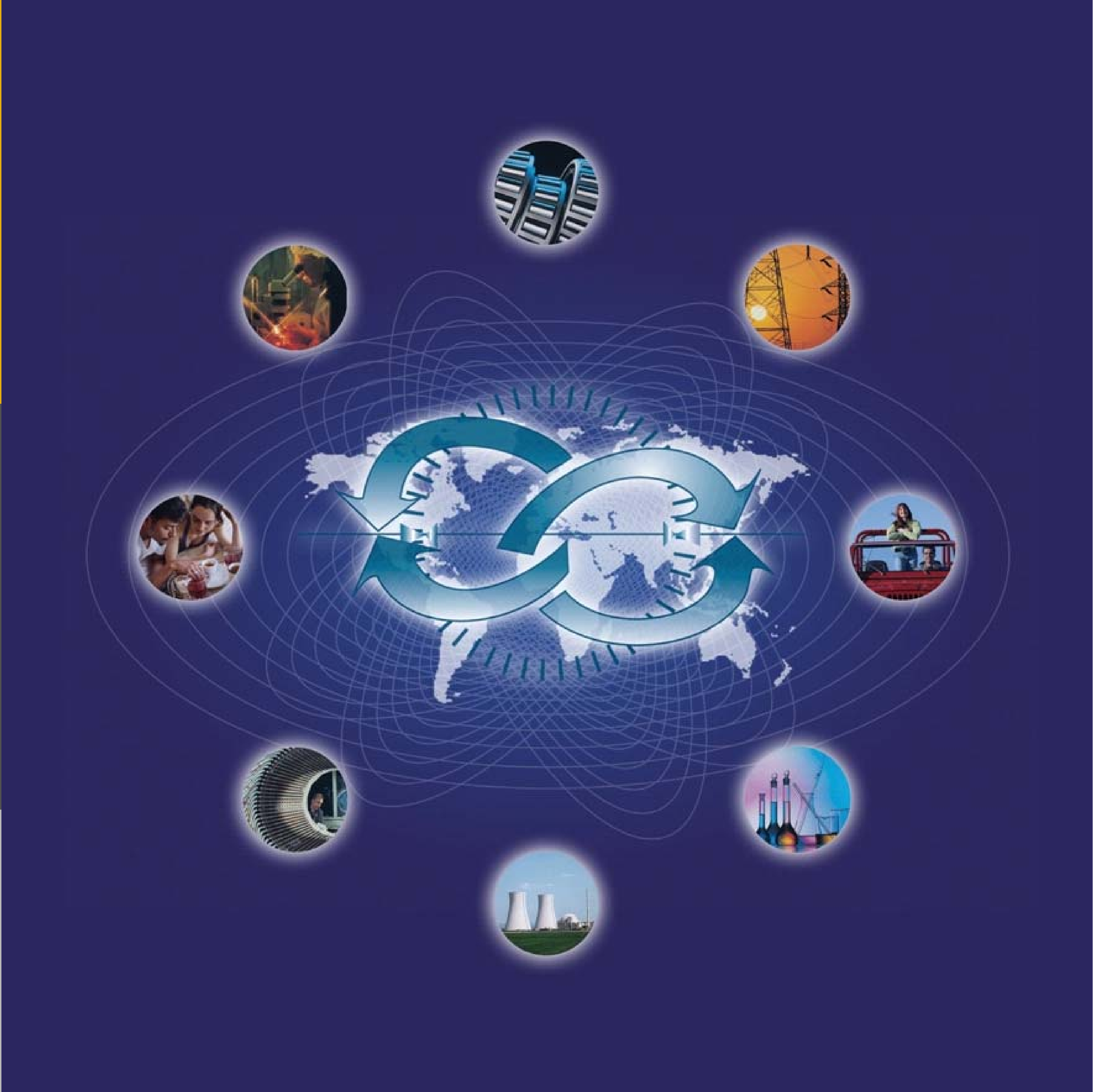

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Optimization of Sustainability by Means of IKARUS-FLP and Energy Indicators for Sustainable Development (EISD)

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Systemforschung und Technologische Entwicklung (IEF-STE)

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Content

Optimization of Sustainability by Means of IKARUS-FLP and Energy Indicators for Sustainable Development (EISD)

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Abstract

The German energy system model IKARUS-LP has been enhanced to make the computation of a best compromise between various and partly contradictory targets possible. This enhancement, IKARUS-FLP is based on fuzzy linear programming. It is well-suited to model sustainability targets by means of energy indicators for sustainable development and to optimize the energy system according to these targets. IKARUS-FLP is useful to determine how an energy system can be transformed into a sustainable energy system from a technology point of view. This document is both a manual about how to use IKARUS-FLP practically and a description of the sustainability targets and their basics.

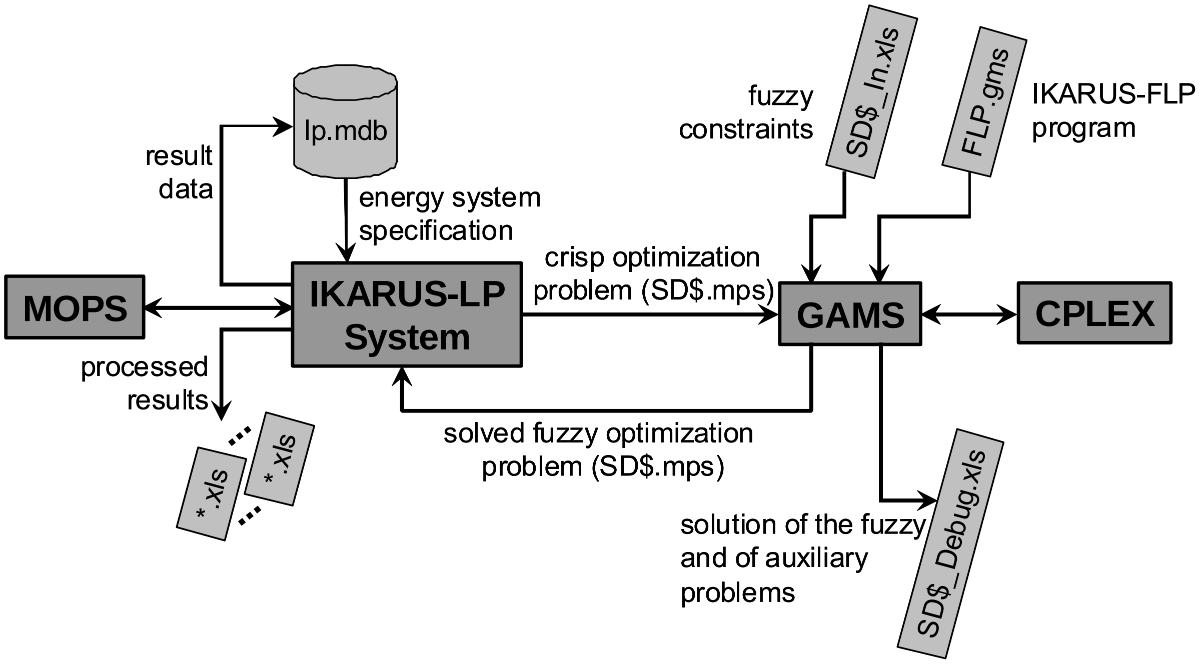
Keywords

Sustainable energy system, energy indicators for sustainable development (EISD), IKARUS-FLP, fuzzy linear programming

I Introduction

The German energy system model IKARUS-LP has been enhanced to the fuzzy linear program-based energy system model IKARUS-FLP [Martinsen & Krey, 2008, Weber & Martinsen, 2008, Weber & Martinsen, 2009]. It is implemented by the IKARUS-LP system and by a GAMS program. Both parts are linked by a file interface (see Figure 1).

Figure 1: Integration of IKARUS-LP and its GAMS-based fuzzy enhancement



Wildcard “SD$” is related to the user case identifier in the IKARUS system, e.g. “SDA00120” designates user case “SDA001” and optimization period “2020”.

Source:	IEF-STE 2010

The working procedure is as follows:

1. The specification of the German energy system is stored in the MS Access database “lp.mdb”.
2. The IKARUS-LP system reads the energy system specification from the database and generates the file “SD$.mps” which describes the related linear program in the common mps format. It is a crisp optimization problem.
3. The fuzzy enhancement of IKARUS-LP is the fuzzy linear program IKARUS-FLP. It is implemented by the program file “FLP.gms” in the modeling language GAMS and by fuzzy constraints which are stored in the MS Excel file “SD$_In.xls”.
4. The GAMS software, e.g. by means of the GAMS integrated development environment (IDE) runs the program “FLP.gms” which comprises reading instructions for the fuzzy specification file “SD$_In.xls”.

5. GAMS solves the fuzzy optimization problem by means of the commercial solver CPLEX and generates the file “SD$.mps”. This file describes the solution of the fuzzy optimization problem in the shape of a crisp linear program.
6. Results of the fuzzy problem and of auxiliary problems are stored in the MS Excel file “SD$_Debug.xls”.
7. The problem described in the file “SD$.mps” is solved by the IKARUS-LP System by means of the commercial solver MOPS. This step is performed pro forma in order to get the results of the fuzzy problem into the IKARUS system.
8. The fuzzy optimization results are stored in the database “lp.mdb”.
9. The IKARUS-LP system results processor generates various MS Excel result files.

In Section II we describe how the MS Excel file “SD$_In.xls” with the specification of the fuzzy constraints is created.

IKARUS-FLP supports the transformation of the current German energy system into a sustainable energy system. In order to make sustainability subject to optimization, we utilize a set of energy indicators for sustainable development (EISD) developed by the International Atomic Energy Agency and other institutions [IAEA et al., 2005, Unander, 2005]. As the IKARUS model is a technology-based bottom-up model without geographical resolution, only a subset of the EISD set can be modeled. The choice of this subset is explained in Section III. Targets for the EISD and related fuzzy constraints are derived in Section IV. As sustainability targets are subject to all other constraints and variable bounds in the model, it is important to check and adjust bound which are related to sustainability indicators. This is done in Section V.

The calculation of CO_2 emission values is a science of its own and has changed from time to time. Final adjustments in the IKARUS model are explained in Section VI.

Abbreviations are summarized in Table 1.

Table 1: Abbreviations used in the document

Abbreviation	Meaning
ECO	economic indicator
EISD	energy indicators for sustainable development
ENV	environmental indicator
EPR	European pressurized reactor
FEC	final energy consumption
FLP	fuzzy linear program
GDP	gross domestic product

Abbreviation	Meaning
H	household sector
I	industry sector
IKARUS	Instrumente für Klimagasreduktionsstrategien
LP	linear program
lb	lower bound
pax	passenger
PI	domestic primary energy carriers
PM	imported primary energy carriers
PT	exported primary energy carriers
SOC	social indicator
TFC	total final consumption
TPES	total primary energy supply
ub	upper bound

Source: IEF-STE 2010

II Generating Input Files with Fuzzy Constraints for IKARUS-FLP

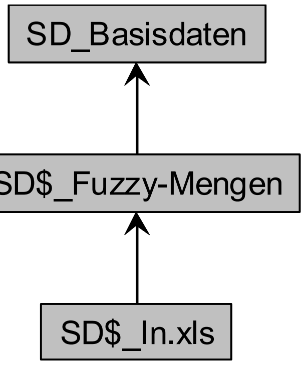
II.1 Input Files and their Relations

Following MS Excel files are involved in providing input data to the GAMS program "FLP.gms" (see Figure 2):

- File "**SD_Basisdaten**" contains
  - exogenous quantities in tab sheet "exogene Größen" (see Section II.3),
  - unit conversion factors in tab sheet "Umrechnungsfaktoren" and
  - the indicator values of period 2005 in tab sheet "Analyse 2005".
- File "**SD_Fuzzy-Mengen**" contains
  - definitions of all fuzzy sets in tab sheets designated by the corresponding indicator identifier, e.g. "ECO011" (for details about indicators see Section III),
  - links to exogenous quantities, unit conversion factors, optimization results of period 2005 which needed to calculate indicator values, the indicator values of period 2005, the fulfillment of the indicator targets, and statistics on the fulfillment of indicator targets in tab sheet "Analyse".
  - Furthermore, tab sheet "Analyse" contains space to insert the optimization result values which are needed to calculate the indicator values for the periods 2010 – 2050 (in lines 9 – 29) and formulas which calculate indicator values (in

lines 40 – 60) and the fulfillment of indicator targets (in lines 62 – 82) and statistics of these values (in lines 84 – 86).
  - The destination of all links is file “SD_Basisdaten.xls”.
- File “**SD_In**” contains the input data for the GAMS program. For details see [Weber & Martinsen, 2009]. Part of its contents are provided by links. The destination of all links is file “SD$_Fuzzy-Mengen.xls”.

Figure 2: Data provision for the GAMS program FLP.gms



Arrows indicate data links between the MS Excel files.

Source:	IEF-STE 2010

II.2 Creation of the Input File for the GAMS program

In the following we describe how a new scenario is created by means of the files explained in Section II.1.

II.2.1 Creation of Templates

- Copy the files “SD_Basisdaten.xls”, “SD_Fuzzy-Mengen.xls” and “SD_In.xls” to the folder which shall contain the input data.
- Open “SD_Fuzzy-Mengen.xls” and “SD_In.xls”.
- Save “SD_Fuzzy-Mengen.xls” under a new file name, e.g. “SDA001_Fuzzy-Mengen.xls”. (Typically, the name corresponds to the IKARUS user case name; here: “SDA001”.)
- Save “SD_In.xls” under a new file name, e.g. “SDA001_In.xls”. (If the files “SD_Fuzzy-Mengen.xls“ and “SD_In.xls” are saved in this order, MS Excel automatically adjusts the links between the files.)

II.2.2 Creation and Preparation of the Input File for a Specific Optimization Period

Let us assume the user case is “SDA001” and the optimization period is 20xx.

- Open the file “SDA001_In.xls” and save it as “SDA00120_In.xls”.
- Select tab sheet “u_a_c”.

- If the first line of a specific sustainability indicator contains a link to exogenous quantities in file “SD_Basisdaten.xls”, then adjust it:
  - Change the letter of the destination cell according to the optimization period 20xx.
  - Pay attention that links to unit conversion factors do not need to be adjusted!
- Copy the formula from the first line and insert it as formula into all other lines which belong to the same sustainability indicator.
- If coefficient values in tab sheet “u_a_c” depend on quantities other than exogenous quantities or unit conversion factors, and these quantities depend on the optimization period, then select the correct optimization period by the corresponding push down menu in the MS Excel sheet. (The year selection controls the linking to tab sheet “u_a_c_(t)”.

II.3 Exogenous quantities

Following quantities have to be defined exogenously:

- Population of Germany,
- Gross domestic product (GDP) of Germany,
- value added in the industry sector,
- heated floor area in the household sector,
- demand of passenger transport,
- demand of cargo transport.

These quantities are stored in the MS Excel file “SD_Basisdaten.xls”. A summary for each optimization period is presented in tab sheet “exogene Größen”.

III Energy Indicators for Sustainable Development (EISD)

III.1 Basics

The International Atomic Energy Agency (IAEA) and other transnational institutions have developed a set of 30 energy indicators for sustainable development (EISD)

> *“… for consideration and use, particularly at the national level, and to serve as a starting point in the development of a more comprehensive and universally accepted set of energy indicators relevant to sustainable development.” ([IAEA et al., 2005], Foreword).*

The indicators are classified into the three “dimensions”: social, economic and environmental, and into themes and sub-themes. The EISD set comprises

- 4 social indicators (SOC 1, …, SOC 4),
- 16 economic indicators (ECO 1, …, ECO 16),
- 10 environmental indicators (ENV 1, …, ENV 10).

In its current state (as of spring 2010) the IKARUS energy system model provides the quantities to calculate

- none of the social indicators,
- 9 economic indicators,
- 2 environmental indicators,
- 1 additional environmental indicator which is not part of the EISD set.

Section III.2 presents all EISD which can be considered by IKARUS-FLP. EISD which cannot be taken into account by IKARUS-FLP and the reasons for this are explained in Section III.3.

III.2 Energy Indicators for Sustainable Development used by IKARUS-FLP

III.2.1 Overview

Table 2 presents all EISD which can be considered by IKARUS-FLP. In the first column the indicator abbreviation and in the second column the indicator name and a brief definition according to [IAEA et al., 2005] are listed. In the column on the very right the specification of the indicator as it is used by IKARUS-FLP is declared. There are three possibilities:

- "**P**" indicates that a partial aspect of the indicator in the EISD set is specified for use by IKARUS-FLP.
- "**M**" indicates that a modification of the indicator in the EISD set is specified for use by IKARUS-FLP.
- "**N**" indicates that the indicator specified for use by IKARUS-FLP is not part of the EISD set.

