Available online at www.sciencedirect.com
ScienceDirect
Energy Procedia 57 (2014) 940 – 949
Energy Procedia

2013 ISES Solar World Congress

Assessment of renewable energy integration for a village using the energy hub concept

Kristina Orehounig[1,2]*, Ralph Evins[1,2], Viktor Dorer[2], Jan Carmeliet[1,2]

[1] *Chair of Building Physics, Swiss Federal Institute of Technology Zurich (ETHZ), Zurich, Switzerland*
[2] *Laboratory for Building Science and Technology, Empa, Dübendorf, Switzerland*

Abstract

The built environment represents a major share of global energy consumption. To effectively reduce the energy consumption of urban conglomerations, concepts to sufficiently integrate and manage energy from renewables are necessary. In this paper the energy-hub concept will be applied, which describes the relation between input and output energy flows and can be used to optimize the energy consumption during planning and operation. The concept will be used to evaluate a number of future energy scenarios for a village in Switzerland which has the goal of eliminating the consumption of fossil fuels. As a starting point the existing situation concerning the energy demand of the village with respect to different uses, the different energy carriers, their origin, their distribution and networks is captured and analyzed. In the next step the potential for different means of decentralized energy production is evaluated. Decentralized energy production includes building integrated or local renewable energy production by photovoltaics, biomass, or small hydro power. In the third step, different future energy scenarios for an energy sustainable community are defined. These different scenarios are distinguished by their scale of implementation. Finally an energy hub model of the village is developed and used to evaluate the different energy scenarios.

Selection and/or peer-review under responsibility of ISES.

Keywords: energy concept; renewables; energy sustainable community; energy hub

1. Introduction

With the continuously growing demand for energy and the dependency on diminishing fossil fuels the need to integrate energy from renewables has increased. Since renewable energy generation is known to be highly fluctuating in time, and as such energy demand and energy production do not match necessarily, new concepts to manage these fluctuating power sources, like energy storage, energy

* Corresponding author. Tel.: +41 58765 4357; fax: +41 44 633 10 41
E-mail address: orehounig@arch.ethz.ch

Selection and/or peer-review under responsibility of ISES.
doi:10.1016/j.egypro.2014.10.076

conversion from one energy carrier to another, the integration of district heating networks, micro grids, and energy hubs have been developed. These concepts can be more effectively integrated at building block or quarter level than just taking individual buildings into account.

Based on this background this paper applies the energy hub concept to evaluate a number of different future energy scenarios integrating renewable energy technologies for a village in Switzerland. The modeling concept of an energy hub describes the relation between input and output energy flows and can be used to optimize the energy consumption during planning and operation. In this paper the energy hub concept will be applied to a village which has decided to increase renewable energy sources, and reduce the consumption of fossil fuels. As a starting point the existing situation concerning the energy demand of the village with respect to different uses (heating, lighting, etc.), the different energy carriers (fossil fuel, gas, or electricity), their origin (hydropower, combustion, etc.), their distribution and supply (e.g. district heating) is captured and analyzed. In a next step the potentials for different means of decentralized energy production is evaluated. Decentralized energy production includes building integrated or local renewable energy production by photovoltaic, biomass, or small hydro power. In a third step, different future energy scenarios towards an energy sustainable community are defined. These different scenarios can be distinguished regarding their scale of implementation. Finally an energy hub model of the village is developed and used to evaluate the different future energy scenarios for the village.

Nomenclature

L	hub-output vector	υ	dispatch factor
C	converter coupling matrix	PV	photovoltaic
P	hub-input vector	CHP	combined heat and power
α,β,…,ω	energy carriers		

