun, wind). Therefore, it was decided to make a number of assumptions in a further model calculation that would facilitate reaching the CO_2 reduction targets (scenario “85% active”):

- it was assumed that energy saving and energy efficiency measures reduce the base electricity demand from 481 TWh to 360 TWh,
- the energy demand of the industry decreases by 0.5 percent per annum,
- solar thermal energy plays a greater role in the provision of low-temperature heat by a given growth of appr. 2 GW for small scale systems and appr. 3 GW for district heating related systems,
- by 2040, an exit from the use of coal for power generation takes place and

[3] Mathiesen, B. V., & Hansen, K. (2017). The role of Solar thermal in Future Energy Systems: Country cases forGermany, Italy, Austria and Denmark

- electricity exchange with neighboring countries is doubled by 2050 through the expansion of the European interconnected grid.

Table 1 summarizes the main assumptions of all model calculations performed.

Table 1: Overview on differences in the boundary conditions of the scenarios. The scenarios with open optimization are highlighted in blue, the key reference scenario (85%) open in darker blue.

	60% open	**75% open**	**85% open**	**90% open**	**85% ST exp.**	**85% bio/mob**	**85% H2**	**85% PtG/PtF**	**85% active**
CO2 reduction 2020	-30%	-35%	-40%	-40%	-40%	-40%	-40%	-40%	-40%
2030	-40%	-50%	-55%	-55%	-55%	-55%	-55%	-55%	-55%
2040	-50%	-65%	-75%	-75%	-75%	-75%	-75%	-75%	-75%
2050	-60%	-75%	-85%	-90%	-85%	-85%	-85%	-85%	-85%
Heating technologies	open	open	open	open	open	open	Open	**HP <= 40%**	open
Solar thermal					**price as today**				**+5 GW / year**
Process heat demand TWh	440	440	440	440	440	440	440	**-0.5% / year**	**-0.5% / year**
Biomass potential TWh	293	293	293	293	293	**1172**	293	293	293
Transport	open	open	open	open	open	**el. cars limited to 65%**	**100% H2 in 2050**	**el. cars limited to 50%**	open
H2 in gas grid in %	5%	5%	5%	5%	5%	5%	**30%**	5%	5%
Electricity base load TWh	480	480	480	480	480	480	480	480	**310 (-25%)**
Potential PV + Wind GW	500	500	500	**600**	500	500	**600**	**600**	**600**

4 Scenario analysis

4.1 Primary and final energy

Compared with today, primary energy drops significantly in all model calculations (2014: 4,288 TWh) to values nearly or below 2,500 TWh, even in the model calculation with the lowest reductions of energy-related CO_2 emissions (Figure 5). The highest amount of primary energy used within these scenarios is when a high amount of biomass is assumed to be available (85% Bio&Mob).

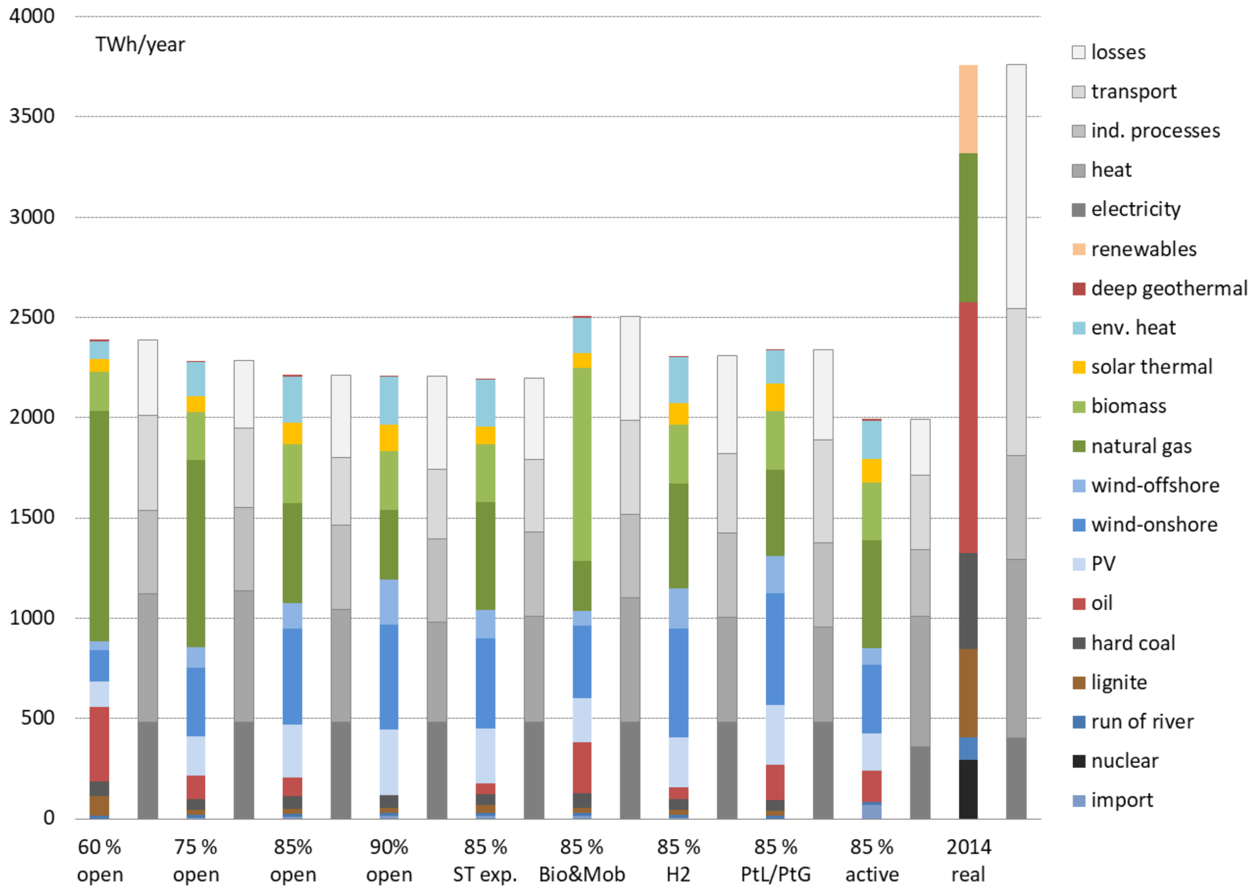

Figure 5: Primary energy and end energy use in 2050.

Of main importance are lower losses in the conversion chains, in particular by the much lower power generation in thermal power plants and by the replacement of internal combustion engines by electric drives and boilers by heat pumps. Final energy is strongly linked to the use of electricity in the heating and transport sector. Overall, the losses between primary energy and final energy are smaller than today, mainly due to the lower percentage of combustion-based processes. In the calculations with focus on biomass, hydrogen or other regeneratively produced fuels (85% Bio&Mob, 85% H2 and 85% PtL/PtG), the primary energy requirement is higher than in the calculations with free optimization, which have a higher proportion of direct electricity use.

The share of solar thermal in the annual primary energy production increases by rising ambitions regarding CO_2 reduction from 61 TWh (60% open) to 129 TWh (90% open). The amount of energy produced by this technology when aiming for a 85% reduction is the lowest in the high biomass availability scenario (77 TWh, 108 TWh in the open scenario).

4.2 Power Generation

First, the system development in the field of power generation technologies for the examined model calculations is considered. For this, the installed capacity of wind and PV (Figure 6) is considered. It becomes clear that the different boundary conditions investigated cause strong differences in the required expansion of renewable energies, especially in wind power and photovoltaics.

