Compromises in energy policy—Using fuzzy optimization in an energy systems model

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Abstract

Over the last year in Germany a great many political discussions have centered around the future direction of energy and climate policy. Due to a number of events related to energy prices, security of supply and climate change, it has been necessary to develop cornerstones for a new integrated energy and climate policy. To supplement this decision process, model-based scenarios were used. In this paper we introduce fuzzy constraints to obtain a better representation of political decision processes, in particular, to find compromises between often contradictory targets (e.g. economic, environmentally friendly and secure energy supply). A number of policy aims derived from a review of the ongoing political discussions were formulated as fuzzy constraints to explicitly include trade-offs between various targets. The result is an overall satisfaction level of about 60% contingent upon the following restrictions: share of energy imports, share of biofuels, share of CHP electricity, CO2 reduction target and use of domestic hard coal. The restrictions for the share of renewable electricity, share of renewable heat, energy efficiency and postponement of nuclear phase out have higher membership function values, i.e. they are not binding and therefore get done on the side.

1. Introduction

Energy systems models are frequently used to aid scenario analysis and to provide quantitative information about possible future development pathways in the energy sector (see for example the scenario for the German energy summit (EWI/Prognos, 2007)). Although it has a number of drawbacks, linear programming (LP) is still the standard methodology used in large-scale energy systems models (e.g. MARKAL (Fishbone et al., 1983; Loulou et al., 2004), TIMES (Loulou et al., 2005), MESSAGE (Messner et al., 1996; Messner and Strubegger, 1995)). Among the frequently criticized characteristics of LP models is the fact that the optimal solution strongly depends on a limited number of binding constraints, whose numerical specification often lacks the precision needed to justify this strong influence. The so-called soft constraints, based on fuzzy sets, can remedy this drawback and increase the applicability of LP to real-world problems (cf. e.g. Rommelfanger, 1996). Examples of applications of fuzzy LP to energy systems models can be found for example in Canz (1998), Oder et al. (1993). We introduce fuzzy constraints to obtain a better representation of political decision processes, in particular, to find compromises between often contradictory targets (e.g. economic, environmentally friendly and secure energy supply). In addition, some of the targets formulated by policy makers apparently push in the same direction; as for instance, a minimum share of renewables and GHG emission reduction.
means that fuzzy aspiration levels are assumed for each of the targets. The main idea then is to maximize “total satisfaction”, i.e. maximize a minimum operator for the set of targets. This approach results in a solution being some kind of compromise.

The paper is organized as follows: Section 2 gives a brief introduction to the IKARUS energy systems model and the methodological extension that we use in this paper, i.e. the implementation of fuzzy constraints. In Section 3 we outline the general scenario setup, concentrating on key drivers, such as development of GDP, population, employment and transport demand. In addition, the soft constraints are parametrized on the basis of political targets recently discussed among decision makers. Section 4 contains the results of the fuzzy optimization procedure. We focus on the differences from and advantages over LP with crisp restrictions. Finally, we summarize our main results and provide concluding remarks in Section 5.

2. The IKARUS energy systems model

2.1. Model structure

In order to examine the interaction of numerous political targets, we employ the bottom-up IKARUS model (Martinsen et al., 2003, 2006). The IKARUS model is a time-step dynamical linear optimization model mapping the energy system of the Federal Republic of Germany in the form of cross-linked processes from primary energy supply to energy services (Fig. 1). All relevant sectors with a detailed representation of the technological options are included, characterized by their corresponding specific emissions and costs as well as possible networks of energy fluxes. Demands for energy services are the driving forces of the model, and equilibria are formed on various intermediate conversion levels (partial equilibrium model). In addition, general political set-ups are considered (e.g. phase-out of nuclear power in Germany, coal subsidies).

The model's time horizon extends to 2030 and is divided into 5-year intervals. Each time interval is optimized by itself, taking into account past events by the heritage due to results from all previous periods in a separate dynamic program module. In contrast to the more common class of perfect-foresight energy systems models, such as MARKAL (Fishbone et al., 1983; Loulou et al., 2004), TIMES (Loulou et al., 2005) or MESSAGE (Messner et al., 1996; Messner and Strubegger, 1995), the time-step model is myopic and does not take into account future changes in each optimization step. It is therefore a model with a more realistic character of prognosis and projection.