Explanations for each indicator are given in Section III.2.2.

Table 2: Overview of the EISD realizations for IKARUS-FLP

Indicator	**Indicator name and brief definition according to [IAEA et al., 2005]**	**Theme**	**Sub-theme**	**Specification for IKARUS-FLP**
ECO 1	Energy use per capita: Energy use in terms of total primary energy supply (TPES), total final consumption (TFC) and final electricity use per capita (ibid, p. 40)	use and production patterns	overall use	**P**: TPES per capita
ECO 2	Energy use per unit of GDP: Ratio of TPES, TFC and electricity use	use and production patterns	end use	**P**: TPES per unit of GDP

Indicator	Indicator name and brief definition according to [IAEA et al., 2005]	Theme	Sub-theme	Specification for IKARUS-FLP
	to gross domestic product (GDP) (ibid, p. 42)			
ECO 6	Industrial energy intensities: Energy use per unit of value added in the industrial sector and by selected energy-intensive industries (ibid, p. 52)	use and production patterns	end use	**P**: energy use per unit of value added in the industrial sector
ECO 9	Household energy intensities: Amount of total residential energy used per person or household or unit of floor area. Amount of energy use by residential end use per person or household or unit of floor area, or per electric appliance (ibid, p. 63)	use and production patterns	end use	**P**: amount of total residential energy used per person
ECO 10-1	Transport energy intensities: Energy use per unit of freight-kilometer (km) hauled and per unit of passenger-km travelled by mode (ibid, p. 67)	use and production patterns	end use	**P**: energy use per unit of passenger-km
ECO 10-2				**P**: energy use per unit of freight-kilometer
ECO 11-1	Fuel shares in energy and electricity: The structure of energy supply in terms of shares of energy fuels in total primary energy supply (TPES), total final con-	use and production patterns	diversification	**M**: fuel share of hard coal in fossil fuels
ECO 11-2				**M**: fuel share of lignite in fossil fuels
ECO 11-3				**M**: fuel share

Indicator	Indicator name and brief definition according to [IAEA et al., 2005]	Theme	Sub-theme	Specification for IKARUS-FLP
	sumption (TFC) and electricity generation and generating capacity (ibid, p. 71)			of natural gas in fossil fuels
ECO 11-4				**M**: fuel share of crude oil in fossil fuels
ECO 11-5				**M**: fuel share of nuclear fuel in non-renewables
ECO 12	Non-carbon energy share in energy and electricity: The share of non-carbon energy sources in primary energy supply (TPES) and in electricity generation and generating capacity (ibid, p. 74)	use and production patterns	diversification	**P**: share of non-carbon fuels in TPES
ECO 13	Renewable energy share in energy and electricity: The share of renewable energy in total primary energy supply (TPES), total final consumption (TFC) and electricity generation and generating capacity (excluding non-commercial energy) (ibid, p. 76)	use and production patterns	diversification	**P**: share of renewable energy in TPES
ECO 15-1	Net energy import dependency: The ratio of net import to total primary energy supply (TPES) in a given year in total	security	imports	**P**: ratio of net import to TPES
ECO 15-2				**M**: share of

Indicator	Indicator name and brief definition according to [IAEA et al., 2005]	Theme	Sub-theme	Specification for IKARUS-FLP
	and by fuel type such as oil and petroleum products, gas, coal and electricity (ibid, p. 83)			imported renewable energy carriers in the total of renewable energy carriers
ENV 1-1	Greenhouse gas (GHG) emissions from energy production and use, per capita and per unit of GDP (ibid, p. 87)	atmosphere	climate change	**M**: total amount of CO_2 emissions
ENV 1-2				**P**: CO_2 emissions per capita
ENV 9	Ratio of solid radioactive waste to units of energy produced: Radioactive waste arisings from nuclear fuel cycles or other fuel cycles per unit of energy produced. Waste arisings destined for disposal in solid form are classified and categorized according to national definitions or as proposed here. These quantities consider all radioactive wastes from energy fuel cycles, including mining, milling, energy generation and other related processes. This indicator represents a set of indicators that includes one for each type of radioactive	land	solid waste generation and management	**M**: total amount of electricity generated by nuclear power plants

Indicator	Indicator name and brief definition according to [IAEA et al., 2005]	Theme	Sub-theme	Specification for IKARUS-FLP
	waste (ibid, p. 122)			
ENV 11	---	---	---	**N**: ratio of stored CO_2 to CO_2 emitted into the atmosphere

Source:	STE 2010

III.2.2 Explanations

In the following for each indicator in Table 2 an explanation is given. The explanation in particular clarifies the specification of each indicator, why only partial aspects are realized (“**P**” in brackets), why indicators are realized in a modified way (“**M**” in brackets), and why new indicators which are not part of the EISD set are introduced (“**N**” in brackets).

- ECO 1 (**P**): Among the possible realizations of the indicator, TPES per capita is the most significant one.
- ECO 2 (**P**): Among the possible realizations of the indicator, TPES per unit of GDP is the most significant one.
- ECO 6 (**P**): The development of the industrial structure in the IKARUS model is mainly set exogenously. Thus, it is of little informative value to consider the energy intensity of single industries. It is sufficient to realize the overall energy intensity of the industry sector.
- ECO 9 (**P**): The amount of energy use by residential end use would be important in a particular study of the household sector. For an analysis of the entire national energy system it is sufficient to focus on the total residential energy. Individual households are not modeled in IKARUS. Floor area and population are exogenous quantities. As the living space per capita increases over time, it is more significant to relate the total residential energy to population than to floor area.
- ECO 10 (**P**): The transport energy intensity by mode would be important in a particular study of the transport sector. For an analysis of the entire national energy system it is sufficient to focus on the energy intensity for the entire passenger transport or cargo freight transport, respectively.
- ECO 11 (**M**): Energy system optimization models compute a mix of technologies and fuels which is optimal with regard to one or a variety of objectives. So, the share of particular fuels can change over time. For instance, in a CO_2 mitigation

scenario the overall share of fossil fuels will decrease. Therefore, it would not be appropriate to define targets for the share of fuels in TPES. Instead, these shares are related to the total amount of primary energy supply of a particular fuel type. Here, fuel shares of fossil fuels are related to the total amount of fossil fuels (ECO 11-1, …, ECO 11-4), and the share of nuclear fuel is related to the total amount of non-renewable fuels, i.e. fossil fuels and nuclear fuel (ECO 11-5). The fuel shares of a variety of fuels can be summarized in a single number, e.g. the "dual concept diversity index" ([Groenenberg et al., 2009], p. 2178). However, in order to avoid additional non-linearities in the mathematical model underlying IKARUS-FLP each fuel is considered individually, here. The result is similar.

- ECO 12 (**M**): Among the possible realizations of the indicator, the share of non-carbon energy sources in TPES is the most significant one.
- ECO 13 (**P**): Among the possible realizations of the indicator, the share of renewable energy in TPES is the most significant.
- ECO 15 (**P**, **M**): The ratio of net import to TPES in total is more significant than this ratio by fuel type. Furthermore, the latter is related to fuel diversity and already covered by the indicators ECO 11, ECO 12 and ECO 13. The German import quote of traditional, i.e. fossil primary energy carriers is high, whereas currently the amount of imported renewables is low. In order to avoid in the future a dependency on imported renewables similar to the current dependency on imported fossil fuels, an additional realization of the indicator for renewable primary energy sources is applied.

  Note: The benefit of this indicator is questionable. Actually, the ratio of imported energy does not completely describe energy security, because the latter also depends on the reliability of supplier countries and transit countries, on the security of trade channels, on the type of energy carrier and its importance in the national energy system etc. In principle, these aspects could be covered by the definition of additional corresponding indicators. However, as IKARUS does not model these aspects related indicators would be of no use. Although the original indicator is questionable, it is at least plausible, because in general a low import ratio is better than a high import ratio.
- ENV 1 (**M**, **P**): CO_2 emissions per capita is an appropriate indicator to enable burden sharing between nations of different populations and levels of economic development. However, according to climatologists, the total amount of emitted CO_2 needs to be reduced. Therefore, an according realization of this indicator is added. The realization for CO_2 emissions per unit of GDP is omitted due to the lack of significance.
- ENV 9 (**M**): The definition of the indicator would only make sense, if the related ratio of solid radioactive waste to units of energy produced could vary. This would require that the energy system model comprises different types of nuclear power plants together with a nuclear fuel cycle system (including future partitioning and

transmutation) which could be chosen by the model. This is not the case with IKARUS-FLP. Therefore, the indicator is specified in order to restrict the annual amount of nuclear waste. Furthermore, it is assumed that the amount of nuclear waste is proportional to the quantity of electricity generated by nuclear power plants.

- ENV 11 (**N**): CO_2 is waste irrespective of whether it is emitted into the atmosphere or stored in geological formations or in the sea. For this reason and due to the environmental uncertainties of CO_2 storage and related public concerns, it is justified to evaluate stored CO_2 similar to emitted CO_2 or nuclear waste.

III.3 Energy Indicators for Sustainable Development not Taken Into Account by IKARUS-FLP

Indicator	Indicator name[1]	Theme	Sub-theme	Reason why indicator is not taken into account
SOC 1	Share of households (or population) without electricity or commercial energy, or heavily dependent on non-commercial energy (ibid, p. 29)	equity	accessibility	not relevant for Germany
SOC 2	Share of household income spent on fuel and electricity (ibid, p. 32)	equity	affordability	The household income is not modeled.
SOC 3	Household energy use for each income group and corresponding fuel mix (ibid, p. 35)	equity	disparities	The household income is not modeled.
SOC 4	Accident fatalities per energy produced by fuel chain (ibid, p. 38)	health	safety	Fatality figures are not modeled.
ECO 3	Efficiency of energy conversion and distribution (ibid, p. 45)	use and production patterns	supply efficiency	Efficiency evaluation is distorted, because primary energy

1 If necessary, brief definition according to [IAEA et al., 2005] in brackets.

Indicator	Indicator name[1]	Theme	Sub-theme	Reason why indicator is not taken into account
				carriers are treated differently, e.g. renewable energy sources and nuclear fuel.
ECO 4	Reserves-to-production ratio (ibid, p. 48)	use and production patterns	production	Reserves are not modeled.
ECO 5	Resources-to-production ratio (ibid, p. 50)	use and production patterns	production	Resources are not modeled.
ECO 7	Agricultural energy intensities (ibid, p. 56)	use and production patterns	end use	The agricultural sector is part of the small consumer sector, but not modeled explicitly.
ECO 8	Service/commercial energy intensities (Final energy use per unit of service and commercial value added or per floor area) (ibid, p. 59)	use and production patterns	end use	The small consumer sector is modeled, however units of service and commercial value added are not available.
ECO 14	End-use energy prices by fuel and by sector (ibid, p. 79)	use and production patterns	prices	The end-use prices not modeled[2].
ECO 16	Stocks of critical fuels	security	strategic fuel	Stocks of fuels

[2] The related shadow prices of the optimal solution could be interpreted as end-use energy prices.

Indicator	Indicator name[1]	Theme	Sub-theme	Reason why indicator is not taken into account
	per corresponding fuel consumption (ibid, p. 85)		stocks	are not modeled.
ENV 2	Ambient concentrations of air pollutants in urban areas (ibid, p. 91)	atmosphere	air quality	Not all pollutants are available, e.g. particulate matter, lead. IKARUS does not have regional resolution.
ENV 3	Air pollutant emissions from energy systems (ibid, p. 95)	atmosphere	air quality	Not all pollutants are available, e.g. fine particulates. Some air pollutant emission factors are not up-to-date.
ENV 4-1	Contaminant discharges in liquid effluents from energy systems (ibid, p. 101)	water	water quality	Contaminant discharges are not modeled.
ENV 4-2	Oil discharges into coastal waters (ibid, p. 105)	water	water quality	Oil discharges are not modeled.
ENV 5	Soil area where acidification exceeds critical load (ibid, p. 108) (Soil area where damage could occur due to acidification levels that exceed critical loads)	land	soil quality	Acidification is not modeled. IKARUS does not have regional resolution.
ENV 6	Rate of deforestation attributed to energy use	land	forest	Deforestation is not modeled.

Indicator	Indicator name[1]	Theme	Sub-theme	Reason why indicator is not taken into account
	(ibid, p. 112)			IKARUS does not have regional resolution.
ENV 7	Ratio of solid waste generation to units of energy produced (ibid, p. 115)	land	solid waste generation and management	Solid waste is not modeled.
ENV 8	Ratio of solid waste properly disposed of to total generated solid waste (ibid, p. 118)	land	solid waste generation and management	Solid waste is not modeled.
ENV 10	Ratio of solid radioactive waste awaiting disposal to total generated solid radioactive waste (ibid, p. 127)	land	solid waste generation and management	The IKARUS model comprises only one type of nuclear reactor. The option of a nuclear fuel cycle system is not part of the model. So, the indicator value cannot vary.

Source:	STE 2010

IV Sustainability Targets and Related Fuzzy Constraints in IKARUS-FLP

In Section IV.3 targets for any indicator specified in Table 2 are provided. Systematics, notation and particularities of the targets and their setting is introduced in Section IV.1. General rules of target setting are motivated and set up in Section IV.2.

IV.1 Systematics, Notation and Particularities

IV.1.1 Systematics

For each indicator specified in Table 2 information is provided according to following systematics:

- Target definition (only if target definition is not obvious)
- Sources and related information
- Worst case and ideal case
- Fuzzy constraint
- IKARUS variables involved
- Units and conversions
- Fuzzy sets according to the worst and the ideal case

Any monetary value is given in prices as of the year 2000.

IV.1.2 Notation, Notions and Abbreviations

- The IKARUS model comprises thousands of variables. In the description of fuzzy constraints most of them are summarized by means of auxiliary variables. Single variables are identified by their six letter code.
- Fuzzy sets are designated by a tilde, e.g.

  $$\tilde{a}, \tilde{b}\,.$$

  The same holds for fuzzy operators, e.g. $2 \,\tilde{\cdot}\, \tilde{a}$. All fuzzy sets are of LR type

  $$\tilde{x} = \left(\underline{x}, \overline{x}, \underline{\xi}, \overline{\xi}\right)_{LR}$$

  where $L(x) = R(x) := \max(1 - x, 0)$. For details see e.g. [Böhme, 1993], p. 13ff.
- Notions “energy productivity”, “energy intensity”

$$\text{energy intensity}_{\text{of <output>}} = \frac{\text{energy input}}{\text{<output>}} \tag{1}$$

$$\text{energy productivity}_{\text{wrt <output>}} = \frac{\text{<output>}}{\text{energy input}} \tag{2}$$

  [Erdmann & Zweifel, 2008], p. 77f., 100f.; [Bressand et al., 2007], p. 18

IV.1.3 Particularities

In any constraint related to amounts of energy some variables have to be multiplied by a coefficient unequal one (see Table 3).

Table 3: Variables with energy coefficients unequal one

Variable	Meaning	Coefficient
PIXCWA	crop containing starch: maize	2.21
PIXCWB	crop containing sugar: turnip	1.85
PIXCWC	crop containing starch: corn	1.77

PIXCWD	crop containing starch: potato	1.17
PIXDWA	oil-bearing crop	1.94
PIXEGB	fermenter	-0.843

Source: IEF-STE 2010

IV.2 Rules of Target Setting

Energy indicators for sustainable development can be seen from different points of view. For instance, the fuel share of fossil fuels and nuclear fuel (see Table 2: ECO 11) has following aspects:

> *"Regarding the economic dimension, the energy supply mix is a key determinant of energy security. Therefore, the 'right' energy mix for a particular country relies on a well-diversified portfolio of domestic and imported or regionally traded fuels and sources of energy. Also, the particular mix of fuels used in energy and electricity affects energy intensities.*
>
> *With respect to the environmental dimension, the energy supply mix has a major effect since the environmental impacts of each energy source differ greatly and include the following …" ([IAEA et al., 2005], p. 71)*

Taking into account further aspects, we summarize:

- Waste: Burning hard coal emits CO_2 in the atmosphere. CO_2 captured and stored by CCS technology is waste, too. Both should be avoided.
- Energy security: A particular share of hard coal supports fuel diversification and, thus, energy security. However, if this causes increased imports, diversification impedes energy security.

In fact, three aspects overlap:

- waste avoidance,
- energy security: fuel diversity,
- energy security: import dependency.