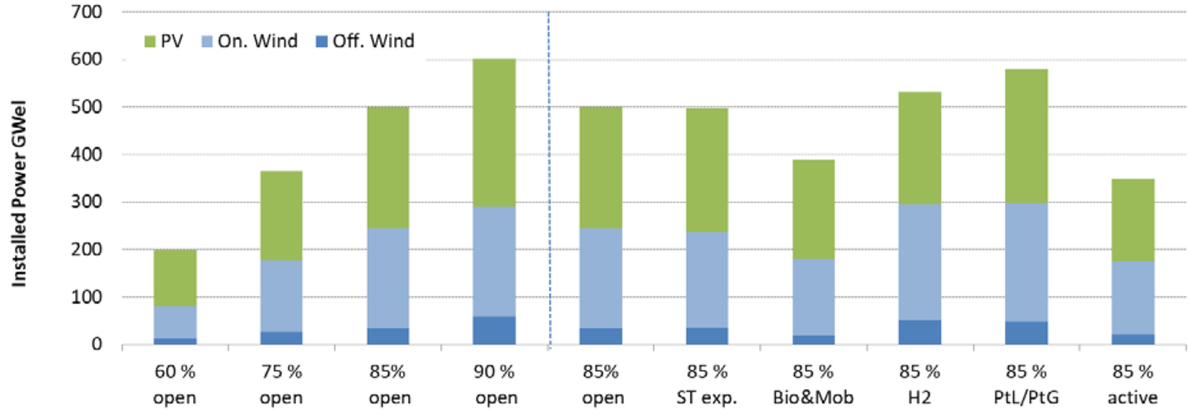

Figure 6: Installed capacity of the fluctuating renewables PV and wind.

The results of the scenario calculations carried out show three conspicuous relationships:

1. The higher the required CO_2 reduction target, the higher the required installed capacity of fluctuating power generators (wind turbines (WTG) and PV). In the model calculation with a reduction target of -60 percent energy-related CO_2 emissions, only an installed capacity of about 200 GW_{el} is required. Increasing the required CO_2 reduction target to -90 percent increases the required installed capacity of wind turbines and PV to more than 600 GW_{el}.
2. The higher the required CO_2 reduction target, the greater the need to produce synthetic fuels and fuels.
3. An Increase of biomass availability and a reduction in demand for electricity (for example through efficiency advances and / or changes in behavior) and a reduction in the energy demand of the industry (for example, through technical progress) considerably dampen the effects described under 1 and 2.

In this case, a total of 200 to 250 GW of onshore wind turbines and PV systems are less necessary. However, they only result in minor differences in the demand for conventional power plants - an important finding is that all of the system developments considered require a similar installed capacity to conventional power plants as they do today. The flexible power plant capacity increases in cases with high CO_2 reduction or the generation of renewable fuels and is between 60 and 100 GW.

The model calculations allow some key conclusions:

1. Wind and PV form the quantitative backbone of electricity generation, and the more so the more ambitious the climate protection goals are. An extensive expansion of wind and PV is a prerequisite for the energy transition.
2. The necessary installed capacity of wind and PV increases continuously with the reduction target and increases - under otherwise identical conditions - from 200 GW for 60 percent reduction over 500 GW for 85 percent to over 600 GW for 90 percent reduction. Without significant increases in energy efficiency and reductions in consumption, as well as an exit from coal use for power generation and greater European connectivity, quantities of wind and PV are needed that are beyond the potential (about 500 GW) based on what can be used today Estimate areas.
3. The installed capacity of flexible conventional thermal power plants is significantly less dependent on the CO_2 target, but the energy generated is very high. For longer phases with insufficient PV and wind power - i.e. situations where all short-term storage is also depleted ("dark skies") - a large back-up capacity must be provided for power generation.

Although decentralized contributions play a much more important role, security of supply still requires central units and large-scale networking for cost reasons.

4.3 Fuels

Closely linked to the target value of CO_2 emissions is the amount of all fuels used. Thus, assuming otherwise identical boundary conditions (i.e. open optimization model calculations), the total amount of fuel used increases continuously with the reduction target of 1,917 TWh (60% open) to around 932 TWh (90% open) (Figure 7). However, the volume of renewable fuels is steadily rising from around 224 TWh (60% open) to around 496 TWh (90% open). This increase is mainly due to an increasing proportion of synthetic chemical energy sources, while the biomass-based fraction remains relatively constant. If the import of biomass is considered as an option, the amount of renewable fuels rise up to 916 TWh (85% Bio&Mob) and will give space for a higher share of fossil fuels used in the transport sector and natural gas in the heating sector.

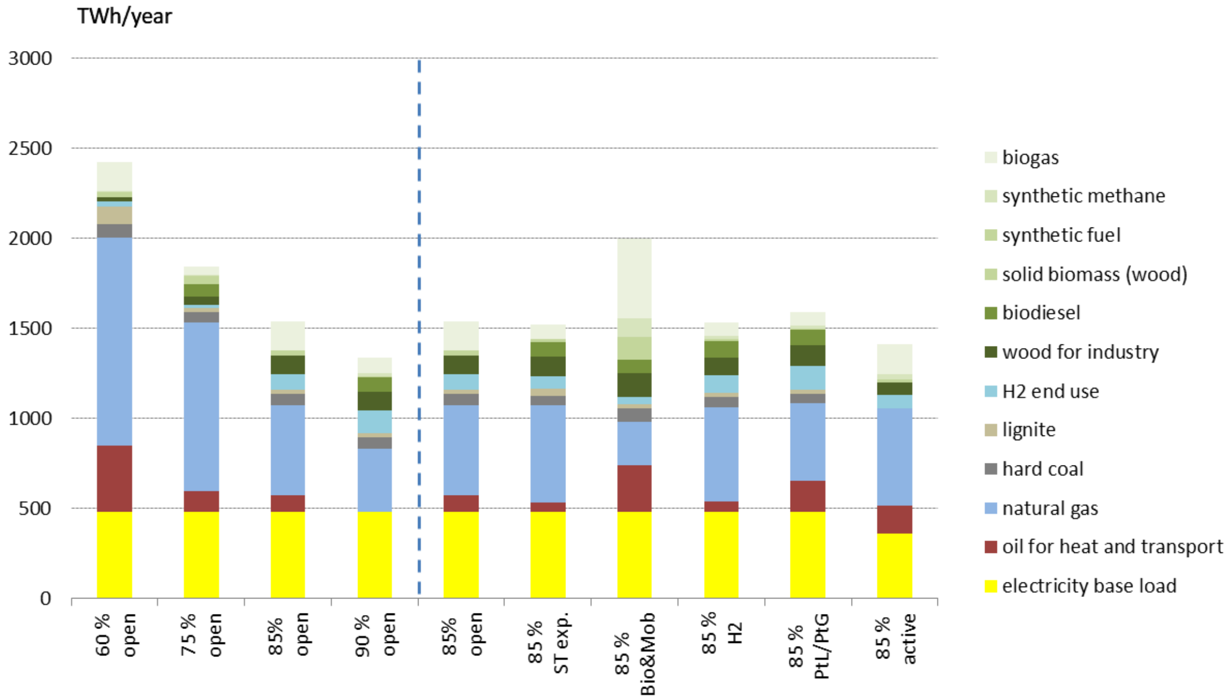

Figure 7: Amount of fuels used in 2050 scenarios. Left side of diagram results of open optimization, right side shows different variations of the"85 open" scenario.

The higher CO_2 emission factor of coal and oil compared to natural gas ensures that under strict CO_2 limitation, mainly natural gas is used as fossil energy source - or 90% exclusively. The model calculations suggest that ambitious climate protection goals can hardly be achieved without electrolysis as the primary conversion step for the production of synthetic energy sources from renewable electricity, at least if not significant successes in energy efficiency and consumption reduction are achieved. The extent to which hydrogen will be used as a final energy source or further conversion into carbon-based energy sources is difficult to assess from today's perspective, as many influencing factors play a role. The share of the different kind of biomass use e.g. wood, biodiesel etc. changes strongly between the different scenarios, indicating that there are different options for system layouts with the same amount of CO_2 reduction at more or less similar cost (Figure 8, scenarios 75% open vs. 85% open and 85% open vs. 85% ST exp.). Another observation is, that the change of the investment cost for solar thermal has a strong impact on the energy delivered by the technologies used – even if these cost are small compared to the overall cost (Figure 8, scenarios and 85% open vs. 85% ST exp.). This underlines the before mentioned statement regarding uncertainties in evaluating the role of one specific technology.