Recent model applications include lifetime extensions for nuclear power plants (Hake et al., 2005), the analysis of carbon capture and storage (CCS) as a mitigation option for Germany (Martinsen et al., 2007b) and the impacts of high oil prices on energy-economy strategies (Martinsen et al., 2007a).

2.2. Implementation of fuzzy sets

In the following section we provide a very brief description of the implementation of the fuzzy constraints that we used in the present analysis. For technical details, the interested reader is referred to the extensive literature on fuzzy optimization.

Fig. 1. Structure of the IKARUS energy systems model.
A comprehensive review of fuzzy LP and its applications is e.g. provided by Rommelfanger (1996).

Table 1 contains a comparison of a generic LP and its fuzzy version as we applied it. We restrict ourselves to fuzzy right-hand sides and therefore obtain the simplest form of a fuzzy linear program as first discussed by Zimmermann (1975). The crisp LP in Table 1 includes the total sytems costs $z$, $C$ is the vector of cost coefficients, $x$ represents the decision variables, $A$ is the technology matrix and $b$ the vector of right hand sides. In the fuzzy version, the crisp right-hand sides are (partly) replaced by fuzzy right-hand sides $\tilde{b}$ and $\tilde{z}$.

Our main objective is to obtain a better representation of the political decision processes; in particular, to find compromises between often contradictory, but sometimes also collinear targets. In our application, fuzzy linear optimization means assuming fuzzy aspiration levels for each of the aims. As illustrated in Fig. 2, the membership function has a value of 1 if the fuzzy constrained linear combination of variables $(Ax)_i$ is below the boundary $b_i$, and value 0 if $(Ax)_i$ is larger than a threshold $b_i+d_i$. For simplicity, we linearly interpolate between these two levels, although in general piece-wise linear interpolation can be used to obtain a different shape of membership function (cf. e.g. Rommelfanger (1996)).

Total system costs $z$, which are typically used as the objective function in energy systems models, should also be included in the set of membership functions to obtain a fuzzy constraint $\tilde{z}$. Otherwise, solutions of the original crisp LP and the fuzzy version are not comparable, because system costs would not matter for the fuzzy solution.

Subsequently, the problem is transformed into a crisp "satisfaction model" by using membership functions $\mu_i(x)$ for the fuzzy constraints. The main idea is to maximize "total satisfaction", i.e. maximizing a minimum operator for the set of membership functions $\mu_i(x)$. The equivalent crisp LP can be written as

$$\begin{align*}
\text{MAX } \tilde{z} \\
\text{s.t. } \tilde{z} \leq \mu_i \\
\mu_i = \frac{1}{b_i} (b_i + d_i - (Ax)_i)
\end{align*}$$

(Rommelfanger, 1996), where $\tilde{z}$ is the total satisfaction and therefore the new objective function, and the index $i$ includes all membership functions. The total satisfaction variable $\tilde{z}$ has to be restricted to the interval [0,1], i.e. constraints $0 \leq \tilde{z} \leq 1$ have to be included. In addition, the crisp part of the original LP remains unchanged. This approach results in a solution which is some kind of compromise, if total satisfaction $\tilde{z}$ is larger than 0, but smaller than 1. It can also be interpreted as a multi-objective optimization system (Rommelfanger, 1996).

3. Scenario definition

In the political decision process, many aims are formulated that are partly complementary, but which partly also conflict each other. In the scenarios, we therefore adopt the following procedure: the general scenario setup, including energy prices, economic growth, behavioral patterns and, correspondingly, the evolution of demands for energy services, will be treated in the traditional way, i.e. they will be implemented as crisp restrictions. On the other hand, policy aims are formulated as fuzzy constraints to explicitly include trade-offs between various targets. This approach allows us to find compromises between these aims.

3.1. General scenario setup

The consistent socio-economic data on which the scenarios are based were compiled as part of the IKARUS project (Markewitz and Stein, 2003). In contrast to the former model applications, we concentrate on development up to 2020, because most targets in the political discussion are formulated for this time horizon. As far as economic development is concerned, a GDP growth of 1.9%/a (2000/2010) to 1.7%/a (2010/2020) is assumed. Accordingly, the evolution of the industrial gross value added shows a real increase in all industrial sectors, however, to a different extent in different industries. The demographic trend is assumed to be in agreement with the 2nd variant of the population development of the Federal Statistical Office (destatis, 2000). Population decreases from about 82 million today to approx. 80 million over the next 15 years. Whereas the number of employees and residential floor space will not change a lot, the demand for transportation increases significantly. The demand for passenger transport increases from about 1054 billion passenger kilometers (pkm) in 2000 to 1160 billion pkm in the year 2020. Far more drastic is the increase in freight transport from about 491 billion ton kilometers (tkm) in the base year 2000 to about 728 billion tkm in 2020, corresponding to a rise of almost 50% (IFEU, 2005). A more detailed description of all the assumed demands and general data can be found in Martinsen et al. (2006).