This problem of eclipsing different targets in the same indicator could be solved by taking into account the themes and sub-themes of the EISD systematics. As the sub-theme of indicator ECO 11 is diversification, its target has to be defined accordingly. The waste aspect is covered by the indicators ENV 1, ENV 9 and ENV 11. The energy security aspect with regard to import dependency is covered by indicator ECO 15. This and other "rules" of target setting are summarized as follows:

- **Consistency of sustainability targets and variable bounds**
  In the standard mode of IKARUS system utilization, i.e. IKARUS-LP, usually variable bounds have been set to model targets or the economic and political framework. Examples are CO_2 mitigation paths, nuclear phase out or the phase out of domestic hard coal mining. In the utilization of IKARUS-FLP targets are defined by means of sustainability indicators. Therefore, all bounds need to be checked

whether they are consistent with the sustainability targets. Alterations with regard to the standard mode are described in Section V.

- **Consistency of sustainability targets and indicator definitions**
  If indicators are defined with regard to partial aspects of sustainability only, they can be consistent with some sustainability targets but deadlock others. In particular this problem can occur for indicators which express shares, e. g. fuel shares. So, if we had in mind fuel diversity and defined the fuel share of hard coal with regard to TPES, then it would be impossible to get rid of this fossil fuel. Therefore, fuel shares have to be defined according to following rules:
  - Keep the fuel diversity among fossil fuels. (This is both consistent with the aspect of energy security and the aim of a fossil-free energy system.)
  - Keep the fuel diversity among non-renewables. (This is both consistent with the aspect of energy security and the aim of an energy system with renewable energy carriers only.)
- **Orientation of sustainability targets towards the ideal state**
  It is the very aim of system analysis to find out up to which degree the system can adapt to changing conditions. Therefore, the setting of sustainability targets should be oriented towards the ideal state and not towards a currently feasible state. Contradictions exist partly between the sustainability targets, and between these targets on the one hand and the system cost on the other hand. IKARUS-FLP can manage contradictory targets. So, when setting the sustainability targets, there is no need to take these contradictions into account.
- **No overlapping of different targets**
  When defining a target for an EISD the theme and sub-theme of the indicator should be exactly taken into account. In a first step the various aspects of the indicator should be distinguished and then one aspect should be chosen in accordance with the theme and sub-theme.

IV.3 Sustainability Targets

The following description of the sustainability targets follows the systematics introduced in Section IV.1.1. Some targets are derived from the Swiss vision of a "2000 Watt society" and from a study of the World Wide Fund for Nature (WWF) for following reasons:

- "2000 Watt society" (Switzerland) [Gutzwiller, 2006 , Novatlantis, 2004, Spreng & Semadeni, 2001]:
  It is sensible to derive sustainability targets from the Swiss vision of a "2000 Watt society" because of two reasons. First, the "2000 Watt society" vision is ambitious. On the one hand, 2 kW was about one third of the average per capita energy consumption in Western Europe in the year 2004. On the other hand it equals the 2004 average per capita energy consumption of the entire world ([Novatlantis, 2004], p. 3). Second, Switzerland has a high human development index and, thus,

may be a prime example for the world ([United Nations Development Programme, 2007], Table 1).

- WWF climate protection study [WWF, 2009]:
  The WWF study is feasible to derive ideal sustainability targets, because it assumes strong CO_2 emission reductions. In the scenario “Innovation” the energy-related CO_2 emissions drop to 95 Mt. Compared to the emissions in the year 1990 (1005 Mt) and 2005 (835 Mt) this corresponds to a decrease by 90.5 % and 88.6 %, respectively (ibid, p. 278). Any of following considerations is related to the “Innovation” scenario.

IV.3.1 ECO 1: TPES per capita

IV.3.1.1 Sources and related information

- International targets and recommended standards:

  “There are no international targets or recommended standards.” ([IAEA et al., 2005], p. 41)

- Global statistics:
  The development of ECO 1 from 1990 until 2005 for different regions of the world is presented in Table 4.

Table 4: Total energy consumption per capita of regions (in kg of oil equivalent)

Region	2005	2000	1990
Asia (excluding Middle East)	1051.5	865.2	775.8
Central America & Caribbean	1365.9	1266.3	1243.1
Europe	3773.4	3580.8	4080.4
Middle East & North Africa	1765.5	1531.5	1184.6
North America	7942.9	8157.9	7686.3
South America	1151.2	1123.8	970.1
Developed Countries	4720.0	4622.6	4755.8
Developing Countries	975.9	807.5	684.6
High Income Countries	5523.6	5468.7	4906.0
Low Income Countries	491.8	457.3	431.5
Middle Income Countries	1509.3	1252.9	1365.4

Source: [World Resources Institute, 2009]

- Statistics for Germany:

In period 2005 (i.e. the years 2003 – 2007) the average TPES was 14,528 PJ [Bundesministerium für Wirtschaft und Technologie (BMWi), 2010].

In period 2005 the average TPES per capita was $176.4\,\mathrm{GJ/cap}$ which corresponds to

$$4.21\frac{\mathrm{toe}}{\mathrm{cap}}$$

([Arbeitsgemeinschaft Energiebilanzen, 2010a], p. 1.1).

- IKARUS value for the period 2005:

  In the period 2005 the TPES was 14,255 PJ at an average population of 82.401 millions [Statisches Bundesamt Deutschland]. From this follows a TPES per capita of

$$4.13\frac{\mathrm{toe}}{\mathrm{cap}}. \tag{3}$$

  The TPES value was used in a project with the VDI [Hake et al., 2009].

  Note: The IKARUS average TPES value and the average TPES per capita value in period 2005 differ from the statistics by -1.9 %. The reason of the difference is most likely the missing calibration of period 2005 in the IKARUS system.

- “2000 Watt society” (Switzerland)

  “The vision of a 2000-watt society allows us to make comparisons between industrialized and developing nations, and thus paves the way for everyone to enjoy a high standard of living ” ([Novatlantis, 2004], p. 3)

  “Im Modell der „2000 Watt-Gesellschaft“ soll – weitgehend mittels technologischer Entwicklungen – der Primärenergieverbrauch von Industrieländern wie z. B. der Schweiz bei gleichbleibender Lebensqualität auf 2000 W pro Person gesenkt werden.” ([Spreng & Semadeni, 2001], p. 2)

  An average electric power of 2 kW per capita corresponds to an annual consumption of 17520 kWh per capita or

$$1.5\frac{\mathrm{toe}}{\mathrm{cap}}. \tag{4}$$

IV.3.1.2 Worst case and ideal case

- The worst case corresponds to the IKARUS value in the period 2005, i.e. (3).
- The ideal case corresponds to the target value of the “2000 Watt society”, i.e. (4).

IV.3.1.3 Fuzzy constraint

$$\frac{\mathrm{TPES}}{\mathrm{population}}\left(\tilde{\leq}!\right)\tilde{b}$$

$$\Leftrightarrow \frac{1}{\mathrm{population}}\mathrm{PI}+\frac{1}{\mathrm{population}}\mathrm{PM}-\frac{1}{\mathrm{population}}\mathrm{PT}\left(\tilde{\leq}!\right)\tilde{b}$$

IV.3.1.4 IKARUS variables involved

TPES: 127 variables

IV.3.1.5 Units and conversions

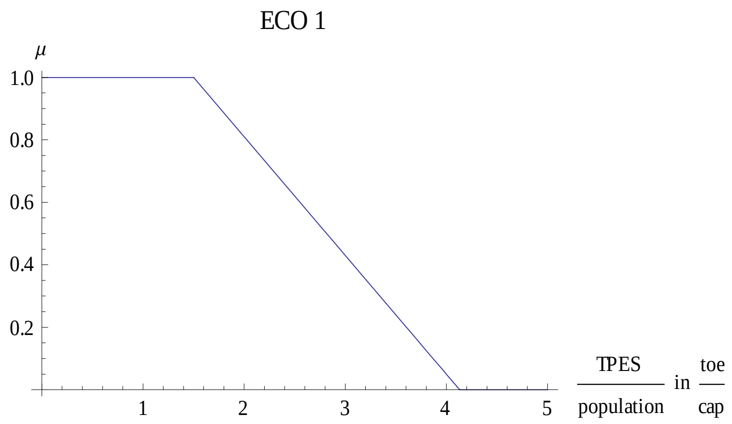
- IKARUS: $\frac{\text{PJ}}{\text{cap}}$
- Literature: tonnes of oil equivalent (toe) per capita: $\frac{\text{toe}}{\text{cap}}$
- Conversion: $1\frac{\text{PJ}}{\text{cap}} = 23884.6\frac{\text{toe}}{\text{cap}}$

IV.3.1.6 Fuzzy sets according to the worst and the ideal case

$$\tilde{b} = (0;1.5;0;2.63)_{LR}$$

Fuzzy set $\tilde{b}$ is illustrated in Figure 3.

Figure 3: Fuzzy set for ECO 1



Source:	IEF-STE 2010

IV.3.2 ECO 2: TPES per unit of GDP

This indicator is also designated as “energy intensity of the GDP”:

$$\text{energy intensity of GDP} = \frac{\text{TPES}}{\text{GDP}}\ ; \qquad (5)$$

see Section IV.1.2 and equation (1).

IV.3.2.1 Sources and related information

- International targets and recommended standards:

  “There is no specific target for energy intensity.” ([IAEA et al., 2005], p. 43)

- Statistics for Germany:
  In the years 2003 – 2007 the energy intensity was

  $$6.74\frac{\text{PJ}}{\text{G€}}$$

  ([Arbeitsgemeinschaft Energiebilanzen, 2010a], p. 1.1).
- IKARUS value for the period 2005:

In the period 2005 the TPES was 14,255 PJ at an average BIP index of 104.2 (2000: index 100 at 2062.5 G€ [Statistische Ämter des Bundes und der Länder]). From this follows an energy intensity of

$$6.63\frac{\text{PJ}}{\text{G€}}. \tag{6}$$

The TPES value was used in a project with the VDI [Hake et al., 2009].

Note: The IKARUS energy intensity value in period 2005 differs from the statistics by -5 %. The reason of the difference is most likely the missing calibration of period 2005 in the IKARUS system.

- Targets of the Federal Government of Germany

  “Dies bedeutet, dass mit einer bestimmten Energiemenge im Jahr 2020 etwa doppelt soviel produziert werden kann wie 1990. Langfristig soll sich die Verbesserung der Energie- und der Rohstoffproduktivität an der „Faktor 4“-Vision orientieren.“ ([Bundesregierung, 2002], p. 93)

  “Die Energieproduktivität hat sich in Deutschland von 1990 bis 2007 um 40,1 % erhöht.“ [ibid, p. 40]

  The “Faktor 4” Vision specifies the improvement of energy productivity from 1990 until 2050 by a factor of four. Taking into account the improvement between 1990 and 2007 by 40.1 %, the improvement between 2005 and 2050 needs to be about $\frac{400}{140} = 2.86$.

- Recommendation of the Helmholtz Association:

  “Sollte sich die internationale Staatengemeinschaft dem anschließen, wäre Deutschland sogar bereit, das o. g. Ziel zu erhöhen und die Emissionen bis 2020 um 40 % gegenüber 1990 zu senken. Dazu soll in Deutschland die Energieproduktivität um 3 % pro Jahr gesteigert … werden.“ ([Helmholtz-Gemeinschaft, 2009], p. 10)

  The extrapolation of an annual improvement of 3 % until the year 2050 results in an overall improvement of factor $(1+0.03)^{45} = 3.78$ from 2005 until 2050. This is a stronger target than the “Faktor 4” vision of the Federal Government of Germany. With regard to (6) the corresponding energy intensity $\frac{\text{TPES}}{\text{GDP}}$ in the year 2050 is

$$1.75\frac{\text{PJ}}{\text{G€}}. \tag{7}$$

IV.3.2.2 Worst case and ideal case

In order to keep the model internally consistent, the IKARUS related values above are considered.

- The worst case corresponds to the IKARUS value in the period 2005, i.e. (6).
- The ideal case corresponds to (7).

IV.3.2.3 Fuzzy constraint

$$\frac{\text{TPES}}{\text{GDP}}\left(\tilde{\lesssim}!\right)\tilde{b}$$

$$\Leftrightarrow \frac{1}{\text{GDP}}\text{PI}+\frac{1}{\text{GDP}}\text{PM}-\frac{1}{\text{GDP}}\text{PT}\left(\tilde{\lesssim}!\right)\tilde{b}$$

IV.3.2.4 IKARUS variables involved

TPES: 127 variables

IV.3.2.5 Units and conversions

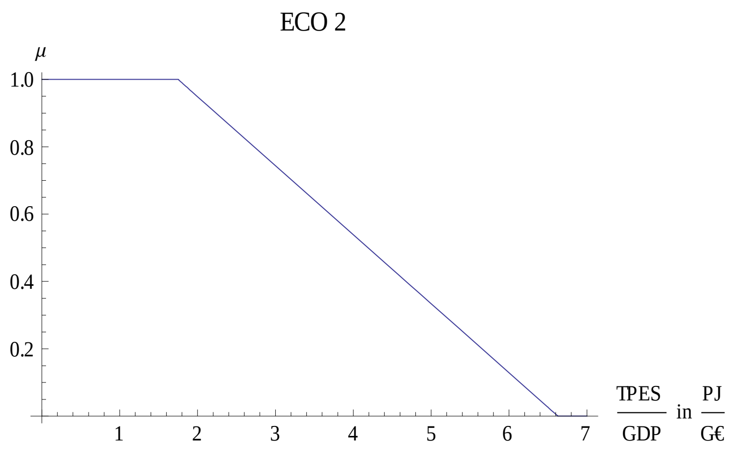
- IKARUS: $\frac{\text{PJ}}{\text{M€}}$
- Literature:
  - Tonnes of oil equivalent per Euro (US$): $\frac{\text{toe}}{\text{€}}$

    Rejected, because on the level of national economies the monetary unit is G€ and the energy unit is PJ.
  - $\frac{\text{PJ}}{\text{G€}}$
- Conversion: $1\frac{\text{PJ}}{\text{M€}}=1000\frac{\text{PJ}}{\text{G€}}$

IV.3.2.6 Fuzzy sets according to the worst and the ideal case

$$\tilde{b}=\left(0;1.75;0;4.88\right)_{LR}$$

Figure 4: Fuzzy set for ECO 2



Source: IEF-STE 2010

IV.3.3 ECO 6: Energy use per unit of value added in the industrial sector

IV.3.3.1 Sources and related information

- International targets and recommended standards:

  "There is no specific target for energy intensity." ([IAEA et al., 2005], p. 52)

- IKARUS value for the year 2005:
  In the year 2005 the energy intensity of the German industry sector was
  $$5.89\frac{PJ}{G€}. \tag{8}$$
  The underlying quantities were used in a project with the VDI [Hake et al., 2009].
- Post VDI project analysis of IEF-STE:
  In the year 2005 the energy intensity of the German industry sector was
  $$5.7\frac{PJ}{G€} \tag{9}$$
  ([Martinsen et al., 2010], Table 4).

  Note: The reason of the inconsistency between (8) and (9) is the different calculation of end energy in the industrial sector.
- Perspective for the USA:

  “Several technical assessments conducted by ACEEE on the potential for energy efficiency in the industrial sector show tremendous opportunity in a variety of states. Recent analyses by ACEEE of the energy efficiency potential in Virginia, Pennsylvania, and Ohio found the potential for economic energy efficiency savings in all three states’ industrial sectors to be 20-25 % by 2025. … using only currently available technology.” ([Chittum et al., 2009], p. 7)

  Note: [Chittum et al., 2009] uses the term “energy efficiency” similar to “energy intensity” (5).

  Above figures are not suitable do define the indicator target, because the energy intensity in the USA is significantly worse (i.e. higher) than in Europe, e.g.