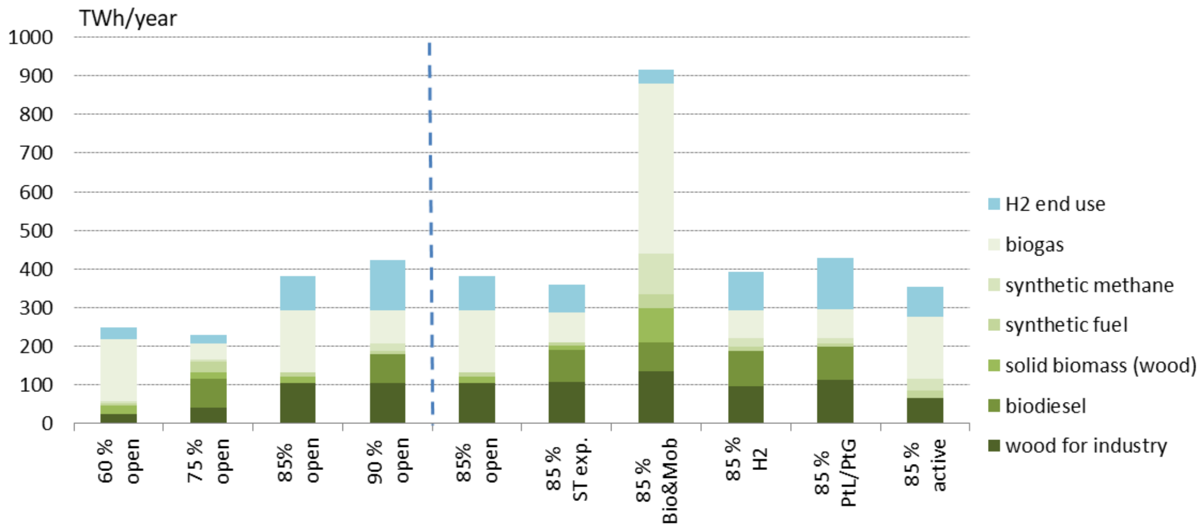

Figure 8: Amount of biomass and H2 used as fuel in 2050 scenarios. Left side of diagram results of open optimization, right side shows different variations of the"85 open" scenario.

4.4 Total system costs by 2050

The system optimization takes place in the calculations with the goal of a cost minimization under observance of the specified climate protection goals. The accumulated systemic total costs over the period from 2014 to 2050 include costs for new purchases (or construction of energy installations and replacement investments), including capital costs, operating and maintenance costs, and costs of fuel (coal, oil, natural gas, biomass). The cost of new purchases will be heavily determined by investments in renewable energy technology installations (wind turbines, PV plants) and sector coupling technologies (as will be seen in greater detail below).

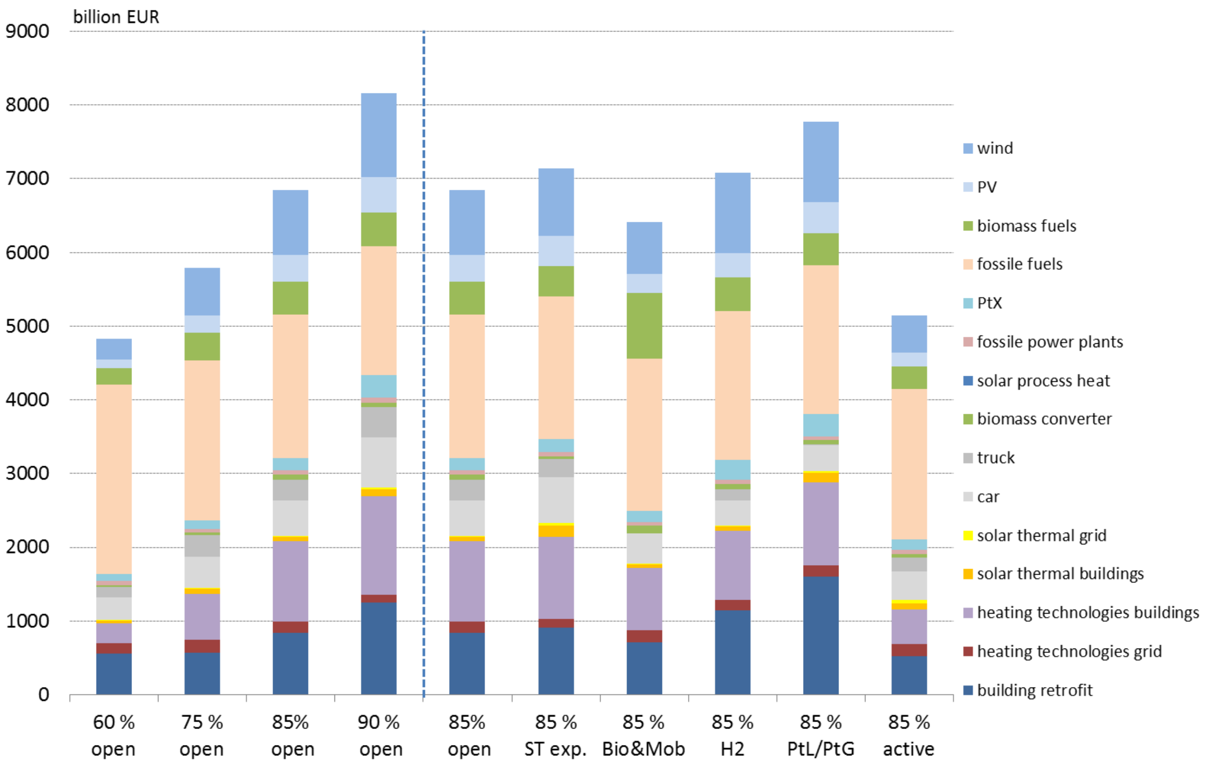

Figure 9: Cumulative systemic total costs by 2050

The cost of fuel is closely related to the CO_2 targets and the corresponding usable amounts of coal, oil and natural gas. The total costs include all costs of the considered technologies and infrastructures, but not costs for unamortized historical costs. Figure 9 shows, that the costs of the energy system as a whole increase sharply with increasing reduction targets under otherwise identical conditions. This increase is more in line with the reduction target: an additional 15 percent reduction (from 60 percent to 75 percent) leads to a higher total systemic cost of around 800 billion euros, while a further 10 percent reduction (from 75 percent to 85 percent) results in nearly 1,000 percent Billions of euros caused additional costs and a further reduction by another 5 percent (from 85 to 90 percent) further about 1.3 billion euros. Certainly, the absolute numerical values are associated with very high uncertainties, because in the system optimization very many assumptions about cost projections of all system components are received. At the same time, it was assumed that the prices of fossil fuels will remain permanently at today's very low levels by 2050. Nevertheless, the observed trend seems plausible: the technical effort for any further reduction is much higher at already high levels, since all potentials for direct electricity use have been exhausted and low-cost fossil natural gas must be replaced by elaborately produced synthetic energy sources. In addition to the conversion plants such as electrolyzers including the entire infrastructure required for this, a high additional investment in solar and wind turbines is necessary, to be able to supply the electricity to operate the electrolysers CO_2-free. The clearly lowest value of the CO_2 avoidance costs of all investigated variants is shown by the system development described as "active" with a reduction of energy-related CO_2 emissions by 85 percent. Here it was assumed that significant reductions in consumption will occur by 2050, which can be implemented at no extra cost. This is certainly an extreme assumption, although it is known that there are significant savings potentials, for example, for electricity in many areas that would be feasible under business conditions, but not due to other barriers. The specific variation of cumulative costs for solar thermal in comparison to the 85% open scenario is shown in Figure 10. It can clearly be seen, that these cost will raise either when high specific cost for solar thermal remain (85% ST exp.) or when a forced implementation is assumed (85% active).