Besides limitations on quantities of domestic and imported energy carriers like coal, lignite and natural gas, other restrictions based on domestic potentials for fossil and renewable energy carriers and the political framework set by the Federal Government are present in the model. In recent applications of the IKARUS model (Hake et al., 2005; Martinsen et al., 2007a, b) these have been modeled as crisp bounds, but will be treated as fuzzy constraints in the scenarios presented in the present paper.

3.2. Fuzzy constraints

Among the energy-related policy targets currently being discussed in Germany are emission reduction targets, security of supply, employment of renewables in electricity and heat generation, application of biofuels, subsidies for domestic hard coal and decommissioning of existing nuclear power plants. Table 2
lists these indicators derived from recent political discussions along with the type of target (share, relative change with respect to some base year, absolute target), the current state for the year 2005 as well as the targeted value and a minimally acceptable value for 2020. On the other hand, economic implications of measures/targets are often criticized by the energy industry, as well as the ministry of economics. Hence, the total system costs have also been included in the set of fuzzy restrictions.

Relatively easy to determine are the targets related to renewable energy carriers. By 2020 it is aimed to supply 30% of electricity generation, 14% of heat generation and 17% of transport fuels from renewable sources (Bundesregierung, 2007a). Electricity production from CHP (target: 25% by 2020) also falls into this category (Bundesregierung, 2007a). In general, much harder to derive are acceptable levels as these are typically not published. Therefore, we either determine the acceptable level by laws already in force (e.g. share of biofuels: 8% by 2015 (Bundestag, 2006)) or by the current deployment level (e.g. CHP electricity). In case of renewable electricity generation we fix the acceptable level at the earlier target of 20% as defined in the coalition agreement of 2005 (Bundesregierung, 2005).

A lot of discussion has centered around the emission target for 2020, ranging from a reduction of 30% to 40% with respect to 1990 levels (BMU, 2007), partly depending on the commitments of the European Union as a whole and on the outcome of a post-Kyoto process (e.g. (Gabriel, 2007)). The more ambitious 40% reduction target is used as the target level throughout this paper, whereas the 30% reduction, being the fallback solution in case other countries do not make a similar commitment, has been adopted as the acceptable level.

The aim is to significantly improve energy efficiency by 2020. With respect to 1990, energy efficiency, defined as gross domestic product per unit of total primary energy consumption (GDP/TPES), is supposed to double by 2020. The lower acceptable improvement of 171% is derived by keeping TPES constant at the 2005 level, whereas GDP develops as described in Section 3.1. Although this target is well defined, there are ambiguities due to different accounting frameworks for total primary energy supply. As commonly done in German energy statistics, we use the physical energy content method (OECD/IEA/Eurostat, 2005). However, in particular, the German situation with its targeted transition away from nuclear energy towards a higher share of renewables can create distortions which should be kept in mind when interpreting the results (Lightfoot, 2007).

In the case of domestic hard coal, the situation is settled until 2012, when a review of policy objectives is scheduled. It then will be decided whether to completely phase out domestic hard coal extraction by 2018 or whether to keep a minimum level (“Sockelbergbau”) of around 12 Mtce (~350PJ) per annum in the long run (Wodopia, 2007). Therefore, we adopt the 350PJ per year as the target value and take the phase out (0 PJ) as still acceptable. In some cases, it is difficult to actually derive numerical values from the political debates, which stresses once again the need to apply fuzzy techniques to deal with these issues. For the import share of TPES, we chose the current level as a lower acceptable limit and ideally would reduce it to 60% of TPES in 2020. The latter corresponds to the lowest value achieved in the set of scenarios analyzed by EWI/Prognos in preparation for the energy summit in July 2007 and is therefore adopted as the target level (EWI/Prognos, 2007).