2. Energy hub concept

The energy hub model was developed by the Power Systems laboratory at ETH Zürich to manage energy flows within a large building complex, city quarter, neighborhood, or even country. It gives the possibility to store energy, convert energy between multiple energy carriers (e.g. electricity to heat, natural gas to heat, thermal solar or bio-mass water heating and hot water storage, etc.) and sufficiently supply electricity, heat, cold, gases or fuels to the community. Thereby it is typically connected to electricity and gas infrastructures at the input port, gives the possibility to convert or store electricity or heat, and provides energy services to the end-users at the output port. The advantage of the energy hub approach is an increase in reliability of the energy infrastructure since usually a number of options to provide heating or electricity to consumers is possible. Additionally it has the advantage to optimize the energy consumption, costs, emissions etc. due to regulating conversion, storage, and distribution of energy. The basic concept of an energy hub, which will be applied in this paper, consists of multiple input energy carriers which will be converted by the hub to multiple outputs. The conversion can be a single device or a combination of multiple devices [1,2]. The conversion between input and output are characterized by energy efficiencies which are defined in the conversion matrix. Three different conversions are considered, a lossless connection indicated by an efficiency of $c_{\alpha\beta}=1$, a conversion with losses, which is indicated with a factor $0 < c_{\alpha\beta} < 1$, and no coupling $c_{\alpha\beta} = 0$ which means that this conversion is not possible. Since one energy carrier might be converted into different forms of energy (e.g. electricity directly used, or converted to heat) so-called dispatch factors have to be determined. The dispatch factors υ define how much of each energy carrier flows into each converter. The sum of all dispatches of a single energy input must be equal to 1. Thus the multiple inputs and multiple outputs concept of an energy hub can be described by the following equation:

$$\begin{bmatrix} L_\alpha \\ L_\beta \\ \vdots \\ L_\omega \end{bmatrix} = \begin{bmatrix} c_{\alpha\alpha} & c_{\beta\alpha} & \cdots & c_{\omega\alpha} \\ c_{\alpha\beta} & c_{\beta\beta} & \cdots & c_{\omega\beta} \\ \vdots & \vdots & \ddots & \vdots \\ c_{\alpha\omega} & c_{\beta\omega} & \cdots & c_{\omega\omega} \end{bmatrix} \begin{bmatrix} P_\alpha \\ P_\beta \\ \vdots \\ P_\omega \end{bmatrix} \tag{1}$$

In this equation L_α, L_β,…, L_ω denotes the hub-output vector, P_α, P_β,…, P_ω the hub-input vector, and C stands for the converter coupling matrix, where α, β, …, ω stands for the set of different energy carriers. Based on this model different optimization problems can be formulated for optimal dispatch, optimal hub layout, optimal storage, etc. The energy hub concept can be applied at different levels of complexity. The basic model is used for the optimal dispatch of a single energy hub for multi-energy carriers, so the power flows through the hub are optimized for a specific period. This could be for peak energy demand or annual energy consumption. More advanced formulations can be applied transiently to time series representing demands and supply capacities.

3. Assessment of energy scenarios using the energy hub approach

3.1. The current energy situation in the village

The village is located in Switzerland at a sea level of 1474 m with a mean annual air temperature of 4.8 °C (from October 2010 to September 2011) and a global horizontal solar radiation incident of 1170 $kWh.m^{-2}$. It has a population of 1150 and consists of approximately 300 buildings, of which about 230 are residential and trade, and some additional buildings pertaining to agriculture, restaurants, industry, hotels, public buildings etc. As a starting point the existing situation concerning the energy demand of the village with respect to different uses (heating, lighting, …), the different energy carriers (fossil fuel, gas, electricity, wood, wood chips), and their distribution and networks (e.g. district heating) are analyzed. Additional available information pertains to building characteristics such as age, type, construction method, insulation quality, and type of heating system. The majority of the buildings are equipped with electrical heating systems; additional energy sources are oil, wood chips for a small district heating network, wood for wood stoves, and some renewables. The village is connected to the national electricity network. It has a small district heating network which is connected to a wood-fired power-station, for which the wood is brought to the village by trucks. Additionally, a small CHP unit connected to a gasification unit fired by organic matter is used. To identify the energy consumption of the buildings, information pertaining to annual electricity, oil, and wood consumption and delivered energy from the district heating network was collected. Collected information was further analyzed to identify the energy used for heating and for electricity. For buildings where electricity is used for space heating, the annual electricity consumption was divided into electricity used for appliances and lighting, and electricity used for space heating based on statistical values. Assumptions for typical electricity demand for appliances [3] are subtracted from the actual electricity consumption; the remainder is defined as electricity consumption for space heating. Installed heating systems differ from house to house in terms of installation date, size, and settings, which makes it difficult to identify the exact efficiency of the system. To get a rough estimation of the net energy required for heating, standard efficiency values have been assumed depending on energy carriers. These values are summarized in Table 1. Based on this analysis the overall energy consumption of the village was 6 950 MWh electricity consumption for appliances and 13 888 MWh for net space heating.