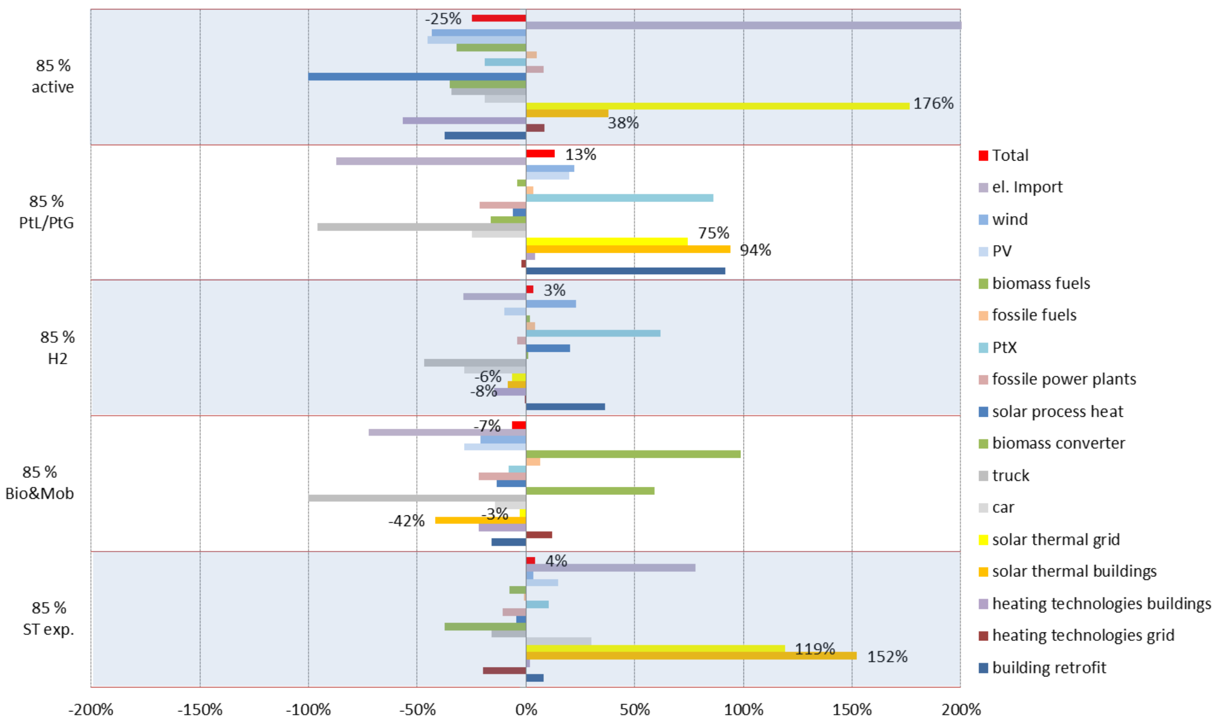

Figure 10: Relative change of cost comparing to the "85 open" scenario.

Again, the absolute values can only give an approximate order of magnitude due to the many assumptions that are made in the optimization. On the other hand, the relative comparison between the investigated system developments is more robust, since similar assumptions have been made in all calculations.

4.5 Heating supply technologies

In the following the heat sector will be analyzed in detail. In the heat supply of buildings, there is a clear trend from fuel-based technologies to heat pumps as CO_2 reduction increases. While at 60 percent reduction still oil boilers are part of the supply and gas boilers account for more than 40 percent of the capacity of all heating systems, at 90 percent reduction oil boilers are no longer part of the solution and gas boilers have only a very small proportion (Figure 11). Accordingly, the proportion of electric heat pumps and also of gas heat pumps is increasing. With electric heat pumps, air source heat pumps always dominate under otherwise identical conditions, except for a reduction of 90 percent. Comparing the installed capacity with the heat delivered by the systems, the boilers are used in larger systems and have lower full load hours (Figure 12). With the higher availability of biomass the installed capacity will raise (85% Bio&Mob).

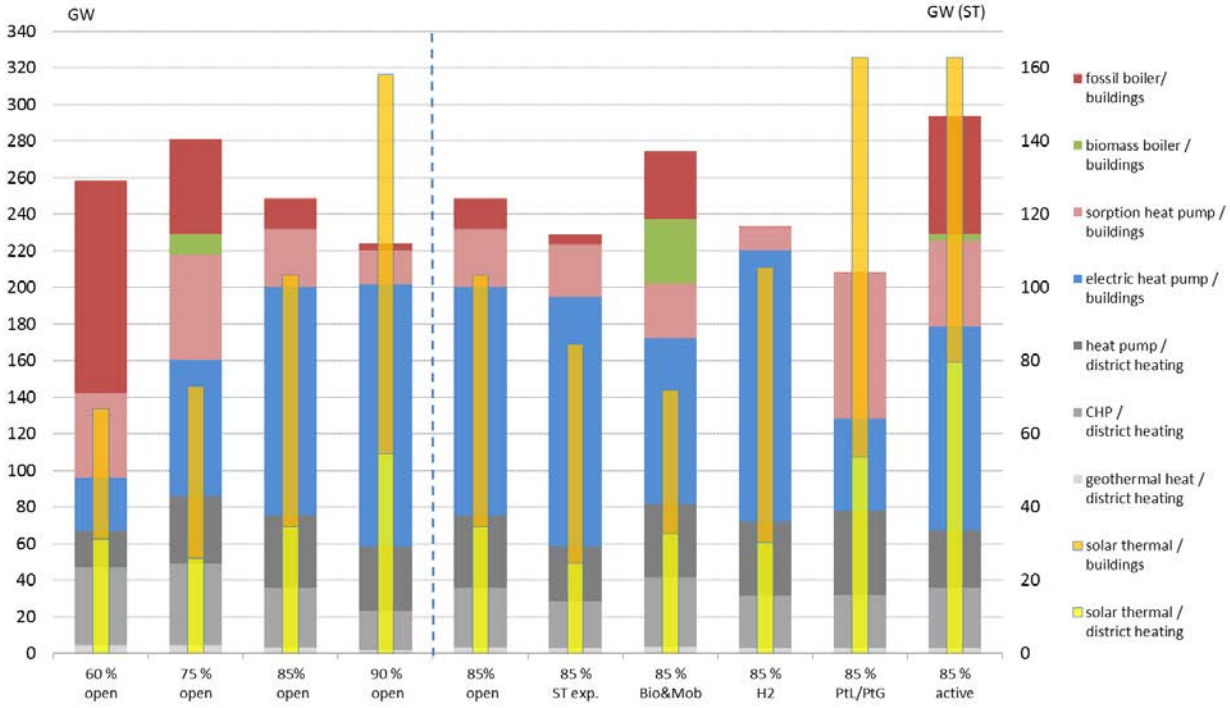

Figure 11: Installed capacity of heating technologies.