The phase-out of nuclear power is determined by the remaining amount of electricity produced in nuclear power stations (Bundesregierung, 2000). However, this translates fairly well into a shut-down of nuclear power stations after 32 years of operation, whereas the design lifetime is usually estimated to be 40 years. Therefore, we define the target to be compliant with the phase-out agreement and an acceptable relaxation to extend the average lifetime by 8 years, i.e. from 32 to 40 years, thus increasing the permissible electricity generation from nuclear power.

To estimate the acceptable range of costs, we adopt the following method. Two scenarios with crisp bounds are analyzed, one adopting the more stringent values from Table 2, i.e. the target values. This scenario is referred to as the “UP” scenario. The second scenario, called the “LO” scenario, uses the relaxed bound values from the table, specifying the still acceptable level of the indicators. The first scenario is, of course, more expensive and therefore determines the maximum acceptable cost level, whereas the relaxed scenario reflects the costs that one ideally is willing to pay. The compromise between those two scenarios is the scenario formulated with fuzzy constraints, named “FUZZY”.

Due to methodical and structural reasons, some of the targets (shares) in Table 2 are split into subtargets and specified as absolute values in the model. This is mainly done to avoid iterations.

4. Scenario results

With the dynamic IKARUS bottom-up model, we performed calculations for the period 2000–2020 for the crisp scenarios LO and UP as well as for the FUZZY scenario where targets and minimum values were defined in a manner similar to Table 2.

Fig. 3 shows the development of total primary energy supply (TPES), final energy consumption and CO₂ emissions for the three scenarios as compared to the reference year 2000, i.e. the model calibration year. The decline of all indicators up to 2020 is noticeable, especially for the UP scenario. Whereas the drop of TPES, final energy and CO₂ in this scenario are 20%, 13% and 30% (40% as compared to 1990), respectively; the corresponding values for the LO scenario are 9%, 5% and about 18% (30% as compared to 1990).
The results for the FUZZY scenario stay—as expected—between the lines for the crisp scenarios giving a decay of about 15%, 8% and 25% for TPES, final energy and CO2 emissions between 2000 and 2020. However, the results for the FUZZY scenario are not to be confused with trivial interpolations between the LO and UP scenarios (as can also be seen in Fig. 3). This type of interpolation would not normally give a consistent scenario due to the interweaving dependencies in the model and it would certainly not represent a maximum satisfaction in the sense of fuzzy membership functions.

As stressed above, system costs are the main limiting factor when searching for a compromise scenario because if very high costs were tolerated any optimal scenario could be accepted. Fig. 4 illustrates the additional annual costs as compared to the LO scenario which is the scenario with preferential or minimum costs. On the left side of the figure, annual costs for the period 2005–2020 are shown as well as the cumulated costs. In the UP scenario, additional cumulated costs from 2005 to 2020 add up to about 116 billion €, whereas additional costs for the FUZZY scenario are considerably less, amounting to 51 billion €, i.e. the cost saving as compared to the expensive UP scenario is 65 billion €. The right-hand side of Fig. 4 shows the structure of costs for the year 2020. In the FUZZY scenario there are additional costs (7.8 billion €/a) in most of the sectors as compared to the LO scenario, especially in the sectors of conversion (power plants, CHP) and transport. When compared to the UP scenario, the FUZZY results for 2020 show considerable cost savings (11.3 billion €/a) particularly in the residential, transport and conversion (CHP) sectors.

The extra costs for primary energy supply shown in Fig. 4 (about 2 billion €/a in 2020 for FUZZY—LO and close to zero for FUZZY-UP) are total net additional costs. Of special interest are, however, the structural changes of costs for primary energy supply, which have positive and negative terms for domestic as well as for imported energy carriers.

Table 3 illustrates the manifold changes in costs for primary energy for the FUZZY scenario in 2020. In comparison with the LO scenario there are higher expenses for domestic carriers (1.8 billion € mainly for hard coal and biomass) and for imported bioethanol, oil products and natural gas. These additional import costs are practically compensated by cost savings for imported hard coal, crude oil and to a minor extent nuclear fuels, giving total additional costs of about 2 billion €/a. As compared to the UP scenario, there is virtually no net cost difference. This might at first be surprising, however, Table 3 shows large differences for different energy carriers. First of all, there is a net saving for domestic primary energy (coal and renewables) in the order of 2.8 billion €. At the same time, there are net additional costs in the same order for imported energy carriers. Higher costs for imported coal, crude oil and natural gas therefore arise, whereas there is a cost reduction for the import of oil products, bioethanol and electricity.