Table 1. Net heating energy in terms of energy carrier for a full year

Energy carrier	Delivered energy [MWh.a^{-1}]	Average efficiency of heating system [-]	Net heating energy demand [MWh.a^{-1}]
electricity	3 515	0.95	3 340
oil	6 730	0.85	5 720
wood chips and organic	3 240	0.95	3 078
wood	2 500	0.70	1 750
			13 888

3.2. Potential assessment of renewables

In the next step the potentials for decentralized energy production are evaluated. Decentralized energy production includes building integrated or local renewable energy production by photovoltaics, for electricity production. To evaluate the potential the simulation tool CitySim is applied. CitySim consists of a thermal model for simulating the energy performance of the building stock within an urban configuration and a model for shortwave radiation to identify solar incident on facades and roofs [4]. It further integrates a number of energy system models such as heat pumps, boilers, cogeneration plants etc. as well as the option to calculate the building integrated photovoltaic potential. As an initial approach roof surfaces of the village with orientations from East, South, and West and inclinations from 0° to 45° have been investigated. Two versions have been calculated namely i) roof surfaces from all buildings that are not protected for historical reasons, and ii) only buildings outside the historic centre. Table 2 shows the available solar gains incident on various inclined roof surfaces together with resulting energy production (assumed efficiency of 18%) simulated for the village. Figure 1 shows the measured total electricity consumption together with the computed available PV potential of 14 different areas within the village. In addition to photovoltaic, the potential to generate electricity by small hydro power turbines is explored. As an initial approach it is assumed that small water turbines could generate 680 MWh per year. An additional approach to increase renewables within the village is the extension of the current district heating network. First assumptions assume that the network is extended to cover also the city centre of the village, which would require an increase in biomass of about 60% based on current energy consumption data.

Table 2. Computed solar radiation incident on various inclined surfaces and orientations together with resulting PV energy production

Orientation	Inclination [°]	Solar incident [kWh.m-2.a-1]	PV Production [kWh.m-2.a-1]
East	5	1155	208
	15	1105	199
	30	995	179
	45	869	156
South	5	1233	222
	15	1335	240
	30	1430	257
	45	1450	261
West	5	1184	213
	15	1191	214
	30	1152	207
	45	1065	192

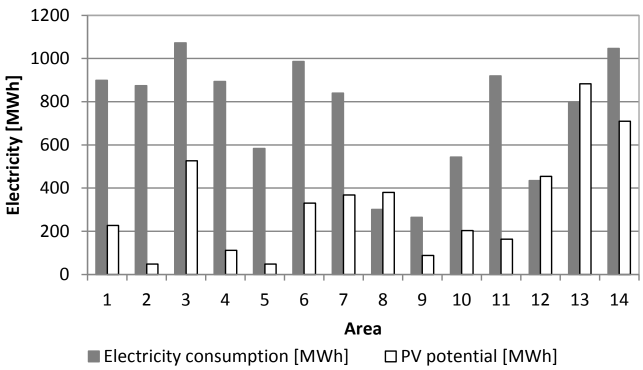

Fig. 1. Total electricity consumption together with the computed available PV potential of the 14 different areas.

3.3. Energy scenarios

As a next step, five different future energy scenarios S1-5 are defined which will be explored with the application of the energy hub concept. The scenarios take the estimated renewable potentials into account. As a starting point the focus lies on the integration of renewables in individual buildings, without integration into energy networks on building cluster or village level. The existing energy demand situation for the period of one year was taken as the target. It was assumed that the new village energy strategy is able to replace all existing energy carriers if required (connection to the electricity network, oil space heating, district heating network fired by wood chips, wood stoves). In the first scenario S1 the possibility of additional electricity from PVs is provided. It was assumed that electricity both from the electric grid and from PVs could be used directly to cover the electricity demand of appliances or it can be converted by the energy hub to heat. The other energy carriers (oil, wood chips, and wood) can be solely used to cover the space heating demand. The electricity available from PV was limited to the feasible production by roof integrated photovoltaics. The second scenario S2 takes the same energy carriers into account and additionally assumes the installation of a small hydro power plant. The third scenario S3 is similar to S2 but the feasible amount of photovoltaic is reduced to buildings outside the centre of the village. The fourth scenario S4 is also similar to S2 but assumes that the current heating district network will be closed. And finally the fifth scenario S5 assumes that the district heating network is further extended to the core centre of the village, assuming an increase in biomass potential. The potential supply for each energy carrier for the scenarios is presented in table 3.