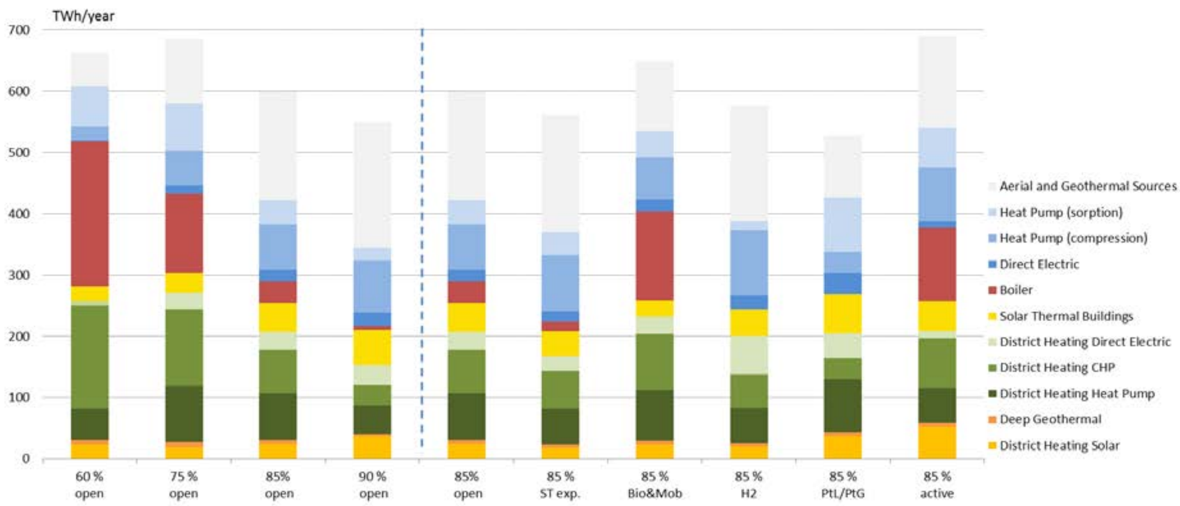

Figure 12: Sources of heat delivered.

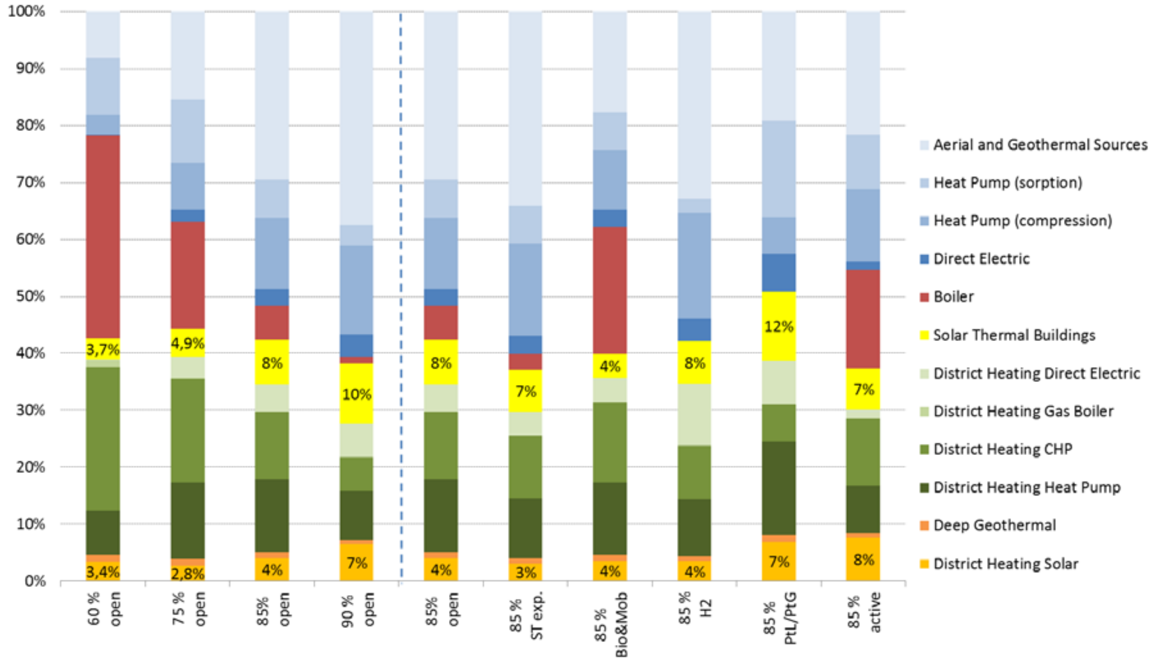

Figure 13: Relative share of heat delivered.

While in the model calculation with 60 percent CO_2 reduction in total about decentralized solar thermal rooftop systems and central ground-mounted systems that are connected to heat networks, about 70 GW_{th} are required, contribute with 90 percent reduction about 160 GW_{th} (heat network-linked systems) to the heat supply in the building sector (Figure 11). Figure 13 shows that with increasing CO_2 reduction, solar thermal heat generation becomes increasingly important to the system. The effect of the availability of biomass is even higher on the installed capacity than the cost. The highest amount of solar thermal will occur in a scenario, where the share of heat pumps is limited and the fuel has to be used in the transport sector (85% PtL/PtG).

Heat networks cover a larger number of buildings in all model calculations than is the case today. Depending on the CO_2 reduction targets considered, the proportion of heat generated by solar thermal energy changes.

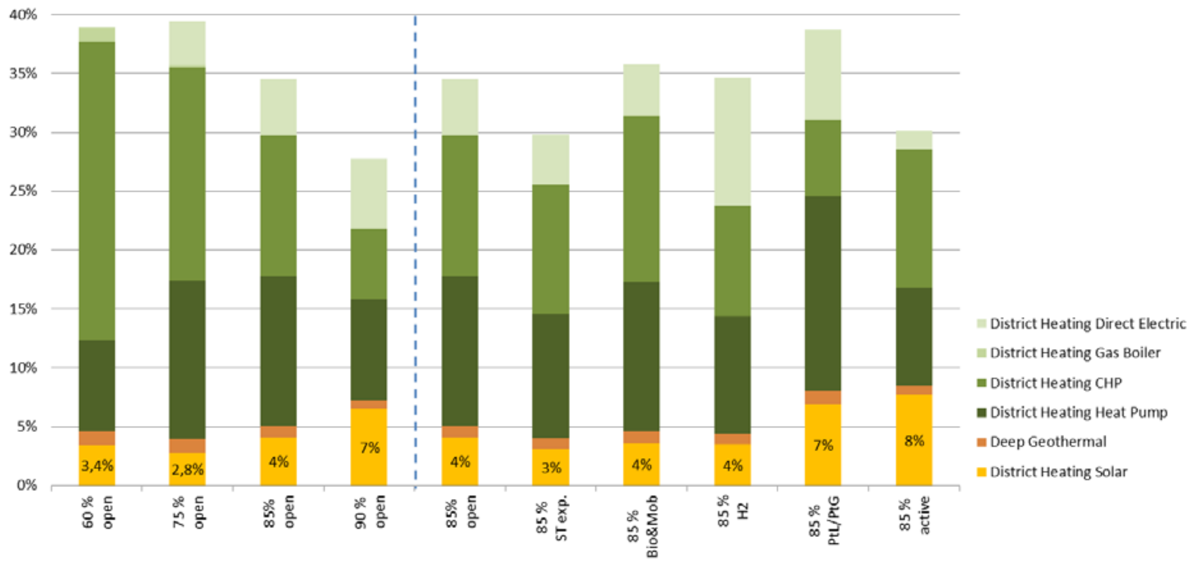

Figure 14: Relative share of heat sources delivered in district heating.

4.6 Building retrofit

The renovation of the building stock leads to a reduction of heat consumption and is a possible contribution to the achievement of climate protection goals. Energetically refurbished buildings were modeled on two energetic standards, which are termed "deep retrofit" and "deep retrofit plus". "deep retrofit" corresponds to the standard of the EnEV 2009 based on the remediation levels defined in the project "Climate neutral Buildings 2050", but tightened by 25 percent (EnEV -25%), and "deep retrofit plus" meets the requirements of a passive house. With one exception, the share of non-renovated buildings falls as the CO_2 reduction target increases, and the proportion of buildings refurbished to a very high energy standard increases (Figure 15). However, the majority of buildings, with one exception, are at a low energy standard under all boundary conditions considered, i.e. not at a passive house standard. Comparing the different scenarios with a reduction of 85%, in the scenario with high cost for solar thermal and with limited use of batteries in the transport sector, all buildings are retrofitted and high shares of deep retrofitted can be seen. The impact of the retrofit on the overall cost is high, see Figure 9.