In the following, we will discuss the most important results for CO2 emissions, primary energy, the electricity sector and final energy. On doing so we will concentrate on the year 2020, which is the year of the main policy targets for the energy economy in Germany. Attention will be focused on the FUZZY scenario as compared to the LO and UP scenarios.
Fig. 5 shows the membership function values (MFVs) in 2020 for the fuzzy constraints in Table 2, i.e. the degree of satisfaction for the different scenario indicators. Among the 10 indicators, 6 of them—primary energy import share, biofuels, CHP electricity, CO2 emissions, use of domestic hard coal and system costs—are settled at the value corresponding to the objective function value, i.e. the maximization of the smallest MFV, of about 0.6 (satisfaction level of 60%). These indicators therefore represent the strongest restrictions limiting the total satisfaction, whereas the indicators of renewable electricity, renewable heat, the ratio of GDP to TPES and the use of nuclear power have values between 0.8 and 1. The higher satisfaction level of the latter indicators can therefore be interpreted as a "spin-off" from the 6 binding constraints.

The compromise values of the fuzzy indicators corresponding to Table 2 can easily be calculated by interpolation between target—and acceptable values using the MFV in Fig. 5. An exception is the value for renewable heat where the target is more than fulfilled. In this case the model shows a share of about 15% of renewables to heat production (target 14%).

A central aspect of future energy supply and an important topic in energy policy is the emissions of greenhouse gases, in particular CO2. In these calculations we did not consider CCS technologies since they are not likely to play any substantial role within the time frame of our calculations, i.e. up to 2020. Fig. 6 shows the share of sectors for CO2 emissions in 2020 (left side) and the corresponding differences between the FUZZY scenario and the LO respectively UP scenario (right-hand side with a magnification factor of 10). In the FUZZY scenario the emissions of CO2 in 2020 are about 60 million tons lower than in the LO scenario. More than half of the reduction is reached in the conversion sector (nearly 35 Mt) where power plants contribute the most (about 24 Mt), but end-use sectors (about 26 Mt) also add a substantial amount to the cutback of CO2 in particular in the residential (8.5 Mt) and transport sector (9.6 Mt). In comparison to the UP scenario, the FUZZY optimization shows a surplus of about 40 Mt CO2. This is of course part of the compromise in the FUZZY scenario. The additional CO2 is mainly emitted in the end-use sectors (35 Mt or 86%), whereas the differences in the conversion sector are relatively small, i.e. the compromise for CO2 is mainly accepted in the end-use sectors where measures for CO2 reduction are generally more expensive than in the conversion sector.

The corresponding changes in the share of energy carriers in TPES are demonstrated in Fig. 7. TPES in the FUZZY scenario is about 950 PJ or 7% lower than in the LO scenario and about 650 PJ or 5.5% higher than in the UP scenario. The use of hard coal is considerably less (−920 PJ of imported hard coal) than in the LO.

![Fig. 5. Evolution of annual additional costs (left) and structure of annual additional costs in 2020 (right).](image-url)
scenario and somewhat greater (+260 PJ) than in the UP scenario. Due to less enhanced energy savings in the end-use sectors in the FUZZY scenario as compared to the UP scenario, the use of natural gas is higher in the FUZZY calculation (+540 PJ). The use of renewables is about 530 PJ higher than in the LO scenario with an increase of biomass (+320 PJ) followed by bioethanol (+110 PJ) and wind (+80 PJ) and somewhat less than in the UP scenario (+280 PJ). The extraction of domestic lignite (for example to reduce the share of imports in TPES) is considerably lower (270 PJ or about 18%) than in the UP scenario where the mining of lignite is at the upper bound. In the LO scenario, we assumed a prolongation of 8 years for the lifetime of nuclear power plants to be the maximum value tolerated. The actual extension of lifetime in the FUZZY scenario is on the average only 1.6 years, i.e. the use of nuclear fuels is much lower in this scenario as compared to the LO scenario.

This is also illustrated in Fig. 8, showing the structure of electricity production.