Table 3. Maximum available amount of energy per energy carrier [MWh]

Scenario	S1	S2	S3	S4	S5
Electricity (Grid)	unlimited	unlimited	unlimited	unlimited	unlimited
PV	4 541	4 541	3 740	4 541	4 541
Small hydro	-	680	680	680	680
Oil	unlimited	unlimited	unlimited	unlimited	unlimited
Wood	2 430	2 430	2 430	2 430	2 430
Wood chips (district heating)	3 200	3 200	3 200	-	5 270

3.4. Set-up of the energy hub model

The next step is the set-up of the energy hub model for the village: the multiple-energy carrier optimal dispatch model. This model evaluates the optimal dispatch of multiple input carriers to effectively cover the required heating and electricity load at the output of the hub. The conversion between the different energy carriers was defined based on assumptions for technologies as per table 4.

Table 4. Proposed technologies based on different energy carriers together with conversion factors of different energy carriers

Symbol	Value	Conversion	Element	Integration
$c_{el\text{-}el}$	0.95	Electricity to electricity	Transformer	Electricity grid
$c_{PV\text{-}el}$	0.95	PV to electricity	Transformer	Building integrated
$c_{ew\text{-}el}$	0.95	Electricity from small hydro power to electricity	Transformer	Electricity grid
$c_{el\text{-}he}$	0.95	Electricity to heat	Direct heating	Electricity grid
$c_{PV\text{-}he}$	0.95	PV to heat	Direct heating	Building integrated
$c_{ew\text{-}he}$	0.95	Electricity from small water turbines to heat	Direct heating	Electricity grid
$c_{oil\text{-}he}$	0.85	Oil to heat	Boiler	Building integrated
$c_{wc\text{-}he}$	0.8	Wood chips to heat delivered by district heating network	Boiler plant	District heating network
$c_{w\text{-}he}$	0.7	Wood to heat	Stove	Building integrated

For optimizing the proposed energy systems a bi-objective function was assumed, aiming for minimal CO_2 emissions and minimal energy costs. These two objectives were combined using a weighting factor. The resulting objective function is as follows:

$$F = \xi \cdot \sum_{\alpha} (a_\alpha P_\alpha) + (1-\xi) \cdot \sum_{\alpha} (b_\alpha P_\alpha) \quad (2)$$

The objective function coefficients a_α define the energy price and b_α the CO_2 emissions coefficients of the individual energy carriers (Table 5). ξ is the cost-emissions weighting factor, which can be adjusted between 0 and 1 where $\xi=0$ refers to minimal emissions and $\xi=1$ refers to minimal costs. With the range $0 \leq \xi \leq 1$ so called Pareto optimal solutions are obtained. To reach a better distribution among the solutions, an adaptive algorithm [5] is used. Note that assumed objective function coefficients are based on literature values [6,7,8,9] but do not necessarily reflect the current situation in the village.

Table 5. Assumed objective function coefficients (a: energy price, b: CO_2 emissions)

Energy carrier	a [CHF/kWh]	b [g CO_2/kWh]
Electricity (mix)	0.178	122
PV	0.12	69.6
Small hydro	0.14	4.7
Oil	0.068	340
Biomass/wood chips	0.076	21.6
Wood	0.048	21.6

4. Results and Discussion

Figure 2 shows energy hub model results for the proposed scenarios S1 to S5 (as per Table 3). The pareto curves show optimization results for different weighting factors $0 \leq \xi \leq 1$. Weighting factors are described as $\xi=1$ aiming for minimal costs and $\xi=0$ aiming for minimal emissions. Results indicate two to three times higher emissions for a weighting factor which prioritizes costs, whereas scenarios aiming for minimal emissions indicate a 40 to 60% increase in costs. Comparing the five different scenarios, S5 showed the lowest values for both CO_2 and costs. Lower graphs in Figure 2 show the distribution of energy demand between different carriers for scenarios S1 to S5. Additionally, Figure 3 shows a summary of distribution of energy demand between different carriers for scenarios S1 to S5 for weighting factors $\xi=1$ (minimal costs) and $\xi=0$ (minimal emissions). Scenarios which are optimized for costs consume mainly oil for space heating, whereas scenarios which are optimized for emissions do not take oil into account, but energy from renewables (photovoltaic and biomass), which clearly shows that emissions and costs are conflicting parameters. Pareto curves of scenarios S1, S2, S3, and S5 furthermore suggest that reducing the oil consumption is more effective in terms of reducing costs and emissions compared to other measures. Table 6 shows the distribution between the resulting CO_2 emissions for the minimum emissions case (weighting factor 0) of all 5 scenarios. The best-performing scenarios showed a reduction of 38% in CO_2 emissions compared to the current energy situation in the village.