  - Steel: $\frac{\text{energy intensity US}}{\text{energy intensity Europe}} = \frac{120}{110} = 1.09$
  - Cement: $\frac{\text{energy intensity US}}{\text{energy intensity Europe}} = \frac{145}{120} = 1.21$
  - Ammonia: $\frac{\text{energy intensity US}}{\text{energy intensity Europe}} = \frac{105}{100} = 1.05$

  ([United Nations Development Programme, 2007], Table 3.4)
- Global analysis by the McKinsey Global Institute:

  “Combining the energy productivity improvement opportunities across industries and regions, we estimate the potential for improvements to be between 16 and 22 percent of our forecasts by 2020.” [Bressand et al., 2007], p. 275

  “This covers opportunities with an IRR of 10 percent or more.” ibid, p. 272

  The improvement in energy productivity of 20 % in 15 years (2005-2020) corresponds to an improvement of 60 % in 45 years (2005-2050) when extrapolated linearly. If the energy productivity in 2050 is 1.6 times the energy productivity in 2005, then the energy intensity in 2050 is $\frac{1}{1.6} = 0.625$ of the energy intensity in 2005. With regard to value (8) this would be

$$3.68\,\frac{\text{PJ}}{\text{G€}} \tag{10}$$

IV.3.3.2 Worst case and ideal case

- The worst case corresponds to the IKARUS value in the period 2005, i.e. (8).
- The ideal case corresponds to (10).

IV.3.3.3 Fuzzy constraint

$$\frac{\text{FEC}_{\text{industry}}}{\text{value added}_{\text{industry}}}\left(\tilde{\lesssim}!\right)\tilde{b}$$

$$\Leftrightarrow \frac{\text{energy input}_{\text{industry}}}{\text{value added}_{\text{industry}}}-\frac{\text{energy output}_{\text{industry}}}{\text{value added}_{\text{industry}}}\left(\tilde{\lesssim}!\right)\tilde{b}$$

IV.3.3.4 IKARUS variables involved

- energy $\text{input}_{\text{industry}}$ (35 variables):

  SEIAED, SEIBED, SEICED, SEIDED, SEIEED, SEIFED, SGIZGE, SGIZGS, SGIZHG, SKIZBC, SKIZBI, SKIZBP, SKIZBT, SKIZGA, SKIZGK, SKIZSC, SKIZSI, SPIZBW, SPIZMX, SPIZSK, SPIZSS, SPIZWA, SPIZWB, SPIZWX, SRIZCP, SRIZPF, SRIZPG, SRIZPL, SRIZPS, SWIZF1, SWIZF2, SWIZF3, SWIZF4, SWIZF5, SWIZF6

- energy $\text{output}_{\text{industry}}$ (16 variables):

  SIE1ET, SIE2ET, SIE3ET, SIEZGG, SIW1FD, SIW2FD, SIW3FD, SIW4FD, SIW5FD, SIW6FD, SIW1FW, SIW2FW, SIW3FW, SIW4FW, SIW5FW, SIW6FW

IV.3.3.5 Units and conversions

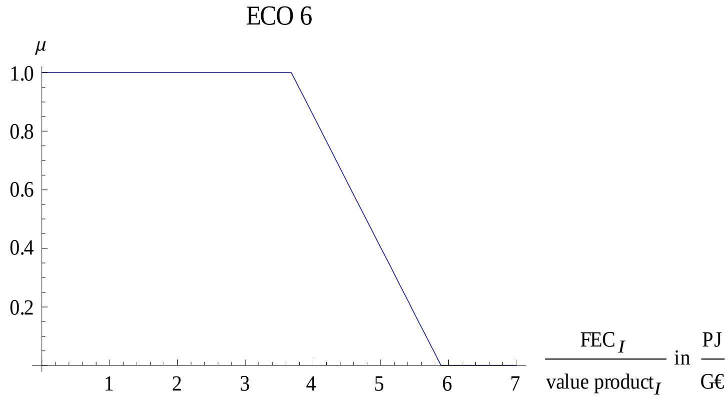
- IKARUS: $\frac{\text{PJ}}{\text{M€}}$
- Literature:
  - Tonnes of oil equivalent per Euro (US$): $\frac{\text{toe}}{\text{€}}$

    Rejected, because on the level of national economies the monetary unit is G€ and the energy unit is PJ.
  - $\frac{\text{PJ}}{\text{G€}}$
- Conversion: $1\frac{\text{PJ}}{\text{M€}}=1000\frac{\text{PJ}}{\text{G€}}$

IV.3.3.6 Fuzzy sets according to the worst and the ideal case

$$\tilde{b}=\left(0;3.68;0;2.21\right)_{LR}$$

Figure 5: Fuzzy set for ECO 6



Source:	IEF-STE 2010

IV.3.4 ECO 9: Amount of total residential energy used per person

IV.3.4.1 Sources and related information

- International targets and recommended standards:

  "There are no international targets or standards; however, thermal standards for new homes are in effect in almost all Organisation for Economic Co-operation and Development (OECD) and East European countries, and in other countries in colder climates. Efficiency standards for boilers and new electric appliances exist and are also important in many countries. Many countries have home energy standards for home appliances." ([IAEA et al., 2005], p. 63f)

- IKARUS value for the period 2005:
  In the period 2005 the FEC of the household sector was 2879 PJ at an average population of 82.4 millions [Statisches Bundesamt Deutschland]. From this follows the indicator value

$$0.83\,\frac{\text{toe}}{\text{cap}}\ . \qquad (11)$$

  The FEC value was used in a project with the VDI [Hake et al., 2009].
- "2000 Watt society" (Switzerland):
  The Swiss 2000 Watt society calculates 730 Watt per capita for housing which is 6394.8 kWh or 0.55 toe per capita in one year [Sturm et al., 2006, Sturm & Egli, 2006]. However, this value includes the energy for building residential buildings and, thus, is not appropriate for the IKARUS energy system model.
- WWF climate protection study [WWF, 2009]:
  In the year 2050 the WWF study shows the energy consumption of 662 PJ in the household sector (ibid, p. 188) at a population of 72.178 millions (ibid, p. 34), i.e. 2547.71 kWh or

$$0.22\,\frac{\text{toe}}{\text{cap}} \qquad (12)$$

in one year.

Note: The population development in the WWF study differs significantly from the assumption made in the project with the VDI. In the latter for the year 2050 a population of 77.3 millions is assumed ([Hake et al., 2009], p. 11). As we do not use the absolute numbers of the energy consumption and the population but their ratio it is nevertheless sensible to use (12) as a target value.

IV.3.4.2 Worst case and ideal case

- The worst case corresponds to the IKARUS value in the period 2005, i.e. (11).
- The ideal case corresponds to (12).

IV.3.4.3 Fuzzy constraint

$$\frac{\text{FEC}_{\text{households}}}{\text{population}} \left(\tilde{\leq}!\right) \tilde{b}$$

$$\Leftrightarrow \frac{1}{\text{population}} \cdot \text{FEC}_{\text{households}} \left(\tilde{\leq}!\right) \tilde{b}$$

IV.3.4.4 IKARUS variables involved

$\text{FEC}_{\text{households}}$ (21 variables):

SKHZAM, SKHZBT, SEH1ED, SEH2ED, SEH3ED, SEH4ED, SEH5ED, SEH6ED, SEH7ED, SEH8ED, SWHFFD, SWHNFD, SGHZGE, SGHZGS, SPHZGB, SGHZHG, SRHZPF, SRHZPL, SPHZRS, SKHXSH, SPHZWA

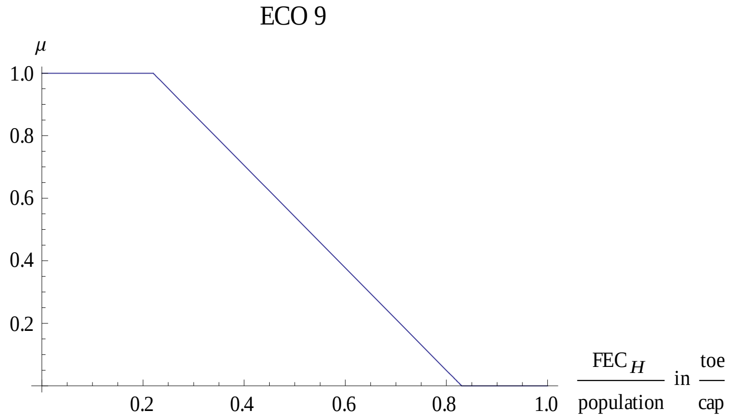
IV.3.4.5 Units and conversions

- IKARUS: $\frac{\text{PJ}}{\text{cap}}$
- Literature: tonnes of oil equivalent (toe) per capita: $\frac{\text{toe}}{\text{cap}}$
- Conversion: $1\frac{\text{PJ}}{\text{cap}} = 23884.6\frac{\text{toe}}{\text{cap}}$

IV.3.4.6 Fuzzy sets according to the worst and the ideal case

$$\alpha = \left(0;0.22;0;0.61\right)_{LR}$$

Figure 6: Fuzzy set for ECO 9



Source:	IEF-STE 2010

IV.3.5 ECO 10-1: Energy use per unit of passenger-km

IV.3.5.1 Sources and related information

- International targets and recommended standards:

  "Many industrialized countries have targets for reducing energy use and carbon emissions from transport." ([IAEA et al., 2005], p. 68)

- Statistics of Germany:
  In the years 2003 – 2007 the FEC of the transport sector was 2603 PJ.
- IKARUS value for the period 2005
  In the period 2005 the FEC of the transport sector was 2734 PJ of which 1792 PJ were consumed in passenger transport to satisfy a demand of 1069.4 billion person-kilometers. From this follows the indicator value

$$5.17 \frac{\text{l petrol}}{\text{pax} \cdot 100\text{km}} \ . \qquad (13)$$

  The FEC value was used in a project with the VDI [Hake et al., 2009].
  Note: The FEC of the transport sector in period 2005 in IKARUS differs from statistics by 5 %. Possible reasons are the missing calibration of IKARUS for period 2005 and different measurement of transit traffic. IKARUS takes all transport in Germany into account, whether transit or not.
- "2000 Watt society" (Switzerland):

  "Die Abschätzungen in Schritt 3 zeigen, dass im Bereich der Mobilität mit technischen Verbesserungen allein keine den Zielen einer 2000-Watt-Gesellschaft genügenden Verbrauchsminderungen erzielbar sind. Deshalb wurde hier gerechnet, welche Fahrleistungsverminderungen (zusätzlich zur Ausschöpfung der technischen Potentiale in Schritt 3) bei der Mobilität gegenüber heute erforderlich wären, um das Ziel 2000 Watt zu erreichen.

  (Wichtig ist dabei zu sehen, dass eine Fahrleistungsverminderung nicht zwingend einen Mobilitätsverzicht erfordert, sondern in vielen Fällen durch eine

bessere Auslastung der Verkehrsmittel erzielt werden kann.)" [Sturm & Egli, 2006], p. 10

Since the IKARUS energy system presets modal split and demand of the transport sector exogenously, only the target owing to technical progress could be achieved, i.e. the 2450 Watt society. In this society 906 Watt would be consumed for leisure mobility and for commuting (ibid, p. 8) which corresponds to an average petrol consumption of $6.23 \frac{\text{l petrol}}{\text{pax} \cdot 100\text{km}}$. This is more than the actual IKARUS value for 2005. The reason is that the Swiss figures include the energy for the production of the vehicles, too. This is not in accordance with the IKARUS energy system model. In IKARUS, energy for vehicle production is converted in the industry sector.

- WWF climate protection study [WWF, 2009]

  In the year 2050 the FEC for passenger transport is 872.8 PJ [3] to satisfy a demand of 998 billion person-kilometers (ibid, p. 92), i.e.

$$2.70 \frac{\text{l petrol}}{\text{pax} \cdot 100\text{km}} \tag{14}$$

Note: This consumption corresponds to 63 g CO_2 emissions per passenger and km [Mickunaitis et al., 2007], p. 160.

IV.3.5.2 Worst case and ideal case

- The worst case corresponds to the IKARUS value of the year 2005, i.e. (13).
- The ideal case corresponds to (14).

IV.3.5.3 Fuzzy constraint

$$\frac{\text{FEC}_{\text{pax}}}{\text{person-km}} \left(\tilde{\leq}!\right) \tilde{b}$$

$$\Leftrightarrow \frac{1}{\text{person-km}} \cdot \text{FEC}_{\text{pax}} \left(\tilde{\leq}!\right) \tilde{b}$$

IV.3.5.4 IKARUS variables involved

FEC_{pax} (23 Variablen):

SKVAAE, SKVAAM, SKVBAE, SKVBAM, SEVAED, SEVBED, SEVCED, SEVDED, SEVEED, SEVFED, SGVAGE, SGVBGE, SGVAHG, SGVBHG, SRVAPB, SRVAPD, SRVAPF, SRVAPO, SRVBPB, SRVBPD, SRVBPF, SRVBPK, SRVBPO

[3] Passenger transport: Road (511 PJ) + local public transport (5.1 PJ) + rail (29.3 PJ) + air (312 PJ) + local services (15.4 PJ) = 872.8 PJ (ibid, pp. 221-229)

IV.3.5.5 Units and conversions

- IKARUS: $\frac{\text{PJ}}{\text{pax} \cdot \text{km}}$
- Literature:

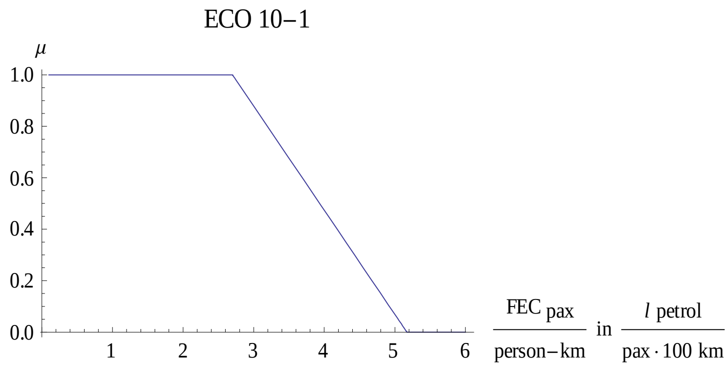
  tonnes of oil equivalent per passenger km: $\frac{\text{toe}}{1}$ Rejected: The common measure in Europe is petrol consumption per 100 km.

  - $\frac{\text{liter petrol}}{\text{pax} \cdot 100\text{km}}$
- Conversion: $1\frac{\text{PJ}}{\text{pax} \cdot \text{km}} = 3082658244.02\frac{\text{l petrol}}{\text{pax} \cdot 100\text{km}}$

IV.3.5.6 Fuzzy sets according to the worst and the ideal case

$$\tilde{b} = (0;2.70;0;2.47)_{LR}$$

Figure 7: Fuzzy set for ECO 10-1



Source:	IEF-STE 2010

IV.3.6 ECO 10-2: Energy use per unit of freight-kilometer

IV.3.6.1 Sources and related information

- International targets and recommended standards:
  see Section IV.3.5.1
- Statistics of Germany:
  see Section IV.3.5.1
- IKARUS value for the year 2005:
  In the period 2005 the FEC of the transport sector was 2734 PJ of which 942 PJ were consumed in freight transport to satisfy a demand of 538.5 billion tonne-kilometers. From this follows the indicator value

  $$4.88\frac{\text{l petrol}}{\text{pax} \cdot 100\text{km}} . \tag{15}$$

  The FEC value was used in a project with the VDI [Hake et al., 2009].
- WWF climate protection study [WWF, 2009]:

In the period 2050 the FEC for freight transport is 687.6 PJ[4] to satisfy a demand of 1047 billion tonne-kilometers (ibid, p. 213), i.e.

$$1.83\frac{\text{l diesel}}{\text{tonne}\cdot 100\text{km}} \tag{16}$$

Note: This consumption corresponds to 49 g CO_2 emissions per tonne and km [Mickunaitis et al., 2007], p. 160.

IV.3.6.2 Worst case and ideal case

- The worst case corresponds to the IKARUS value of the year 2005, i.e. (15).
- The ideal case corresponds to (16).

IV.3.6.3 Fuzzy constraint

$$\frac{\text{FEC}_{\text{freight}}}{\text{tonne-km}}\left(\tilde{\leq}!\right)\tilde{b}$$

$$\Leftrightarrow \frac{1}{\text{tonne-km}}\cdot \text{FEC}_{\text{freight}}\left(\tilde{\leq}!\right)\tilde{b}$$

IV.3.6.4 IKARUS variables involved

$\text{FEC}_{\text{freight}}$ (20 variables)

SKVCAE, SKVCAM, SKVDAE, SKVDAM, SEVGED, SEVHED, SEVIEA, SEVIEB, SEVJED, SGVCGE, SGVDGE, SGVDHG, SGVCHG, SRVCPB, SRVCPD, SRVCPF, SRVCPO, SRVDPD, SRVDPK, SRVDPO

IV.3.6.5 Units and conversions

- IKARUS: $\frac{\text{PJ}}{\text{tonne}\cdot\text{km}}$
- Literature:

  tonnes of oil equivalent per tonne km: $\frac{\text{toe}}{\text{tonne}\cdot\text{km}}$ Rejected: The common measure in Europe is diesel consumption per 100 km.