![Fig. 5. Membership function values (MFV) for the fuzzy indicators in 2020.](image)

![Fig. 6. CO2 emissions in 2020.](image)
Whereas total electricity production (TEP) does not differ very much among the scenarios (less than 20 TWh or 4%), there are some important changes in the share of different power plants in overall electricity production. As already seen for the TPES, the use of nuclear power plants drops from LO via FUZZY to UP, having a share of 22%, 11% and 8%, respectively, in 2020 in TEP. These changes are even more pronounced for hard coal power plants whose share decreases from 19% in the LO scenario to 6% in the FUZZY scenario. In the UP scenario, hard coal power plants will not be used at all, i.e. the annual load will drop to zero. To compensate for the reduction of electricity from nuclear and hard coal power plants, the use of lignite, wind and CHP (mainly based on biomass) increases from LO to UP. Electricity production from natural gas power plants is higher in the FUZZY scenario than in both LO and UP scenarios. This is an example of the fact that a simple interpolation between LO and UP
would lead to a non-optimal compromise and even inconsistent results.

Contrary to TEP, there is an increase of total installed capacity from LO to FUZZY and UP (Fig. 9). This is due to a decline of the average annual load of public utilities because of the extension of wind converters and a decrease of load for hard coal power plants (from 4900 h/a in the LO scenario, 1500 h/a in the FUZZY scenario and to 0 h/a in the UP scenario). Installed capacity needed in the FUZZY scenario is nearly 16 GW higher than in the LO scenario; however, it is about 9 GW lower than in the UP scenario. The changes of the structure of net installed capacity are shown in the right-hand part of Fig. 9.

Besides the noticeable changes in the conversion sector, there are also important differences in the end-use sectors when comparing LO, FUZZY and UP scenarios (Fig. 10). First of all, there are increased savings of final energy in the FUZZY and UP scenarios as compared to the LO scenario. Whereas savings in the FUZZY scenario are rather modest (300 PJ or about 3%), the reduction of final energy in the UP scenario is close to 800 PJ or nearly 9%. Fig. 10 shows that there are energy savings in all sectors, especially in the residential sector. Contrary to the UP scenario, in the FUZZY scenario the changes in the transport sector are very small as compared to the LO scenario. The relative changes in the FUZZY scenario as compared to the LO or UP scenario can be seen in each sector: industry −4.7% and +4.8%, small consumer −3.8% and +8.2%, residential −4.5% and +9.8% and transport −0.9% and +3.0%, respectively.

In the following discussion we will show as an example the different results in the residential and transport sector.

For the residential sector (Fig. 11), there are mainly additional measures for thermal insulation of buildings in the FUZZY and especially in the UP scenario. In the FUZZY scenario these measures are taken for old buildings within the renovation cycle, which are less expensive than measures outside the renovation cycle. In the UP scenario, more expensive measures for thermal insulation are also chosen by the model outside of the renovation cycle in addition to better isolation of new buildings. This results in a smaller demand for natural gas in the FUZZY scenario as compared to the LO scenario, but a higher demand as compared to the UP scenario. The share of fuel oil for heating purposes shows minor changes because the use of heating oil drops considerably even in the LO scenario in the period 2005–2020 and is part of a lower limit describing rural areas where a distribution of gas (or district heat) is not profitable. There is a relatively small (about 50 PJ or 20%) increase of district heat in the FUZZY scenario, mainly replacing natural gas in apartment buildings.

Fig. 12 illustrates the share of energy carriers in the final energy consumption of the transport sector. To sum up, one may say that the total final energy consumption is nearly scenario-independent (showing a variation of maximum 3–4%). However, there is a shift of energy carriers towards alternative fuels (like bioethanol for cars) replacing gasoline (−130 PJ or −12% and −250 PJ or −23%) in the FUZZY and UP scenario, respectively, together with improvements in car engines. In addition, trucks with higher efficiency engines replace conventional trucks in the UP scenario (but not in the FUZZY scenario), giving rise to a moderate saving of diesel (−4%) in relation to the LO scenario.

5. Summary and conclusions

The introduction of fuzzy constraints in a bottom-up energy system model gives a better representation of political decision processes in the energy economy and energy policy than a qualitative examination. It can help policy makers find compromises between often contradictory targets and to focus their efforts on the most relevant indicators, thus avoiding to overload the debate with too many issues. In addition, some of the targets formulated by policy makers apparently push in the same direction, as for instance a minimum share of renewables and GHG emission reduction.