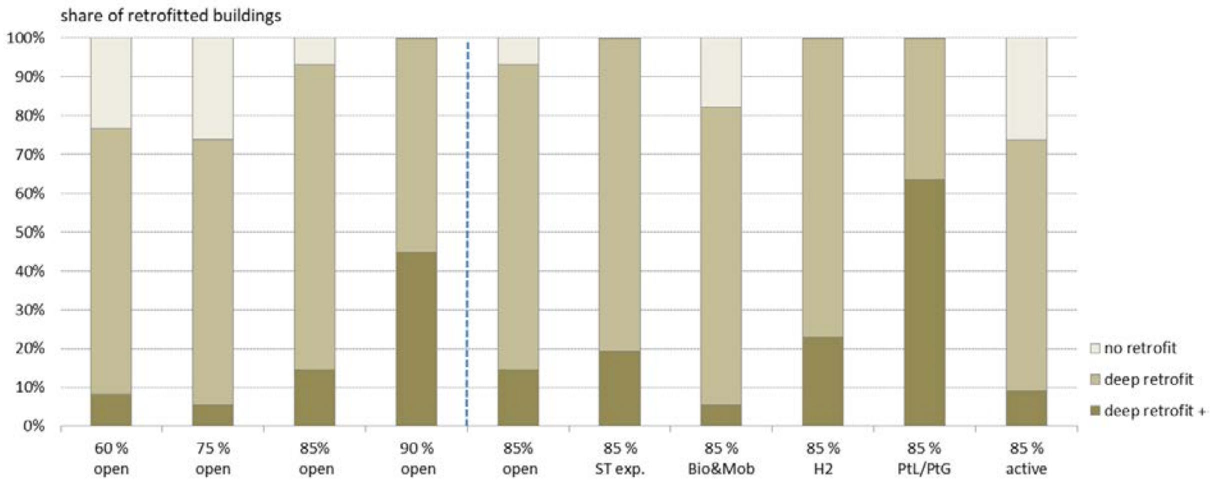

Figure 15: Relative share of retrofitted buildings.

4.7 Transport

The results of the model calculations suggest that significant changes are also expected in the transport sector if the energy transition targets are to be achieved (see Figure 16). In the case of a long-term high use of conventional propulsion based on fossil fuels, achieving the climate goals of more than 80 Percent hardly accomplish. A mix of electro mobility through use between electro mobility and vehicles with renewable energy based fuels is very likely. On the one hand, application technologies make good use of their high efficiency and favorable CO_2 balance and enable long ranges.

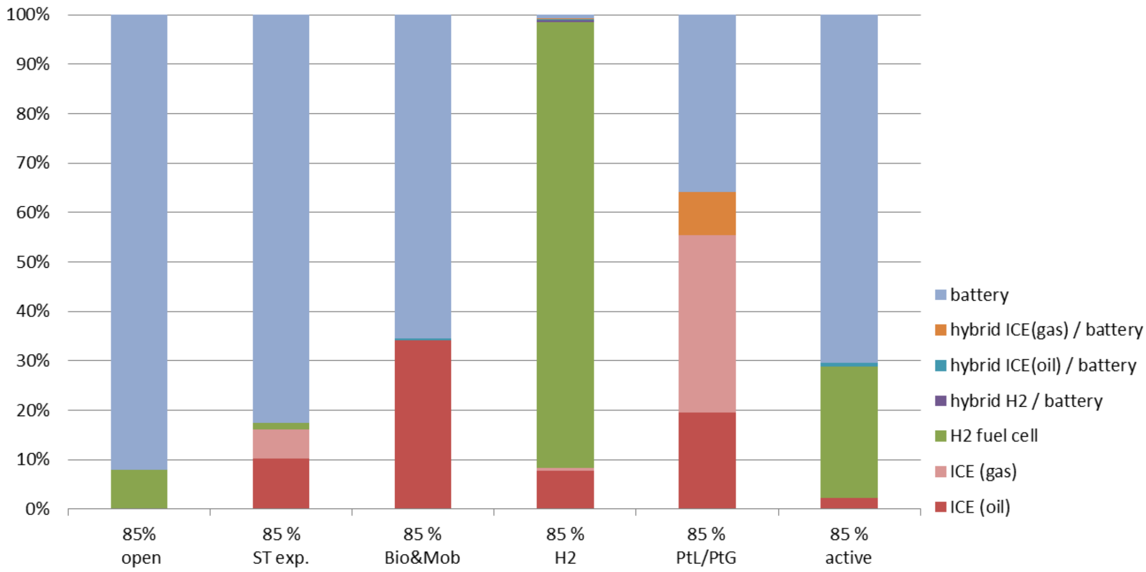

Figure 16: Composition of the drive concepts of cars and trucks in 2050 for the investigated boundary conditions (ICE - Internal Combustion Engine). In the 85 % H2 scenario, the hybrid solutions achieve a relevant number. In the other calculations, the number remains far below and is therefore not visible in the bar chart

The generation of regenerative fuels also allows a temporal decoupling of production and consumption. For the results for 85% H2 and 85% PtL/PtG it has to be taken into account that the results shown are strongly dependent on the costs and efficiencies of the technologies used and there are certainly still very high uncertainties here. In conjunction with the results shown above, it becomes clear that the decisions of home and vehicle owners have a significant impact on the transformation of the energy system.

5 Conclusions - Influence of sector coupling on solar thermal energy

The model results clearly show that the energy transition is accompanied by a strong reduction of the use of fossil fuels with a strong expansion of renewable energy technologies wind and solar and at the same time a much stronger coupling of the consumption sectors transport, heat and industry to the electricity sector. Sector coupling (with coupling technologies such as heat pumps, electric vehicle drives and electrolyzers) becomes even more important the more ambitious the CO_2 reduction targets are. Without an increase in the coupling of the electricity, heat and transport sectors, the achievement of the proposed climate protection goals would only be achieved with a very substantial reduction in consumption, coupled with higher imports of green electricity or imports of biomass or synthetic fuels from countries with much higher potential for the use of renewable energies.

The results show the strong interdependencies of the potential need of solar thermal in future energy on the system layout. It could be seen clearly, that under the given boundaries (upper limits for PV and Wind, limited biomass resources without, limited import of electricity) solar thermal will play an increasing role in the buildings sector heat supply aiming for higher reduction of $CO_{2.}$ The sensitivity analysis shows strong sector coupling effects. Easing the pressure on the availability of renewables by importing biomass will reduce the installed solar thermal capacity. The same will happen when specific cost of solar thermal will remain on the cost level of today. The installed capacity will drop down and part of that share will be covered by a higher amount of retrofitted building and heat pump technologies. Some link can be seen between the transport sector and the installed solar capacity – when the remaining fossil fuels or natural gas have to be used in the transport sector, the role of solar thermal will increase.

In the electricity sector, renewable energy technologies such as photovoltaics and wind turbines are the main drivers of total electricity generation, but CHP plants and gas-fired power plants are an important pillar of supply security, but with much lower full load hours than today. With the gas-fired power plants as back-up power plants and the CHP plants as a link between the electricity sector and the heat supply via heating grids, a large number of flexible power plants remain in the system. Depending on the current need, CHP plants are operated using heat or electricity. In the heat sector, all calculations show an enormous amount of electrically supplied heating energy. The heat supply can be made more flexible in conjunction with thermal storage (or in combination with battery storage). To stimulate this flexibility, time-variable tariffs are a possible means. In the transport sector, the switch to electro mobility and hydrogen vehicles is central to a substantial reduction in CO2 emissions. The infrastructural and systemic investment decisions are particularly important here, since network and lock-in effects are not negligible. These include effects of charging and distribution / storage infrastructure, but also internationalization and network boundaries through European and global markets. Early development of technologies and their investigation into pilot projects and demonstration projects is therefore essential to ensure that they are ready for use when widespread deployment becomes necessary. Techniques such as solar thermal energy, biomass and geothermal energy can make significant contributions to achieving the goals.