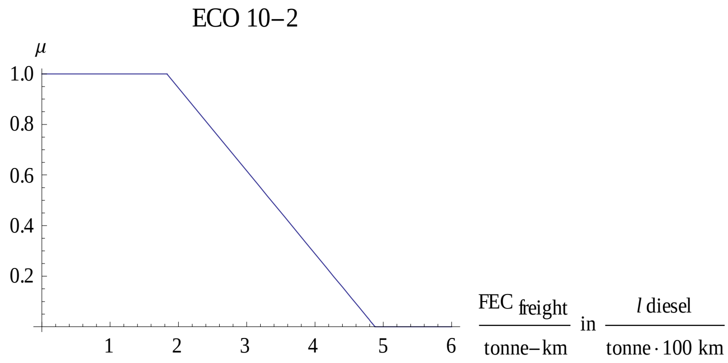
  o $\frac{\text{l diesel}}{\text{tonne}\cdot 100\text{km}}$
- Conversion: $1\frac{\text{PJ}}{\text{tonne}\cdot\text{km}} = 2787720648.09\frac{\text{l diesel}}{\text{tonne}\cdot 100\text{km}}$

IV.3.6.6 Fuzzy sets according to the worst and the ideal case

$$\tilde{b} = \left(0;1.83;0;3.05\right)_{LR}$$

[4] Freight transport: Road (622.5 PJ) + rail (31.7 PJ) + inland navigation (18 PJ) + local services (15.4 PJ) = 687.6 PJ (ibid, pp. 221-229)

Figure 8: Fuzzy set for ECO 10-2



Source:	IEF-STE 2010

IV.3.7 ECO 11-1: Fuel share of hard coal in fossil fuels

IV.3.7.1 Target definition

Waste aspect:

- Reduce CO_2 emissions: This aspect is covered by the indicators
  - ENV 1-1
  - ENV 1-2
- Avoid CO_2 sequestration and storage: This aspect is covered by indicator
  - ENV 11

Energy security aspect:

- Reduce import share: This aspect is covered by indicator
  - ECO 15-1
- Diversify fossil fuels:
  This aspect actually defines the target. In the ideal case the share of this fossil fuel of all fossil fuels (hard coal, lignite, natural gas, crude oil) shall equal 25 %, where a spread of ± 15 % is possible.

Related bounds (see Section V.1.1):

- No pre-set phase-out of hard coal mining.
- The upper limit of hard coal mining equals the 2005 level.

IV.3.7.2 Sources and related information

- International targets and recommended standards

  "In some countries there is a target for the percentage of electricity from re-newable sources. For example, in the European Union a directive sets the quantitative target of 21% for electricity from renewable energy by the year 2010, as well as indicative targets for each Member State." ([IAEA et al., 2005], p. 72)

- IKARUS value for the year 2005

In the year 2005 the fuel share of hard coal was 16 %. This value was used in a project with the VDI [Hake et al., 2009].

IV.3.7.3 Worst case and ideal case

- The worst case are shares of 10 % and below or 40 % and above.
- The ideal case is a share of 25 %.

IV.3.7.4 Fuzzy constraints

$$\frac{PES_{\text{hard coal}}}{PES_{\text{fossil}}} (\tilde{\leq}!) \tilde{a}_{ub}$$
$$\Leftrightarrow PES_{\text{hard coal}} (\tilde{\leq}!) \tilde{a}_{ub} \tilde{\cdot} \left(PES_{\text{hard coal}} + PES_{\text{lignite}} + PES_{\text{gas}} + PES_{\text{oil}}\right)$$
$$\Leftrightarrow \left(1 \tilde{-} \tilde{a}_{ub}\right) \tilde{\cdot} PES_{\text{hard coal}} \tilde{-} \tilde{a}_{ub} \tilde{\cdot} \left(PES_{\text{lignite}} + PES_{\text{gas}} + PES_{\text{oil}}\right) (\tilde{\leq}!) 0$$

and

$$\frac{PES_{\text{hard coal}}}{PES_{\text{fossil}}} (\tilde{\geq}!) \tilde{a}_{lb}$$
$$\Leftrightarrow PES_{\text{hard coal}} (\tilde{\geq}!) \tilde{a}_{lb} \tilde{\cdot} \left(PES_{\text{hard coal}} + PES_{\text{lignite}} + PES_{\text{gas}} + PES_{\text{oil}}\right)$$
$$\Leftrightarrow \left(\tilde{a}_{lb} \tilde{-} 1\right) \tilde{\cdot} PES_{\text{hard coal}} \tilde{+} \tilde{a}_{lb} \tilde{\cdot} \left(PES_{\text{lignite}} + PES_{\text{gas}} + PES_{\text{oil}}\right) (\tilde{\leq}!) 0$$

IV.3.7.5 IKARUS variables involved

As Germany does not import lignite and also does not export natural gas and crude oil, variables for PM_{lignite}, PT_{gas} and PT_{oil} do not exist.

- $PI_{\text{hard coal}}$:
  PIXASX, PIXBSX, PIXCSX
- $PM_{\text{hard coal}}$:
  PMXASX, PMXBSX, PMXCSX
- $PT_{\text{hard coal}}$:
  PTXASC, PTXASX
- PI_{lignite}:
  PIXABX, PIXBBX, PIXCBX}
- PT_{lignite}:
  PTXABP
- PI_{gas}:
  PIXAGE, PIXBGE, PIXCGE
- PM_{gas}:
  PMXAGE, PMXBGE, PMXCGE
- PI_{oil}:
  PIXAPR
- PM_{oil}:
  PMXAPR, PMXBPR, PMXCPR

(alltogether 22 variables)

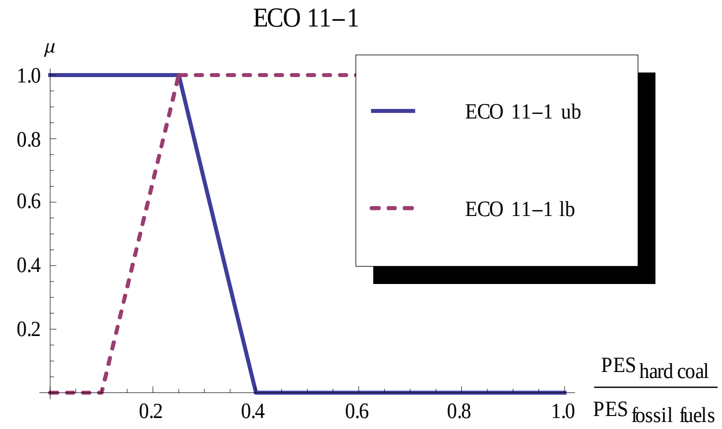
IV.3.7.6 Units and conversions

1 (100 %)

IV.3.7.7 Fuzzy sets according to the worst and the ideal case

$$\tilde{a}_{ub} = (0;0.25;0;0.15)_{LR}$$
$$\tilde{a}_{lb} = (0.25;1;0.15;0)_{LR}$$

Figure 9: Fuzzy set for ECO 11-1



Source: IEF-STE 2010

IV.3.8 ECO 11-2: Fuel share of lignite in fossil fuels

IV.3.8.1 Target definition

The target definition is the same as for hard coal (see Section IV.3.7.1).

Related bounds (see Section V.1.2): No mining limits.

IV.3.8.2 Sources and related information

- International targets and recommended standards: see Section IV.3.7.2
- IKARUS value for the year 2005:
  In the year 2005 the fuel share of lignite was 14 %. This value was used in a project with the VDI [Hake et al., 2009].

IV.3.8.3 Worst case and ideal case

The worst and the ideal cases are the same as for hard coal (see Section IV.3.7.3).

IV.3.8.4 Fuzzy constraints

$$\frac{PES_{lignite}}{PES_{fossil}} (\tilde{\lesssim}!)\, \tilde{a}_{ub}$$
$$\Leftrightarrow PES_{lignite} (\tilde{\lesssim}!)\, \tilde{a}_{ub} \tilde{\cdot} (PES_{hard\ coal} + PES_{lignite} + PES_{gas} + PES_{oil})$$
$$\Leftrightarrow (1 \tilde{-} \tilde{a}_{ub}) \tilde{\cdot} PES_{lignite} \tilde{-} \tilde{a}_{ub} \tilde{\cdot} (PES_{hard\ coal} + PES_{gas} + PES_{oil}) (\tilde{\lesssim}!) 0$$

and

$$\frac{PES_{\text{lignite}}}{PES_{\text{fossil}}}\left(\tilde{\geq}\,!\right)\tilde{a}_{lb}$$

$$\Leftrightarrow PES_{\text{lignite}}\left(\tilde{\geq}\,!\right)\tilde{a}_{lb}\,\tilde{\cdot}\left(PES_{\text{hard coal}}+PES_{\text{lignite}}+PES_{\text{gas}}+PES_{\text{oil}}\right)$$

$$\Leftrightarrow\left(\tilde{a}_{lb}\,\tilde{-}\,1\right)\tilde{\cdot}\,PES_{\text{lignite}}\,\tilde{+}\,\tilde{a}_{lb}\,\tilde{\cdot}\left(PES_{\text{hard coal}}+PES_{\text{gas}}+PES_{\text{oil}}\right)\left(\tilde{\leq}\,!\right)0$$

IV.3.8.5 IKARUS variables involved

The IKARUS variables involved are the same as for hard coal (see Section IV.3.7.5).

IV.3.8.6 Units and conversions

1 (100 %)

IV.3.8.7 Fuzzy sets according to the worst and the ideal case

The fuzzy sets are the same as for hard coal (see Section IV.3.7.7).

IV.3.9 ECO 11-3: Fuel share of natural gas in fossil fuels

IV.3.9.1 Target definition

The target definition is the same as for hard coal (see Section IV.3.7.1).

IV.3.9.2 Sources and related information

- International targets and recommended standards: see Section IV.3.7.2
- IKARUS value for the year 2005
  In the year 2005 the fuel share of natural gas was 29 %. This value was used in a project with the VDI [Hake et al., 2009].

IV.3.9.3 Worst case and ideal case

The worst and the ideal cases are the same as for hard coal (see Section IV.3.7.3).

IV.3.9.4 Fuzzy constraints

$$\frac{PES_{\text{gas}}}{PES_{\text{fossil}}}\left(\tilde{\leq}\,!\right)\tilde{a}_{ub}$$

$$\Leftrightarrow PES_{\text{gas}}\left(\tilde{\leq}\,!\right)\tilde{a}_{ub}\,\tilde{\cdot}\left(PES_{\text{hard coal}}+PES_{\text{lignite}}+PES_{\text{gas}}+PES_{\text{oil}}\right)$$

$$\Leftrightarrow\left(1\,\tilde{-}\,\tilde{a}_{ub}\right)\tilde{\cdot}\,PES_{\text{gas}}\,\tilde{-}\,\tilde{a}_{ub}\,\tilde{\cdot}\left(PES_{\text{hard coal}}+PES_{\text{lignite}}+PES_{\text{oil}}\right)\left(\tilde{\leq}\,!\right)0$$

and

$$\frac{PES_{\text{gas}}}{PES_{\text{fossil}}}\left(\tilde{\geq}\,!\right)\tilde{a}_{lb}$$

$$\Leftrightarrow PES_{\text{gas}}\left(\tilde{\geq}\,!\right)\tilde{a}_{lb}\,\tilde{\cdot}\left(PES_{\text{hard coal}}+PES_{\text{lignite}}+PES_{\text{gas}}+PES_{\text{oil}}\right)$$

$$\Leftrightarrow\left(\tilde{a}_{lb}\,\tilde{-}\,1\right)\tilde{\cdot}\,PES_{\text{gas}}\,\tilde{+}\,\tilde{a}_{lb}\,\tilde{\cdot}\left(PES_{\text{hard coal}}+PES_{\text{lignite}}+PES_{\text{oil}}\right)\left(\tilde{\leq}\,!\right)0$$

IV.3.9.5 IKARUS variables involved

The IKARUS variables involved are the same as for hard coal (see Section IV.3.7.4).

IV.3.9.6 Units and conversions

1 (100 %)

IV.3.9.7 Fuzzy sets according to the worst and the ideal case

The fuzzy sets are the same as for hard coal (see Section IV.3.7.7).

IV.3.10 ECO 11-4: Fuel share of crude oil in fossil fuels

IV.3.10.1 Target definition

The target definition is the same as for hard coal (see Section IV.3.7.1).

IV.3.10.2 Sources and related information

- International targets and recommended standards: see Section IV.3.7.2
- IKARUS value for the year 2005
  In the year 2005 the fuel share of natural gas was 41 %. This value was used in a project with the VDI [Hake et al., 2009].

IV.3.10.3 Worst case and ideal case

The worst and the ideal cases are the same as for hard coal (see Section IV.3.7.3).

IV.3.10.4 Fuzzy constraints

$$\frac{PES_{oil}}{PES_{fossil}} (\tilde{\leq}!) \tilde{a}_{ub}$$

$$\Leftrightarrow PES_{oil} (\tilde{\leq}!) \tilde{a}_{ub} \tilde{\cdot} \left(PES_{hard\ coal} + PES_{lignite} + PES_{gas} + PES_{oil}\right)$$

$$\Leftrightarrow \left(1 \tilde{-} \tilde{a}_{ub}\right) \tilde{\cdot} PES_{oil} \tilde{-} \tilde{a}_{ub} \tilde{\cdot} \left(PES_{hard\ coal} + PES_{lignite} + PES_{gas}\right) (\tilde{\leq}!) 0$$

and

$$\frac{PES_{oil}}{PES_{fossil}} (\tilde{\geq}!) \tilde{a}_{lb}$$

$$\Leftrightarrow PES_{oil} (\tilde{\geq}!) \tilde{a}_{lb} \tilde{\cdot} \left(PES_{hard\ coal} + PES_{lignite} + PES_{gas} + PES_{oil}\right)$$

$$\Leftrightarrow \left(\tilde{a}_{lb} \tilde{-} 1\right) \tilde{\cdot} PES_{oil} \tilde{+} \tilde{a}_{lb} \tilde{\cdot} \left(PES_{hard\ coal} + PES_{lignite} + PES_{gas}\right) (\tilde{\leq}!) 0$$

IV.3.10.5 IKARUS variables involved

The IKARUS variables involved are the same as for hard coal (see Section IV.3.7.4).

IV.3.10.6 Units and conversions

1 (100 %)

IV.3.10.7 Fuzzy sets according to the worst and the ideal case

The fuzzy sets are the same as for hard coal (see Section IV.3.7.7).

IV.3.11 ECO 11-5: Fuel share of nuclear fuel in non-renewables

IV.3.11.1 Target definition

Waste aspect

- Reduce CO_2 emissions: This aspect is covered by indicator
  - ENV 1-1
- Avoid nuclear waste: This aspect is covered by indicator
  - ENV 9

Energy security aspect

- Reduce import share: This aspect is covered by indicator
  - ECO 15-1: Ratio of net import to total primary energy supply (TPES)
- Diversify fossil fuels:
  This aspect actually defines the target. In the ideal case the share of nuclear fuel of all non-renewable fuels (hard coal, lignite, natural gas, crude oil, nuclear fuel) shall equal 20 %, where a spread of ± 15 % is possible.

Related bounds (see Section V.4.1):

- No pre-set phase-out of nuclear energy.
- The operational life of nuclear power plants is extended to 60 years.
- No limit for the new building of nuclear power plants.
- Shutdown of nuclear power plants is possible.

IV.3.11.2 Sources and related information

- International targets and recommended standards: see Section IV.3.7.2
- IKARUS value for the year 2005:
  In the year 2005 the share of nuclear fuel was 14 %. This value was used in a project with the VDI [Hake et al., 2009].

IV.3.11.3 Worst case and ideal case

- The worst case are shares of 5 % and below or 35 % and above.
- The ideal case is a share of 20 %.