Fuzzy linear optimization was carried out assuming fuzzy aspiration levels for each of the targets. The main idea was to maximize ”total satisfaction”, i.e. to maximize a minimum
operator for the set of targets in order to find a solution which is some kind of compromise. In the scenarios we adopted the following procedure:

The general scenario setup, including energy prices, economic growth, behavioral patterns and, correspondingly, the evolution of demands for energy services and demands (although highly uncertain) was treated in the traditional way, i.e. they were implemented as crisp restrictions. On the other hand, policy aims were formulated as fuzzy constraints to explicitly include trade-offs between various targets. This approach allowed us to find compromises between political aims.

Another advantage of such a quantitative method is the ability to reproduce results and calculate different scenarios with different boundary conditions. It further separates targets which have opponent effects from targets pushing in the same direction and makes the dependencies of targets more transparent. Besides determining the set of values for the fuzzy targets, i.e. the degree of satisfaction within the compromise, the conciliated solution
(FUZZY scenario) also shows the impact on emissions, costs, and structure of energy supply and demand in different sectors when compared to crisp scenarios with exact target values (UP scenario) and crisp scenarios where the minimally acceptable values are fixed (LO scenario).

The results shown above do not claim to represent an in-depth analysis of energy-related decision processes. However, they are an example using targets of current interest with up-to-date values for Germany. We thus demonstrate the utilization of fuzzy optimization for a typical problem using fuzzy restrictions for 10 quantities that have been intensively discussed over the past few years, with increasing intensity in the last year.

The result is an overall satisfaction level of about 60% contingent upon the following restrictions: share of energy imports, share of biofuels, share of CHP electricity, CO2 reduction target and use of domestic hard coal in addition to extra costs. The restrictions for the share of renewable electricity, share of renewable heat, energy efficiency (relation GDP/TPES) and postponement of nuclear phase-out have higher MFVs, i.e. they get done on the side. This raises the question whether it is necessary to define so many targets which do not provide any added value, but might lead to the implementation of suboptimal solutions. On the other hand, market inefficiencies, which are not covered by the model, could require additional guidance to assure that the most central targets are reached.

For the important indicators TPES and CO2 emissions, the FUZZY scenario shows values in 2020 closer to the UP scenario than to the LO scenario, whereas final energy is closer to the LO scenario—showing a certain preference for fuzzy measures in the conversion sector as compared to end-use sectors. As a result, costs of primary energy supply turn out to be almost identical in the FUZZY and UP scenarios, since more expensive supply options in the UP scenario are compensated by reduced total primary energy supply. There is also a considerable saving of costs (65 billion € in the period from 2005 to 2020) in the FUZZY scenario as compared to the target scenario UP (with additional costs of 116 billion € compared to the LO scenario).

A typical compromise solution features lower shares of domestic lignite and renewables within TPES, but higher shares of imported natural gas, hard coal and nuclear fuels as compared to the UP scenario. Despite the lower share of renewables this would imply a reduction of CO2 emissions relative to the UP scenario. However, as energy saving is less dominant in the FUZZY scenario there is a net increase of CO2 emissions compared to the UP scenario. On the other hand, there is also a net decrease of system costs due to a renunciation of rather expensive measures for energy saving in the end-use sectors. The trade-off between import share, renewables, CO2 emissions and costs is an interesting example for the ability to find compromises in fuzzy calculations.

Similar trade-offs can also be found within the electricity sector. As the model (partly) refrains from extending the lifetime of nuclear power plants, additional capacities for lignite- and gas-fired power plants are built to replace nuclear power. In order to compensate for the increase of CO2 emissions caused by this substitution, the annual load of existing hard coal power plants is reduced considerably and new wind turbines and CHP plants are built leading to an increase of installed capacity for the FUZZY and UP scenarios as compared to the LO scenario, whereas TEP stays nearly constant. The result is an increase of costs for power plants and CHP of approximately 2.7 billion €/a in the FUZZY scenario and 5.1 billion €/a in the UP scenario in 2020 as compared to the LO scenario. This balance between postponement of nuclear phase out, surplus capacity, CO2 emissions and costs in electricity generation is another aspect of compromise solutions extracted from our calculations.

The process of determining the fuzzy constraints from political discussion processes has shown that it is not easy and sometimes anything but unambiguous to fix parameters and therefore has underlined the need to apply soft or fuzzy instead of crisp constraints that might have an unjustifiably strong impact on the optimal solution.

In our further work we intend to include more fuzzy quantities and extend the fuzzy method to also include uncertainties in
demand for energy services, future prices of energy carriers and technology attributes like costs and efficiencies. Also sensitivity of results with respect to the impact of threshold values and shape of membership functions need to be investigated.

References