6 References

[1] A. Palzer, “Sektorübergreifende Modellierung und Optimierung eines zukünftigen deutschen Energiesystems unter Berücksichtigung von Energieeffizienzmaßnahmen im Gebäudesektor”. Karlsruhe, Karlsruher Institut für Technologie. (eingereichte) Dissertation. Day of oral exam: 2016-04-28

[2] BMWi: Zahlen und Fakten. Energiedaten. Nationale und internationale Entwicklung – Last checked 2015-09-22

[3] DWD: CDC - Climate Data Center. URL http://www.dwd.de/cdc – Last checked 2015-03-18

[4] DWD: Veröffentlichungen zum COSMO-Modell (COSMO-EU, COSMO-DE, COSMO-DE EPS). URL www.dwd.de – Last checked 2015-03-18

[5] KAH, Oliver ; FEIST, Wolfgang: Wirtschaftlichkeit von Wärmedämm - Maßnahmen im Gebäudebestand 2005. Darmstadt, Mai 2005

[6] PILLEN, Nicole ; DISCHER, Henning ; HINZ, Eberhard ; ENSELING, Andreas: Bericht 2010. dena-Sanierungsstudie. Teil 1 : Wirtschaftlichkeit energetischer Modernisierung im Mietwohnungsbestand. Begleitforschung zum dena-Projekt „Niedrigenergiehaus im Bestand“. 2010

[7] STOLTE, Christian ; MARCINEK, Heike ; DISCHER, Henning ; HINZ, Eberhard ; ENSELING, Andreas: Bericht 2011. dena-Sanierungsstudie. Teil 2 : Wirtschaftlichkeit energetischer Modernisierung in selbstgenutzten Wohngebäuden. Begleitforschung zum dena-Projekt „Niedrigenergiehaus im Bestand“. Berlin, 2012

[8] BÜRGER, Veit ; HESSE, Tilmann ; PALZER, Andreas ; HERKEL, Sebastian ; ENGELMANN, Peter: Klimaneutraler Gebäudebestand 2050. aktuell in Bearbeitung. Dessau - Roßlau, 2016.

[9] FEIST, Wolfgang: EnerPHit und EnerPHio+i – Zertifizierungskriterien für die Modernisierung mit Passivhaus-Komponenten. URL http://www.passiv.de/de/03_zertifizierung/02_zertifizierung_gebaeude/04_enerphit/04_enerphit.htm – Last checked 2015-03-19

[10] Cornelius Kuba (2015): Energiewirtschaftliche Perspektiven der Solarthermie in urbanen Energieversorgungssystem. Masterarbeit. Technische Universität Hamburg-Harburg, Hamburg.

[11] UBA (Hg.) (2014): Treibhausgasneutrales Deutschland im Jahr 2050. Umweltbundesamt. Dessau - Roßlau. Online verfügbar unter https://www.umweltbundesamt.de/sites/default/files/medien/378/publikationen/climate-change_07_2014_treibhausgasneutrales_deutschland_2050_0.pdf, zuletzt geprüft am 11.02.2015.

[12] Ausfelder et al.:”Sektorkopplung –Untersuchungen und Überlegungen zur Entwicklung eines integrierten Energiesystems

Annex: Data

The following data were used for calculation of the cost functions (see chapter2.3)

component	item	unit	value	component	item	unit	value	component	item	unit	value
Off. Wind	cost 2013	€/kW	3978	sorption heat pump	cost 2013	€/kW	2081	truck hybrid H2-fuel cell/battery	cost 2013	€/kW	497430
	cost 2050	€/kW	2251		cost 2050	€/kW	800		cost 2050	€/kW	165294
	cost Expo	-	1,5		cost Expo	-	2,0		cost Expo	-	7,7
	live time	a	20		live time	a	20		live time	a	15
	M/O-cost	% Invest	3,0		M/O-cost	% Invest	1,5		M/O-cost	% Invest	1,0
	int. rate	%	8		int. rate	%	8		int. rate	%	8
On. Wind	cost 2013	€/kW	1400	el. geothermal heat pump	cost 2013	€/kW	1540	truck Hybrid ICE fuel/battery	cost 2013	€/kW	134022
	cost 2050	€/kW	1035		cost 2050	€/kW	1232		cost 2050	€/kW	105722
	cost Expo	-	4,0		cost Expo	-	1,2		cost Expo	-	2,7
	live time	a	23		live time	a	20		live time	a	15
	M/O-cost	% Invest	3,4		M/O-cost	% Invest	3,5		M/O-cost	% Invest	1,3
	int. rate	%	8		int. rate	%	8		int. rate	%	8
PV	cost 2013	€/kW	1254	el. air ssource heat pump	cost 2013	€/kW	1195	truck Hybrid ICE Gas/battery	cost 2013	€/kW	142702
	cost 2050	€/kW	571		cost 2050	€/kW	956		cost 2050	€/kW	114901
	cost Expo	-	2,5		cost Expo	-	1,2		cost Expo	-	2,6
	live time	a	30		live time	a	20		live time	a	15
	M/O-cost	% Invest	2,0		M/O-cost	% Invest	3,5		M/O-cost	% Invest	1,3
	int. rate	%	8		int. rate	%	8		int. rate	%	8
Elektrolysis	cost 2013	€/kW	840	el/gas hybrid heat pump air	cost 2013	€/kW	1215	truck batter -electric drive	cost 2013	€/kW	246437
	cost 2050	€/kW	200		cost 2050	€/kW	972		cost 2050	€/kW	106822
	cost Expo	-	3,0		cost Expo	-	2,0		cost Expo	-	8,1
	live time	a	19		live time	a	20		live time	a	15
	M/O-cost	% Invest	4,0		M/O-cost	% Invest	3,0		M/O-cost	% Invest	0,9
	int. rate	%	8		int. rate	%	8		int. rate	%	8
stationary batterys	cost 2013	€/kWh	1260	micro-CHP	cost 2013	€/kW	1780	floor heating	cost 2013	€/kW	60
	cost 2050	€/kWh	200		cost 2050	€/kW	1424		cost 2050	€/kW	60
	cost Expo	-	6,0		cost Expo	-	3,0		cost Expo	-	0,0
	live time	a	25		live time	a	20		live time	a	50
	M/O-cost	% Invest	1,0		M/O-cost	% Invest	3,0		M/O-cost	% Invest	1,5
	int. rate	%	8		int. rate	%	8		int. rate	%	8
E-H2-Storage	cost 2013	€/kWh	1	solar thermal decentral	cost 2013	€/m²	1200	solid-biomass- to CH4	cost 2013	0	2426
	cost 2050	€/kWh	0		cost 2050	€/m²	400		cost 2050	0	1244
	cost Expo	-	2,5		cost Expo	-	4,0		cost Expo	-	3,0
	live time	a	40		live time	a	30		live time	a	20
	M/O-cost	% Invest	1,6		M/O-cost	% Invest	1,3		M/O-cost	% Invest	6,0
	int. rate	%	8		int. rate	%	8		int. rate	%	8
P-H2-capacity (Gas)	cost 2013	€/kW	20	local storage	cost 2013	€/l	2	solid-biomass- to H2	cost 2013	0	3670
	cost 2050	€/kW	20		cost 2050	€/l	1		cost 2050	0	1882
	cost Expo	-	2,5		cost Expo	-	2,0		cost Expo	-	3,0
	live time	a	25		live time	a	20		live time	a	20
	M/O-cost	% Invest	1,6		M/O-cost	% Invest	1,3		M/O-cost	% Invest	6,0
	int. rate	%	8		int. rate	%	8		int. rate	%	8
Sabatier	cost 2013	€/kW	3000	heat pump heat grid	cost 2013	€/kW	781	solid-biomass- to fuel	cost 2013	0	3315
	cost 2050	€/kW	800		cost 2050	€/kW	625		cost 2050	0	1700
	cost Expo	-	3,0		cost Expo	-	6,0		cost Expo	-	2,0
	live time	a	25		live time	a	20		live time	a	20
	M/O-cost	% Invest	2,5		M/O-cost	% Invest	3,5		M/O-cost	% Invest	6,0
	int. rate	%	8		int. rate	%	8		int. rate	%	8
raw biogas electrification (el. Power)	cost 2013	€/kW	560	large storage (district heating)	cost 2013	€/m³	171	solid-biomass Industrie	cost 2013	€/kW	280
	cost 2050	€/kW	500		cost 2050	€/m³	120		cost 2050	€/kW	280
	cost Expo	-	1,7		cost Expo	-	2,0		cost Expo	-	5,0
	live time	a	20		live time	a	40		live time	a	20
	M/O-cost	% Invest	2,5		M/O-cost	% Invest	1,0		M/O-cost	% Invest	3,0
	int. rate	%	8		int. rate	%	8		int. rate	%	8
P-H2-Reformation fossil	cost 2013	€/kW	955	solar thermal heat grid	cost 2013	€/m²	800	Biodiesel plant (rape seed)	cost 2013	€/kW	150
	cost 2050	€/kW	955		cost 2050	€/m²	290		cost 2050	€/kW	150
	cost Expo	-	1,0		cost Expo	-	3,5		cost Expo	-	1,0
	live time	a	15		live time	a	30		live time	a	20
	M/O-cost	% Invest	2,5		M/O-cost	% Invest	1,4		M/O-cost	% Invest	5,0
	int. rate	%	8		int. rate	%	8		int. rate	%	8