IV.3.11.4 Fuzzy constraints

$$\frac{\mathrm{PES}_{\text{nuclear}}}{\mathrm{PES}_{\text{non-renewable}}}\left(\tilde{\leq}!\right)\tilde{a}_{ub}$$

$$\Leftrightarrow \mathrm{PES}_{\text{nuclear}}\left(\tilde{\leq}!\right)\tilde{a}_{ub}\cdot\left(\mathrm{PES}_{\text{hard coal}}+\mathrm{PES}_{\text{lignite}}+\mathrm{PES}_{\text{gas}}+\mathrm{PES}_{\text{oil}}+\mathrm{PES}_{\text{nuclear}}\right)$$

$$\Leftrightarrow \left(1-\tilde{a}_{ub}\right)\cdot\mathrm{PES}_{\text{nuclear}}-\tilde{a}_{ub}\cdot\left(\mathrm{PES}_{\text{hard coal}}+\mathrm{PES}_{\text{lignite}}+\mathrm{PES}_{\text{gas}}+\mathrm{PES}_{\text{oil}}\right)\left(\tilde{\leq}!\right)0$$

and

$$\frac{PES_{nuclear}}{PES_{non\text{-}renewable}} (\tilde{\gtrsim}!) \tilde{a}_{lb}$$

$$\Leftrightarrow PES_{nuclear} (\tilde{\gtrsim}!) \tilde{a}_{lb} \tilde{\cdot} \left(PES_{hard\ coal} + PES_{lignite} + PES_{gas} + PES_{oil} + PES_{nuclear}\right)$$

$$\Leftrightarrow (\tilde{a}_{lb} \tilde{-} 1) \tilde{\cdot} PES_{nuclear} \tilde{+} \tilde{a}_{lb} \tilde{\cdot} \left(PES_{hard\ coal} + PES_{lignite} + PES_{gas} + PES_{oil}\right) (\tilde{\lesssim}!) 0$$

IV.3.11.5 IKARUS variables involved

As Germany imports nuclear fuel, only, variables for $PI_{nuclear}$ and $PT_{nuclear}$ do not exist.

The IKARUS variables involved are the same as for hard coal (see Section IV.3.7.4) plus additional variables for $PM_{nuclear}$:

PMXAKH, PMXAKL, PMXBKH, PMXBKL, PMXCKH, PMXCKL

(altogether 28 variables).

IV.3.11.6 Units and conversions

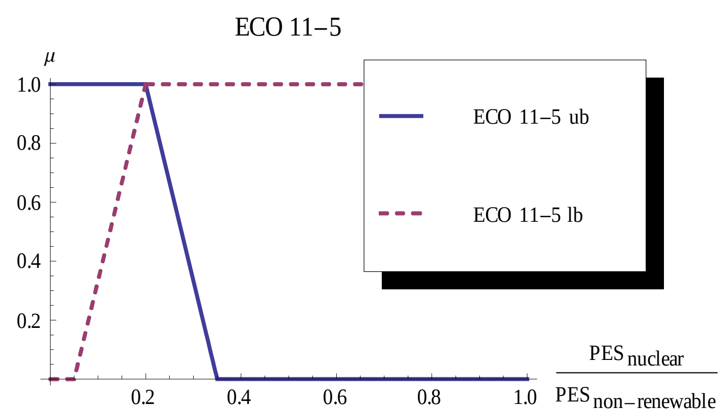
1 (100 %)

IV.3.11.7 Fuzzy sets according to the worst and the ideal case

$$\tilde{a}_{ub} = (0;0.2;0;0.15)_{LR}$$

$$\tilde{a}_{lb} = (0.2;1;0.15;0)_{LR}$$

Figure 10: Fuzzy set for ECO 11-5



Source:	IEF-STE 2010

IV.3.12 ECO 12: Share of non-carbon fuels in TPES

IV.3.12.1 Target definition

Waste aspect:

- This aspect actually defines the target: Increase the share of non-carbon fuels up to 100 % and do not undercut the share in the year 2005.
- Avoid nuclear waste: This aspect is covered by indicator
    - ENV 9

Energy security aspect:

- Reduce import share: This aspect is covered by indicator
  - ECO 15-1
- Diversify renewable fuels:
  In principle, diversity of renewable energy carriers would be important. Due to the specific climatic conditions in Germany a diversity goal is not defined, at first.

Related bounds:

- For bounds related to nuclear power see Section V.4.1.
- As the potential for hydro power is exhausted in Germany, the upper limit of hydro power plant capacity is set to the 2005 level (see Section V.4.2).
- Technology-founded upper capacity limits for solar and wind power (see Section V.4.2)
- Imports of renewable energy carriers are limited upward (see Section V.2.7).
- The import of solar electricity is limited upward (see Section V.2.6).

IV.3.12.2 Sources and related information

- International targets and recommended standards:

  "At the World Summit on Sustainable Development in Johannesburg in 2002, an agreement was reached to increase the global share of renewable energy sources. In some countries, there is a target for a certain percentage of energy supply from renewable sources. For example, in the European Union a directive sets quantitative targets for electricity from renewable energy to be 21% by the year 2010, as well as indicative targets for each Member State." ([IAEA et al., 2005], p. 74)

- IKARUS value for the year 2005:
  In the year 2005 the share of non-carbon energy carriers in TPES was
  $$16\ \%. \qquad (17)$$
  This value was used in a project with the VDI [Hake et al., 2009].

IV.3.12.3 Worst case and ideal case

- The worst case corresponds to the IKARUS value in the year 2005 from the VDI project, i.e. (17).
- The ideal case is a share of 100 %.

IV.3.12.4 Fuzzy constraint

$$\frac{\mathrm{PES}_{\text{non-carbon}}}{\mathrm{TPES}}\left(\tilde{\geq}!\right)\tilde{a}$$
$$\Leftrightarrow \tilde{a}\,\tilde{\cdot}\,\mathrm{TPES}\,\tilde{-}\,\mathrm{PES}_{\text{non-carbon}}\left(\tilde{\leq}!\right)0$$
$$\Leftrightarrow (\tilde{a}\,\tilde{-}\,1)\,\tilde{\cdot}\,\mathrm{PES}_{\text{non-carbon}}\,\tilde{+}\,\tilde{a}\,\tilde{\cdot}\,\mathrm{PES}_{\text{carbon}}\left(\tilde{\leq}!\right)0$$

IV.3.12.5 IKARUS variables involved

- TPES (127 variables)
- $\mathrm{PES}_{\text{non-carbon}}$ (65 variables)

- Assumption: Non-carbon fuels shall not be exported. Therefore variables for $PT_{non\text{-}carbon}$ do not exist.
- $PI_{non\text{-}carbon}$:
  PIXAAE, PIXAGB, PIXAPO, PIXARH, PIXARS, PIXART, PIXARW, PIXAWA, PIXAWB, PIXAWC, PIXAWD, PIXAWG, PIXAWX, PIXBAE, PIXBGB, PIXBPO, PIXBRH, PIXBRS, PIXBRW, PIXBWA, PIXBWB, PIXBWC, PIXBWX, PIXCGB, PIXCPO, PIXCRH, PIXCRS, PIXCRW, PIXCWA, PIXCWB, PIXCWC, PIXCWD, PIXCWX, PIXDRS, PIXDWA, PIXDWB, PIXDWX, PIXEGB, PIXEWA, PIXEWB, PIXEWC, PIXEWD
- $PM_{non\text{-}carbon}$:
  PMXAHG, PMXAKH, PMXAKL, PMXBHG, PMXBKH, PMXBKL, PMXCHG, PMXCKH, PMXCKL, PMXDHG, PMXEHG, PMXAAE, PMXAEP, PMXAPO, PMXBAE, PMXBEP, PMXBPD, PMXBPO, PMXCAE, PMXCEP, PMXCPD, PMXCPO, PMXDEP

- PES_{carbon}, PI_{carbon}, PM_{carbon}: Complement sets of $PES_{non\text{-}carbon}$, $PI_{non\text{-}carbon}$ and $PM_{non\text{-}carbon}$, respectively.

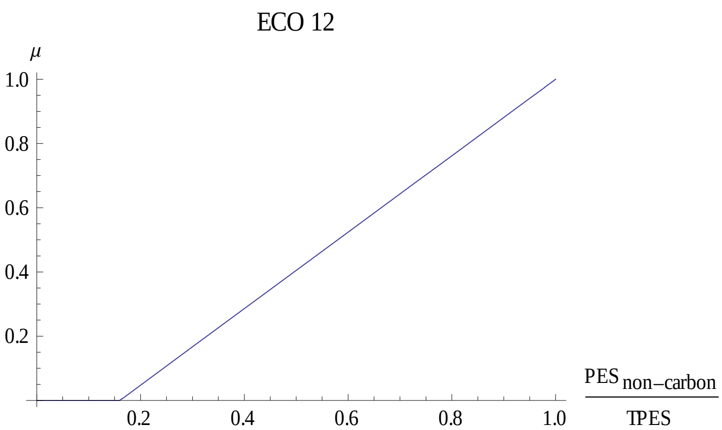
IV.3.12.6 Units and conversions

1 (100 %)

IV.3.12.7 Fuzzy sets according to the worst and the ideal case

$$\tilde{a} = (1;1;0.84;0)_{LR}$$

Figure 11: Fuzzy set for ECO 12



Source: IEF-STE 2010

IV.3.13 ECO 13: Share of renewable energy in total primary energy supply (TPES)

IV.3.13.1 Target definition

Waste aspect:

- This aspect actually defines the target: Increase the share of renewable energy carriers up to 100 % and do not undercut the share in the year 2005.

Energy security aspect:

- see Section IV.3.12.1

Related bounds:

- see Section IV.3.12.1

IV.3.13.2 Sources and related information

- International targets and recommended standards: see Section IV.3.12.1
- IKARUS value for the year 2005
  In the year 2005 the share of renewable energy carriers in TPES was
  $$3\ \%. \qquad (18)$$
  This value was used in a project with the VDI [Hake et al., 2009].

IV.3.13.3 Worst case and ideal case

- The worst case corresponds to the IKARUS value in the year 2005 from the VDI project, i.e. (17).
- The ideal case is a share of 100 %.

IV.3.13.4 Fuzzy constraint

$$\frac{PES_{renewables}}{TPES} \left(\tilde{\geq}\,!\right) \tilde{a}$$
$$\Leftrightarrow \tilde{a} \tilde{\cdot} TPES \tilde{-} PES_{renewables} \left(\tilde{\leq}\,!\right) 0$$
$$\Leftrightarrow (\tilde{a} \tilde{-} 1) \tilde{\cdot} PES_{renewables} \tilde{+} \tilde{a} \tilde{\cdot} PES_{non\text{-}renewables} \left(\tilde{\leq}\,!\right) 0$$

IV.3.13.5 IKARUS variables involved

- TPES (127 variables)
- Assumption: Renewable energy carriers shall not be exported. Therefore variables for $PT_{renewables}$ do not exist.
- $PES_{renewables}$ (54 variables)
  - $PI_{renewables}$:
    PIXAAE, PIXAGB, PIXAPO, PIXARH, PIXARS, PIXART, PIXARW, PIXAWA, PIXAWB, PIXAWC, PIXAWD, PIXAWG, PIXAWX, PIXBAE, PIXBGB, PIXBPO, PIXBRH, PIXBRS, PIXBRW, PIXBWA, PIXBWB, PIXBWC, PIXBWX, PIXCGB, PIXCPO, PIXCRH, PIXCRS, PIXCRW, PIXCWA, PIXCWB, PIXCWC, PIXCWD, PIXCWX, PIXDRS, PIXDWA, PIXDWB, PIXDWX, PIXEGB, PIXEWA, PIXEWB, PIXEWC, PIXEWD
  - $PM_{renewables}$:
    PMXAAE, PMXAEP, PMXAPO, PMXBAE, PMXBEP, PMXBPD, PMXBPO, PMXCAE, PMXCEP, PMXCPD, PMXCPO, PMXDEP
- $PES_{non\text{-}renewables}$, $PI_{non\text{-}renewables}$, $PM_{non\text{-}renewables}$: Complements of $PES_{renewables}$, $PI_{renewables}$ and $PM_{renewables}$, respectively

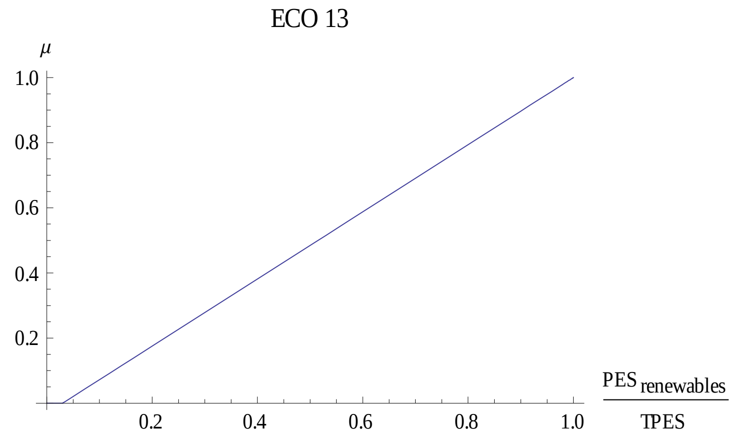
IV.3.13.6 Units and conversions

1 (100 %)

IV.3.13.7 Fuzzy sets according to the worst and the ideal case

$$\tilde{a} = (1;1;0.97;0)_{LR}$$

Figure 12: Fuzzy set for ECO 13



Source:	IEF-STE 2010

IV.3.14 ECO 15-1: Ratio of net import to total primary energy supply (TPES)

IV.3.14.1 Target definition

Energy security aspect:

- Autarky of energy supply is neither necessary nor desirable.
- This aspect actually defines the target: Decrease the ratio of net import to TPES and do not exceed the ratio of the year 2005.

Related bounds

- Practically no upper limits for the import of primary energy carriers exist; these imports are only controlled by the sustainability targets.
- The import of secondary energy carriers is limited. For details see Section V.2.

IV.3.14.2 Sources and related information

- International targets and recommended standards:

  "In some countries there is a recommended level to which a country may rely on energy import." ([IAEA et al., 2005], p. 83)

- IKARUS value for the year 2005:
  In the year 2005 the ratio of net import to TPES was

  $$75\,\%. \qquad (19)$$

  This value was used in a project with the VDI [Hake et al., 2009].

IV.3.14.3 Worst case and ideal case

- The worst case corresponds to the IKARUS value in the year 2005 from the VDI project, i.e. (19).
- The ideal case is set to 33 %. This value is in accordance with the target definition (i.e. no autarky; see Section IV.3.14.1). It mainly expresses that the majority of

primary energy carriers is domestic. This purpose would be achieved as well if the target would be set to another value, e.g. 30 % or 40 %.

IV.3.14.4 Fuzzy constraint

$$\frac{\mathrm{PM}}{\mathrm{TPES}} \tilde{\leq} \tilde{a}$$
$$\Leftrightarrow \mathrm{PM} \tilde{\leq} \tilde{a} \tilde{\cdot} \left(\mathrm{PI} + \mathrm{PM} - \mathrm{PT}\right)$$
$$\Leftrightarrow (1 \tilde{-} \tilde{a}) \tilde{\cdot} \mathrm{PM} \tilde{-} \tilde{a} \cdot \left(\mathrm{PI} - \mathrm{PT}\right) \tilde{\leq} 0$$

IV.3.14.5 IKARUS variables involved

TPES (127 variables)

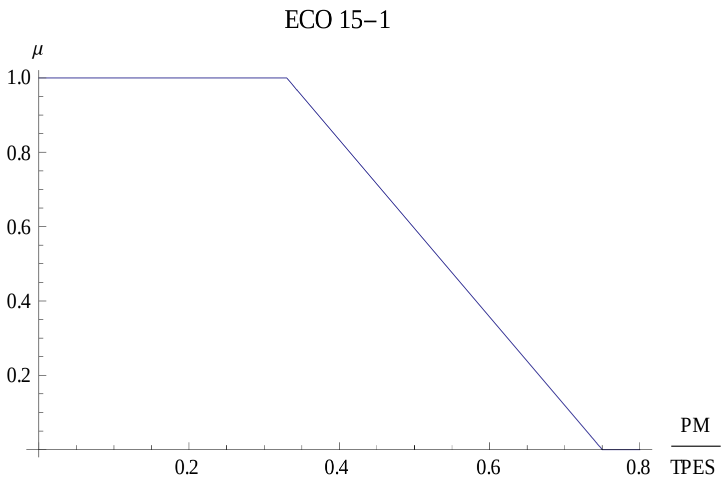
IV.3.14.6 Units and conversions

1 (100 %)

IV.3.14.7 Fuzzy sets according to the worst and the ideal case

$$\tilde{a} = \left(0;0.33;0;0.42\right)_{LR}$$

Figure 13: Fuzzy set for ECO 15-1



Source: IEF-STE 2010

IV.3.15 ECO 15-2: Share of imported renewable energy carriers in the total of renewable energy carriers

IV.3.15.1 Target definition

Energy security aspect

- The share of imported renewable energy carriers in the total of renewable energy carriers shall be “very small”.