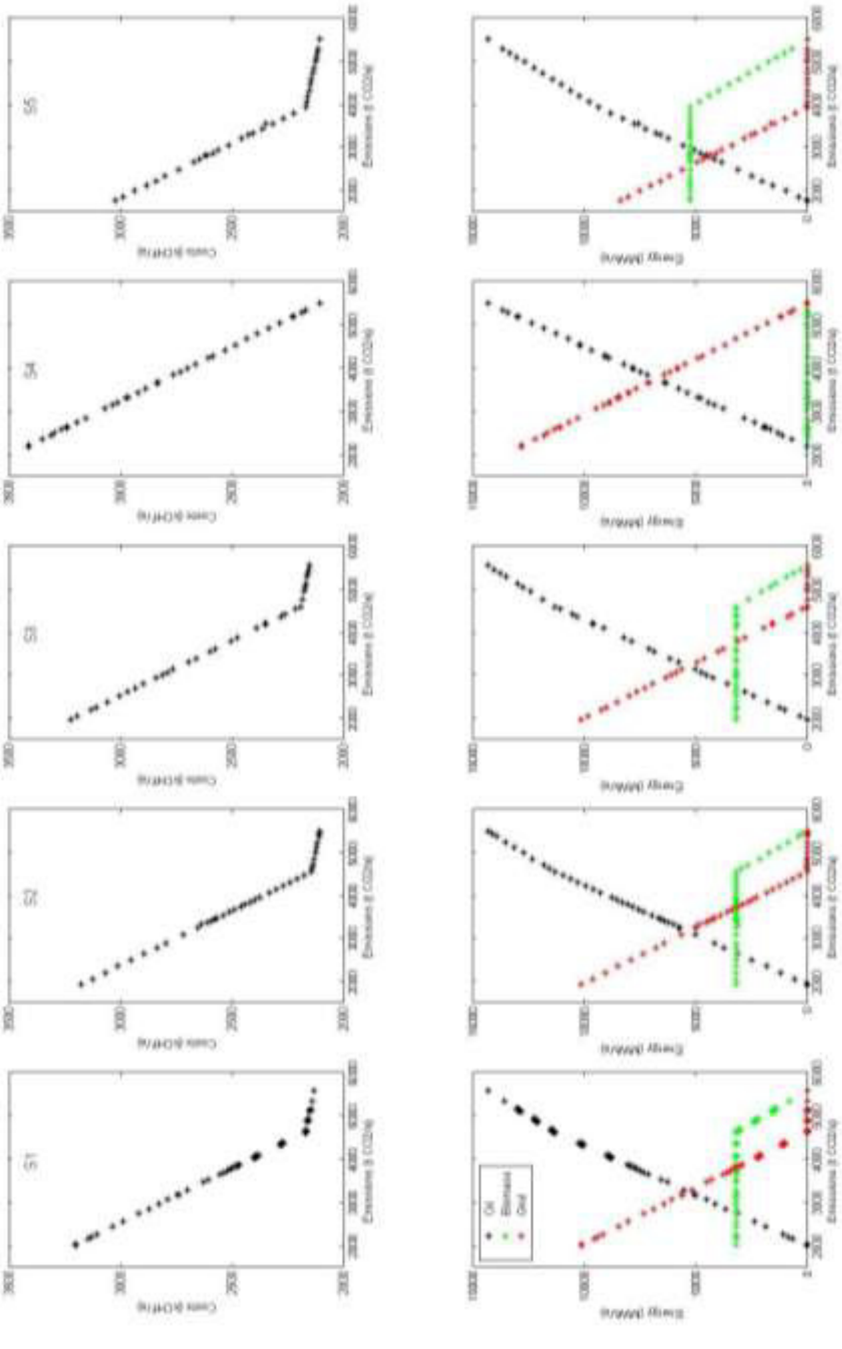

Fig. 2. Pareto fronts (minimal costs ξ=1, minimal emissions ξ=0) of energy hub results for different scenarios S1-S5 (upper graphs). Lower graphs show distribution of energy demand between different energy carriers (oil, biomass, and grid) for the same scenarios.