component	item	unit	value	component	item	unit	value	component	item	unit	value
	cost 2013	€/kWh	750		cost 2013	€/kW	22429		cost 2013	€/kW	1105
	cost 2050	€/kWh	240		cost 2050	€/kW	21100		cost 2050	€/kW	697
BioNgas production	cost Expo	-	3,0	car ICE-fuel	cost Expo	-	1,4	Biogas plant	cost Expo	-	3,0
	live time	a	25		live time	a	15		live time	a	20
	M/O-cost	% Invest	3,0		M/O-cost	% Invest	1,6		M/O-cost	% Invest	5,0
	int. rate	%	8		int. rate	%	8		int. rate	%	8
	cost 2013	€/kW	800		cost 2013	€/kW	24729		cost 2013	€/kWh	0
	cost 2050	€/kW	532		cost 2050	€/kW	23400		cost 2050	€/kWh	0
H2-to-Fuel	cost Expo	-	3,0	car ICE gas	cost Expo	-	1,4	solar process heat	cost Expo	-	3,0
	live time	a	30		live time	a	15		live time	a	30
	M/O-cost	% Invest	4,0		M/O-cost	% Invest	1,4		M/O-cost	% Invest	1,3
	int. rate	%	8		int. rate	%	8		int. rate	%	8
	cost 2013	€/kW	700		cost 2013	€/kW	77600		cost 2013	€/kW	385
	cost 2050	€/kW	700		cost 2050	€/kW	24800		cost 2050	€/kW	385
Gas power stations	cost Expo	-	1,0	H2 fuel cell	cost Expo	-	7,5	gas turbine	cost Expo	-	1,0
	live time	a	40		live time	a	15		live time	a	50
	M/O-cost	% Invest	3,0		M/O-cost	% Invest	0,9		M/O-cost	% Invest	2,0
	int. rate	%	8		int. rate	%	8		int. rate	%	8
	cost 2013	€/m²	102		cost 2013	€/kW	110857		cost 2013	€/kW	1700
	cost 2050	€/m²	102		cost 2050	€/kW	35429		cost 2050	€/kW	1700
building deep retrofit	cost Expo	-	1,0	car hybrid H2-fuel cell/battery	cost Expo	-	7,4	lignite power plant	cost Expo	-	1,0
	live time	a	50		live time	a	15		live time	a	45
	M/O-cost	% Invest	1,0		M/O-cost	% Invest	1,0		M/O-cost	% Invest	1,6
	int. rate	%	8		int. rate	%	8		int. rate	%	8
	cost 2013	€/m²	180		cost 2013	€/kW	31275		cost 2013	€/kW	1500
	cost 2050	€/m²	180		cost 2050	€/kW	24900		cost 2050	€/kW	1500
building deep retrofit +	cost Expo	-	1,0	car hybrid ICE fuel/battery	cost Expo	-	2,7	hard coal power plant	cost Expo	-	1,0
	live time	a	50		live time	a	15		live time	a	45
	M/O-cost	% Invest	1,0		M/O-cost	% Invest	1,3		M/O-cost	% Invest	1,6
	int. rate	%	8		int. rate	%	8		int. rate	%	8
	cost 2013	€/kW	3936		cost 2013	€/kW	33463		cost 2013	€/kWh	1260
	cost 2050	€/kW	3146		cost 2050	€/kW	27200		cost 2050	€/kWh	200
deep geothermal heat heat grid	cost Expo	-	5,0	car hybrid ICE gas/battery	cost Expo	-	2,6	battery-elektrolysis	cost Expo	-	6,0
	live time	a	22		live time	a	15		live time	a	25
	M/O-cost	% Invest	3,7		M/O-cost	% Invest	1,3		M/O-cost	% Invest	1,0
	int. rate	%	8		int. rate	%	8		int. rate	%	8
	cost 2013	€/kWel	839		cost 2013	€/kW	57450		cost 2013	€/kWh	1260
	cost 2050	€/kWel	736		cost 2050	€/kW	26000		cost 2050	€/kWh	200
CHP Heat Grid	cost Expo	-	3,0	car battery-elektric drive	cost Expo	-	8,1	battery methanisation	cost Expo	-	6,0
	live time	a	22		live time	a	15		live time	a	25
	M/O-cost	% Invest	3,0		M/O-cost	% Invest	0,9		M/O-cost	% Invest	1,0
	int. rate	%	8		int. rate	%	8		int. rate	%	8
	cost 2013	€/kW	155		cost 2013	€/kW	97502		cost 2013	€/kWh	850
	cost 2050	€/kW	155		cost 2050	€/kW	91605		cost 2050	€/kWh	850
Oil boiler non-cond.	cost Expo	-	1,1	truck ICE- fuel	cost Expo	-	1,6	pump storage	cost Expo	-	1,0
	live time	a	20		live time	a	15		live time	a	80
	M/O-cost	% Invest	2,0		M/O-cost	% Invest	1,6		M/O-cost	% Invest	2,0
	int. rate	%	8		int. rate	%	8		int. rate	%	8
	cost 2013	€/kW	155		cost 2013	€/kW	106681			Mio	25
	cost 2050	€/kW	155		cost 2050	€/kW	100783			Mio	0
Gas boiler non-cond.	cost Expo	-	1,1	truck ICE gas	cost Expo	-	1,6	number of build (total)		Mio	0,5
	live time	a	20		live time	a	15				
	M/O-cost	% Invest	2,0		M/O-cost	% Invest	1,4				
	int. rate	%	8		int. rate	%	8				
	cost 2013	€/kW	788		cost 2013	€/kW	319925				
	cost 2050	€/kW	631		cost 2050	€/kW	106310				
biomass boiler/wood chip boiler	cost Expo	-	1,0	truck H2-fuel cell	cost Expo	-	7,7				
	live time	a	20		live time	a	15				
	M/O-cost	% Invest	3,0		M/O-cost	% Invest	0,9				
	int. rate	%	8		int. rate	%	8				