Related bounds: see Section IV.3.14.1

IV.3.15.2 Sources and related information

- International targets and recommended standards: see Section IV.3.14.2

- IKARUS value for the year 2005
  In the year 2005 the share of imported renewable energy carriers in the total of renewable energy carriers was
  $$2\,\%. \tag{20}$$
  This value was used in a project with the VDI [Hake et al., 2009].

IV.3.15.3 Worst case and ideal case

Both cases are not well-founded. The ideal case is just a guess of "very small", whereas the worst case is significantly higher, though still below 50 %.

- The worst case is set to 33 %.
- The ideal case is set to 20 %.

IV.3.15.4 Fuzzy constraint

$$\frac{PM_{renewable}}{TPES_{renewable}} \tilde{\leq} \tilde{a}$$
$$\Leftrightarrow PM_{renewable} \tilde{\leq} \tilde{a} \,\tilde{\cdot}\, \left(PI_{renewable} + PM_{renewable}\right)$$
$$\Leftrightarrow (1 \tilde{-} \tilde{a}) \,\tilde{\cdot}\, PM_{renewable} \tilde{-} \tilde{a} \cdot PI_{renewable} \tilde{\leq} 0$$

IV.3.15.5 IKARUS variables involved

$TPES_{renewable}$ (54 variables)

- Assumption: Renewable energy carriers shall not be exported. Therefore variables for $PT_{renewable}$ do not exist.
- $PI_{renewable}$:
  PIXAAE, PIXAGB, PIXAPO, PIXARH, PIXARS, PIXART, PIXARW, PIXAWA, PIXAWB, PIXAWC, PIXAWD, PIXAWG, PIXAWX, PIXBAE, PIXBGB, PIXBPO, PIXBRH, PIXBRS, PIXBRW, PIXBWA, PIXBWB, PIXBWC, PIXBWX, PIXCGB, PIXCPO, PIXCRH, PIXCRS, PIXCRW, PIXCWA, PIXCWB, PIXCWC, PIXCWD, PIXCWX, PIXDRS, PIXDWA, PIXDWB, PIXDWX, PIXEGB, PIXEWA, PIXEWB, PIXEWC, PIXEWD
- $PM_{renewable}$:
  PMXAAE, PMXAEP, PMXAPO, PMXBAE, PMXBEP, PMXBPD, PMXBPO, PMXCAE, PMXCEP, PMXCPD, PMXCPO, PMXDEP

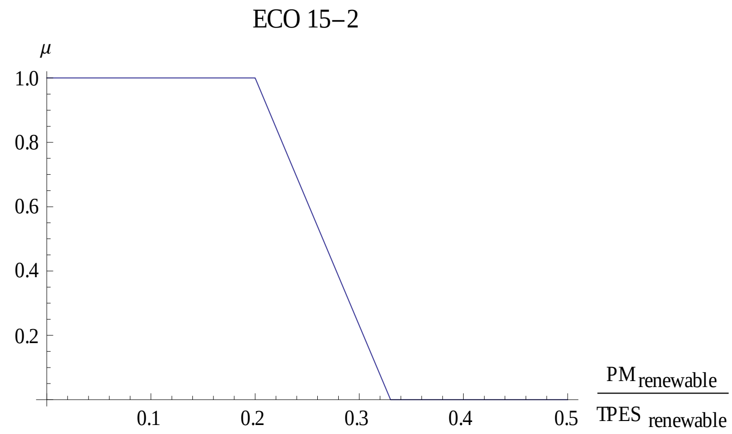
IV.3.15.6 Units and conversions

1 (100 %)

IV.3.15.7 Fuzzy sets according to the worst and the ideal case

$$\tilde{a} = \left(0;0.2;0;0.13\right)_{LR}$$

Figure 14: Fuzzy sets for ECO 15-2



Source:	IEF-STE 2010

IV.3.16 ENV 1-1: Total amount of CO_2 emissions

IV.3.16.1 Sources and related information

- International targets and recommended standards:

  "The Kyoto Protocol sets targets for each Annex I Party with a view to reducing these Parties' overall emissions of the six main GHGs by at least 5% below 1990 levels in the commitment period 2008-2012" ([IAEA et al., 2005], p. 88)

- Statistics for Germany:

  In the years 2003 - 2007 the temperature-adjusted average annual amount of CO_2 emissions was 798 Mt [Bundesministerium für Wirtschaft und Technologie (BMWi), 2010].

- IKARUS value for the period 2005:

  In the period 2005 the annual amount of CO_2 emissions was

  $$799.7 \text{ Mt} \tag{21}$$

  which is very close to statistics; with an error of 0.2 %.

  Note: The IKARUS model records only the energy specific CO_2 emissions. In order to compare statistical values with IKARUS values, the figures from statistics need to be temperature adjusted. This is done for the sectors: households, small consumers and industry. In the IKARUS model, the CO_2 emissions from industry are adjusted according to the manner of calculation in statistics. (This mainly refers to the distinction of energy related and process related CO_2 emissions; see Section VI)

- Intergovernmental Panel on Climate Change [IPCC, 2007]:

  For the determination of the indicator target the 2° C scenario of the IPCC is assumed (ibid, Table 5.1). According to the scenario, CO_2 emissions need to be reduced by 50 – 85 % compared to the year 2000. In the period 2000 the total amount of CO_2 emissions in IKARUS was 837 Mt. A reduction by 85 % corresponds to the CO_2 emission target of

$$126 \text{ Mt}. \qquad (22)$$

IV.3.16.2 Worst case and ideal case

- The worst case corresponds to the IKARUS value in the year 2005, i.e. (21).
- The ideal case corresponds to the 85 % reduction target, i.e. (22).

IV.3.16.3 Fuzzy constraint

$$CO_2 \text{ emissions} \left(\tilde{\leq} ! \right) \tilde{b}$$

IV.3.16.4 IKARUS variables involved

SZZZUD

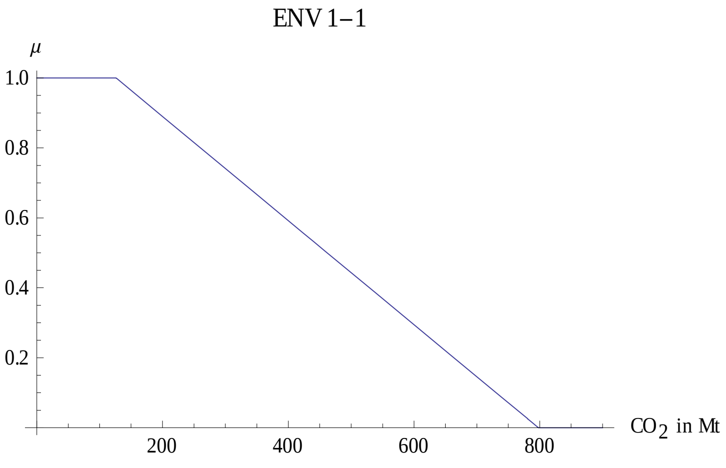
IV.3.16.5 Units and conversions

- IKARUS: kt
- Literature: Mt
- Conversion: $1\text{kt} = 0.001\text{Mt}$

IV.3.16.6 Fuzzy sets according to the worst and the ideal case

$$\tilde{a} = \left(0;126;0;672 \right)_{LR}$$

Figure 15: Fuzzy sets for ENV 1



Source:	IEF-STE 2010

IV.3.17 ENV 1-2: CO_2 emissions per capita

IV.3.17.1 Sources and related information

- International targets and recommended standards: see Section IV.3.16.1
- IKARUS value for the year 2005

  In the period 2005 the IKARUS CO_2 emissions were 799.7 Mt at a population of 82.4 millions [Statisches Bundesamt Deutschland], and thus the CO_2 emissions per capita were

$$9.68\ \frac{\text{t}}{\text{cap}}\ . \tag{23}$$

Note: The difference to statistics is as small as in Section IV.3.16.1.

- Intergovernmental Panel on Climate Change [IPCC, 2007]:
  For the target derived in Section IV.3.16.1 and a population of 77.3 millions in 2050 [BMVBS, 2006], the per capita target is

$$1.63\ \frac{\text{t}}{\text{cap}}\ . \tag{24}$$

- WWF climate protection study [WWF, 2009]:
  According to the WWF study, annual CO_2 emissions need to be lowered down to

$$1.6\ \frac{\text{t}}{\text{cap}} \tag{25}$$

  (ibid, p. 2). Although the WWF population assumption of 77.2 millions in 2050 (ibid, p. 34) differs from the population value used in the IKARUS model, this target matches (24).

IV.3.17.2 Worst case and ideal case

- The worst case corresponds to the IKARUS value in the year 2005, i.e. (23).
- The ideal case corresponds to (25).

IV.3.17.3 Fuzzy constraint

$$\frac{\text{CO}_2\ \text{emissions}}{\text{population}}\left(\tilde{\leq}\,!\right)\tilde{b}$$

$$\Leftrightarrow \frac{1}{\text{population}}\cdot \text{CO}_2\ \text{emissions}\left(\tilde{\leq}\,!\right)\tilde{b}$$

IV.3.17.4 IKARUS variables involved

SZZZUD

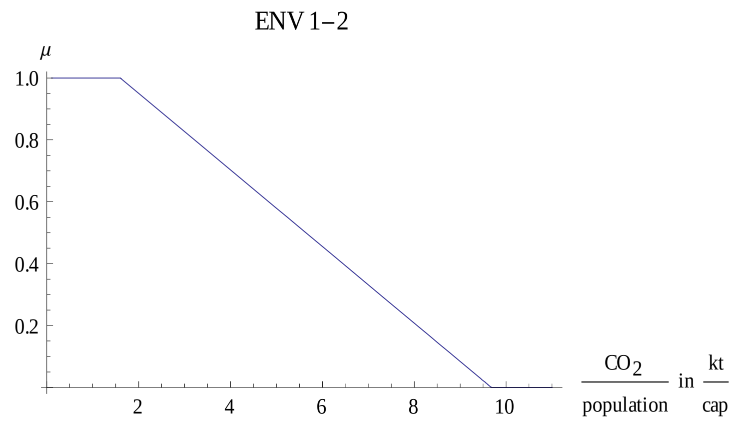
IV.3.17.5 Units and conversions

- IKARUS: $\frac{\text{kt}}{\text{cap}}$
- Literature: $\frac{\text{t}}{\text{cap}}$
- Conversion: $1\frac{\text{kt}}{\text{cap}} = 1000\frac{\text{t}}{\text{cap}}$

IV.3.17.6 Fuzzy sets according to the worst and the ideal case

$$\tilde{b} = \left(0;1.6;0;8.08\right)_{LR}$$

Figure 16: Fuzzy sets for ENV 1-2



Source:	IEF-STE 2010

IV.3.18 ENV 9: Total amount of electricity generated by nuclear power plants

IV.3.18.1 Target definition

Waste aspect:

- Since the permanent storage of nuclear waste has not been solved in Germany, yet, the amount of waste must not exceed the level of 2005.
- Even if the permanent storage of nuclear waste would have be solved, from an ecological point of view waste should be avoided. Ideally, no nuclear waste is generated.

Related bounds: see Section V.4.1

IV.3.18.2 Sources and related information

- International targets and recommended standards:

  "The IAEA has established Safety Standards (Fundamentals, Requirements and Guides) applicable to the management of radioactive wastes generated in nuclear energy facilities. It has also established the International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources, which are consistent with recommendations of the ICRP. No comparable international recommended standards or targets exist for the radioactive waste generated in non-nuclear energy industrie.s" ([IAEA et al., 2005], p. 123)

- Energy statistics of Germany [Bundesministerium für Wirtschaft und Technologie (BMWi), 2010]:

  In the period 2005 (i.e. the years 2003 – 2007) the average annual gross electricity production of nuclear power plants was

$$160.6\text{ TWh} \tag{26}$$

  (ibid, p. 22).

- IKARUS value for the period 2005:

  In the period 2005 the nuclear power plants net electricity production was

$$151.4\ \text{TWh}. \tag{27}$$

This value was used in a project with the VDI [Hake et al., 2009].

Note: The statistics figure in (26) indicates gross electricity production. In 2005 the German net production of electricity was about 6.3 % less than the gross production ([Arbeitsgemeinschaft Energiebilanzen, 2010b], Table 11). Thus, the period 2005 net statistics value is estimated at about 150.5 TWh. The remaining difference between this value and (27) is less than one percent. It is probably the result of the yet missing IKARUS calibration for the period 2005.

IV.3.18.3 Worst case and ideal case

- The worst case corresponds to the IKARUS value in the period 2005, i.e. (27).
- The ideal case would be no electricity generated from nuclear power plants, at all.

IV.3.18.4 Fuzzy constraint

$$\text{electricity}_{\text{nuclear}}\left(\tilde{\leq}!\right)\tilde{b}$$

IV.3.18.5 IKARUS variables involved

- Existing nuclear power plants (6 variables):
  EHE1KL, EHE2KL, EHE3KL, EHE4KL, EHE5KL, EHE6KL
- New built nuclear power plants (6 variables):
  EHE1KH, EHE2KH, EHE3KH, EHE4KH, EHE5KH, EHE6KH
  Note: Originally, these variables designate nuclear power plants with a high temperature reactor (HTR). Actually, in the current IKARUS calculations they model newly built nuclear power plants of the EPR type.

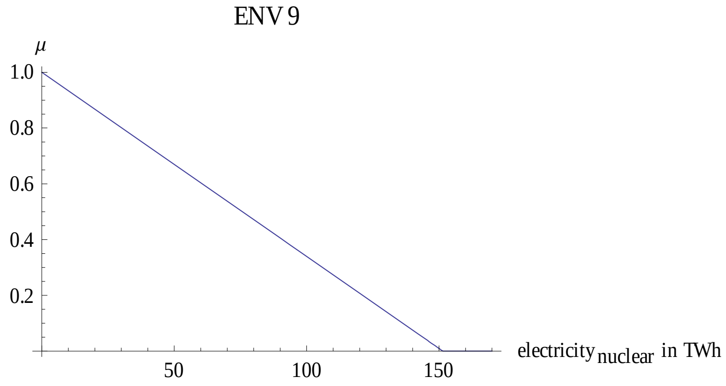
IV.3.18.6 Units and conversions

- IKARUS: PJ
- Literature: TWh
- Conversion: $1\ \text{PJ} = \frac{1}{3.6}\text{TWh}$

IV.3.18.7 Fuzzy sets according to the worst and the ideal case

$$\tilde{b} = \left(0;0;0;151.4\right)_{LR}$$

Figure 17: Fuzzy sets for ENV 9



Source:	IEF-STE 2010

IV.3.19 ENV 11: Ratio of stored CO_2 to CO_2 emitted into the atmosphere

IV.3.19.1 Target definition

CO_2 capture and storage is only considered for the electricity sector.

Waste aspect:

- Since the sequestration and permanent storage of CO_2 in geological formations have not been solved, yet, model computations should not rely heavily on this technology. Therefore, the amount of CO_2 from electricity generation stored in geological formations must be much smaller than the amount of CO_2 emitted into the atmosphere. We specify that at most ¼ of CO_2 is stored and ¾ of CO_2 are emitted. Although, these figures are not well-founded, they reflect our intention.
- Even if the permanent storage of CO_2 in geological formations would have be solved, from an ecological point of view waste should be avoided. Ideally, no CO_2 is stored in geological formations.

Related bounds: see Section V.4.2

IV.3.19.2 Sources and related information

The proved deposit capacity in Germany is 5.8 Gt ([Schlüter, 2009], p. 115). If the amount of CO_2 produced by electricity generation would decrease linearly from its 2005 value to the 2050 target (see Section IV.3.16), then the total amount of CO_2 in the time period 2020-2050 would be 10850 Mt. One fourth of this quantity would be about 2700 Mt which is already half of the estimated German deposit capacity. This comparison shows on one side, that the deposit capacity matches the target specified in Section IV.3.19.1, on the other side it demonstrates that the currently proved deposit capacity would be to small to hold the entire CO_2 emissions. However, the supposed deposit capacities lie in between 19.4 Gt and 48.4 Gt (ibid, p. 115).

IV.3.19.3 Worst case and ideal case

- The worst case corresponds to ¼ of the total amount of CO_2 produced by electricity generation (or ⅓ of CO_2 emitted into the atmosphere).
- The ideal case would be no storage of CO_2 underground, at all.