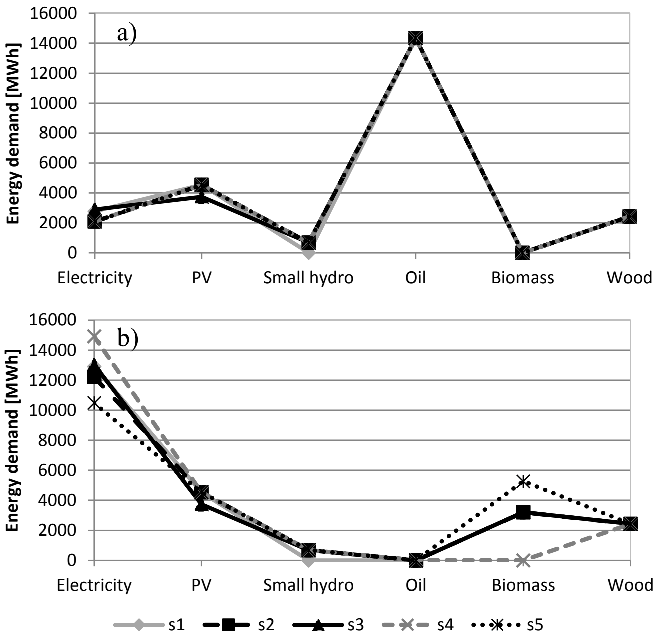

Fig. 3. Distribution of energy demand between different energy carriers for S1 to S5 for a) for minimal costs (ξ=1) and b) minimal emissions (ξ=0).

Table 6. Energy hub results for emissions minimization (ξ=0).

Scenario	S1	S2	S3	S4	S5
tCO2	2 012	1 932	1 974	2 191	1 764

5. Conclusions and Outlook

This paper presents the assessment of a number of future energy scenarios for a village, taking renewable energy sources into account. An energy hub model of the village was generated to optimize the dispatch of different energy carriers for emissions and costs. A CO_2 emission reduction of 38% could be achieved by increasing the consumption of biomass, small hydro power and PV, decreasing the need for electricity from the grid and the use of oil for space heating.

Further work will implement a more advanced version of the energy hub model taking multiple time periods into account. This will allow the potential for energy storage systems to be investigated, including both seasonal and short term storage, to efficiently overcome periods where the potential of renewables is low and additional energy sources will be explored.

Acknowledgements

The research presented in this paper is supported in part by funds from ETH-Z and KTI (Zernez Energia 2020, Nr. 15042.1 Project leader: Prof. Kees Christiaanse, deputy project leader: Michael Wagner). The authors also gratefully acknowledge members of the Architecture & Sustainable Building Technologies (SuAT) group, Prof. Dr. Arno Schlueter towards providing collected information regarding energy use, buildings, systems etc. The authors further acknowledge Prof. Dr. Goeran Andersson and Dr. Thilo Krause for providing the initial energy hub model.

References

[1] Geidl M, Koeppel G, Favre-Perrod P, Andersson G, Froehlich K. Energy Hubs for the Future. IEEE Power & Energy magazin, January/February 2007.

[2] Geidl M. Integrated Modeling and Optimization of Multi-Carrier Energy Systems, Diss. ETH No. 17141, Switzerland, 2007.

[3] Nipkow J, Gasser S, Bush E. Der typische Haushalt Stromverbrauch - Energieverbrauch von Haushalten in Ein- und Mehrfamilienhäusern. Bulletin SEV/AES 19/2007.

[4] Robinson D, Haldi F, Kämpf J, Leroux P, Perez D, Rasheed A, Wilke U. CITYSIM: Comprehensive micro-simulation of resource flows for sustainable urban planning. Eleventh International IBPSA Conference-Glasgow, Scotland, 2009.

[5] Kim I Y, de Weck O L. Adaptive weighted-sum method for bi-objective optimization: Pareto front generation. Structural and Multidisciplinary Optimization, 29(2):149–158, 2005.

[6] Frischknecht R, Itten R, Flury K. Treibhausgas-Emissionen der Schweizer Strommixe. Bundesamt für Umwelt BAFU, 2012.

[7] Moomaw W, Burgherr P, Heath G, Lenzen M, Nyboer J, Verbruggen A. Annex II: Methodology. In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2011.

[8] BFE. Grundlagen fuer die Energiestrategie des Bundesrates, Fruehjahr 2011. Bundesamt fuer Energie BFE, 2011 www.bfe.admin.ch/php/modules/publikationen

[9] Ulrich F. Preisvergleich Brennstoffe, 2012. www.lindenberg-energie.ch