IV.3.19.4 Fuzzy constraint

$$\frac{\text{CO}_2\ \text{stored}}{\text{CO}_2\ \text{emitted}}\left(\tilde{\lesssim}!\right)\tilde{a}$$

or (see Section IV.3.19.5)

$$\frac{\sum_{\$=1}^{6}\sum_{i\in\{B,G,S\}} 9f_{\text{CO}_2}\text{EHE\$}i\text{D}+\sum_{\$=1}^{6}\sum_{i\in\{B,G,S\}} \gamma_{\$,j}\text{EHE\$}i\text{E}}{\text{SEEAUD}}\left(\tilde{\lesssim}!\right)\tilde{a}$$

$$\Leftrightarrow \sum_{\$=1}^{6}\sum_{i\in\{B,G,S\}} 9f_{\text{CO}_2}\text{EHE\$}i\text{D}\,\tilde{+}\sum_{\$=1}^{6}\sum_{i\in\{B,G,S\}} \gamma_{\$,j}\text{EHE\$}i\text{E}\,\tilde{-}\,\tilde{a}\,\tilde{\cdot}\,\text{SEEAUD}\left(\tilde{\lesssim}!\right)0$$

IV.3.19.5 IKARUS variables involved

- The total amount of CO_2 emitted by the electricity sector is given by variable SEEAUD [kt].
- In the IKARUS model CO_2 is sequestrated in CCS power plants and in retrofitted power plants. The amount of CO_2 sequestrated by retrofitted power plants equals:

$$\sum_{\$=1}^{6}\sum_{i\in\{B,G,S\}} \gamma_{\$,j}\text{EHE\$}i\text{E} \tag{28}$$

  where $\gamma_{\$,j}$ is the time-dependent amount of sequestrated CO_2 [kt] per unit of fuel [GJ] (see Table 5). The amount of CO_2 sequestrated by CCS power plants is nine times the amount of CO_2 emitted by these plants:

$$\sum_{\$=1}^{6}\sum_{i\in\{B,G,S\}} 9f_{\text{CO}_2}\text{EHE\$}i\text{D} \tag{29}$$

  where the CO_2 factors f_{CO_2} give the time-dependent amount of emitted CO_2 [kt] per unit of generated electricity [GJ] (see Table 6).

Table 5: Coefficients for the calculation of sequestered CO_2 by retrofitted CCS power plants

Period	Variable [GJ]	f_{CO_2} [kg/GJ]	f_{fuel} [1]	$\gamma_{\$,j} := \left\lvert f_{CO_2}\right\rvert / f_{fuel}$ [kt/GJ]
2020	EHE$BE	-207.0	0.69	0.3000
	EHE$GE	-82.2	0.23	0.3574
	EHE$SE	-165.6	0.59	0.2807
2025	EHE$BE	-205.8	0.55	0.3742
	EHE$GE	-81.8	0.21	0.3895

Period	Variable [GJ]	f_{CO_2} [kg/GJ]	f_{fuel} [1]	$\gamma_{\$,j} := \left\| f_{CO_2} \right\| / f_{fuel}$ [kt/GJ]
	EHE$SE	-164.9	0.49	0.3365
2030	EHE$BE	-204.6	0.43	0.4758
	EHE$GE	-81.4	0.19	0.4284
	EHE$SE	-164.1	0.40	0.4103
2035	EHE$BE	-203.6	0.41	0.4966
	EHE$GE	-81.2	0.19	0.4274
	EHE$SE	-163.6	0.38	0.4305
2040	EHE$BE	-202.7	0.38	0.5334
	EHE$GE	-81.0	0.19	0.4263
	EHE$SE	-163.2	0.36	0.4533
2045	EHE$BE	-198.2	0.33	0.6006
	EHE$GE	-80.0	0.17	0.4706
	EHE$SE	-160.7	0.31	0.5184
2050	EHE$BE	-193.8	0.28	0.6921
	EHE$GE	-79.0	0.17	0.4647
	EHE$SE	-158.2	0.27	0.5859

Source: IEF-STE 2010

Table 6: Coefficients for the calculation of sequestered CO_2 by newly built CCS power plants

Period	Variable [GJ]	f_{CO_2} [kt/GJ]
2020	EHE$BD	0.0305
	EHE$GD	0.0103
	EHE$SD	0.0239
2025	EHE$BD	0.0288
	EHE$GD	0.0102
	EHE$SD	0.0228
2030	EHE$BD	0.0273

Period	Variable [GJ]	f_{CO_2} [kt/GJ]
	EHE$GD	0.0101
	EHE$SD	0.0218
2035	EHE$BD	0.0269
	EHE$GD	0.0100
	EHE$SD	0.0216
2040	EHE$BD	0.0265
	EHE$GD	0.0100
	EHE$SD	0.0214
2045	EHE$BD	0.0254
	EHE$GD	0.0098
	EHE$SD	0.0206
2050	EHE$BD	0.0244
	EHE$GD	0.0097
	EHE$SD	0.0199

Source: IEF-STE 2010

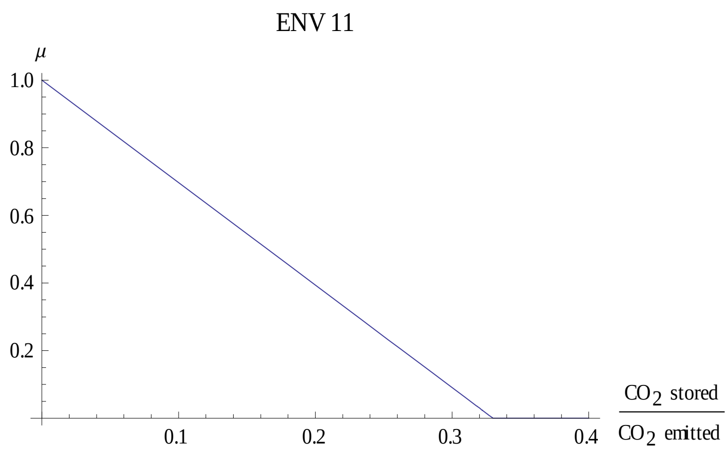
IV.3.19.6 Units and conversions

1 (100 %)

IV.3.19.7 Fuzzy sets according to the worst and the ideal case

$$\tilde{a} = (0;0;0;0.33)_{LR}$$

Figure 18: Fuzzy sets for ENV 11



Source: IEF-STE 2010

V Bounds in IKARUS-FLP

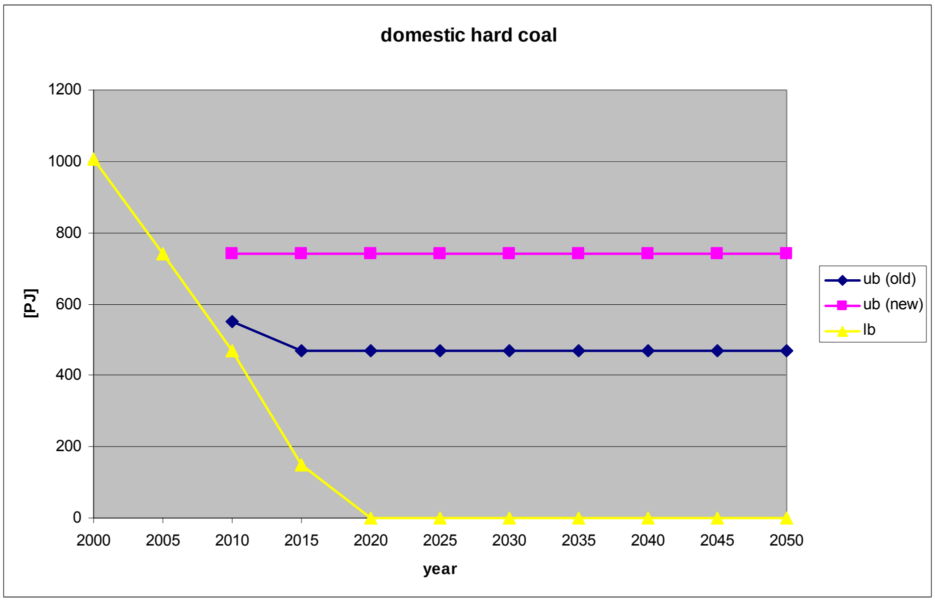
Following subsections show the most important bounds and indicate whether the bounds have been changed compared to the reference scenarios in the VDI project [Hake et al., 2009]. Bounds changes follow the rules stated in Section IV.2. In particular, bounds should be consistent with sustainability targets. Utilization of technologies and energy carriers should be mainly controlled by the sustainability targets and not by pre-settings.

V.1 Mining and Extraction of Energy Carriers

V.1.1 Hard coal

It is assumed that hard coal mining is not phased out but can continue at the level of the year 2005. Therefore, the upper bound is changed (see Figure 19).

Figure 19: Bounds of domestic hard coal mining

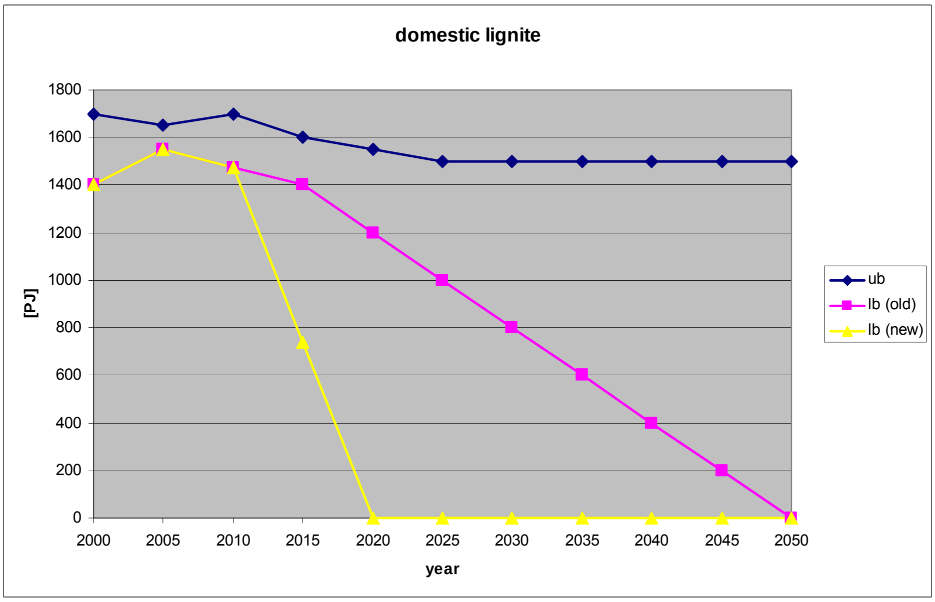


Source:	IEF-STE 2010

V.1.2 Lignite

It is assumed that lignite could be phased out until the year 2020 due to CO_2 mitigation targets. Therefore, the lower bound is changed (see Figure 20).

Figure 20: Bounds of domestic lignite mining

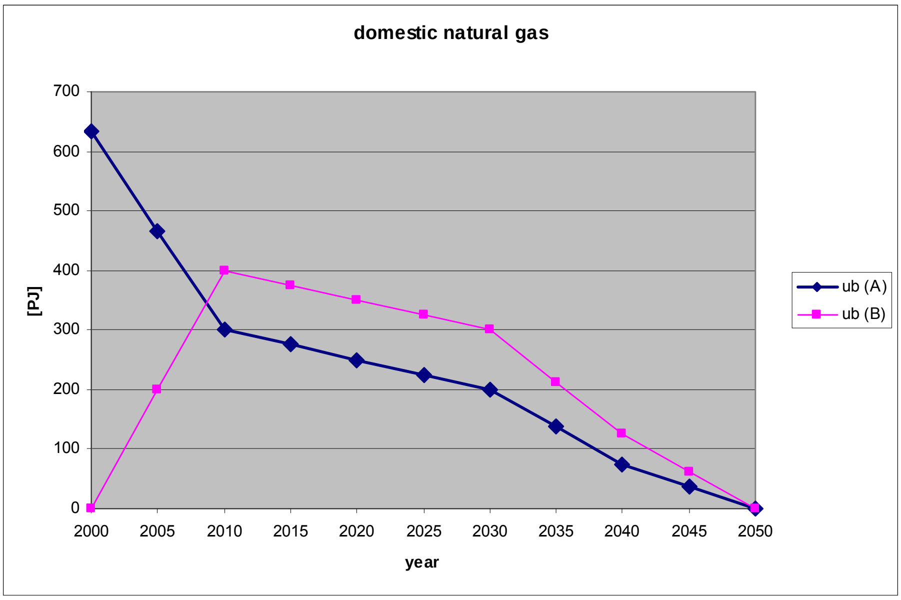


Source:	IEF-STE 2010

V.1.3 Natural gas

No bounds are changes (type A and B) (see Figure 21).

Figure 21: Bounds of domestic natural gas extraction

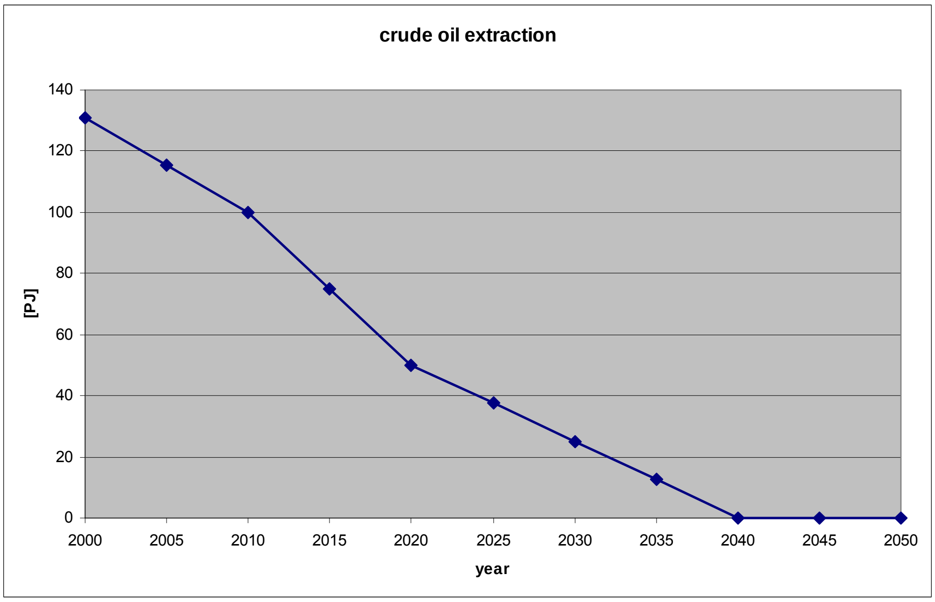


Source:	IEF-STE 2010

V.1.4 Crude oil

The fixed bounds for crude oil are not changed (see Figure 22).

Figure 22: Fixed bounds of domestic crude oil extraction



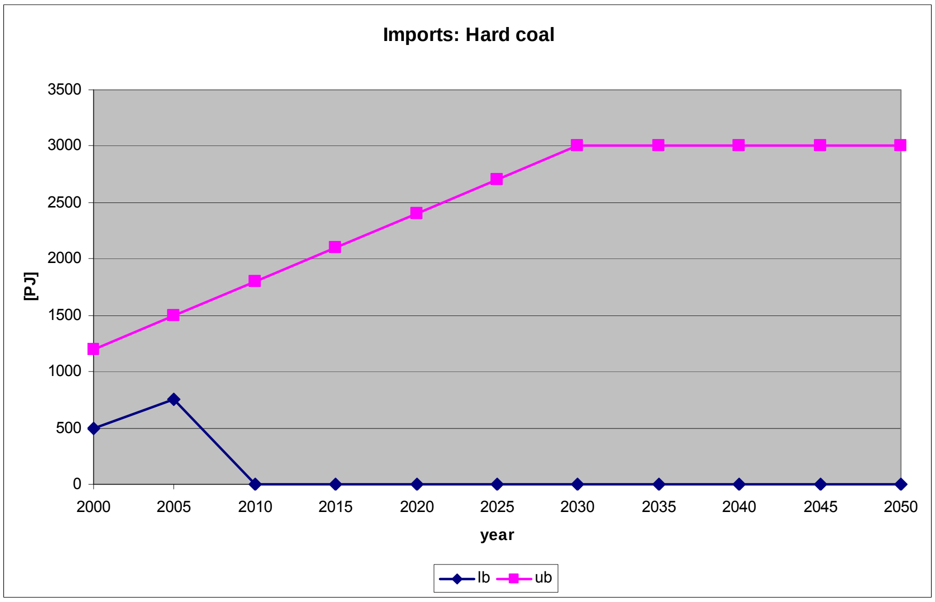
Source:	IEF-STE 2010

V.2 Imports of Energy Carriers

V.2.1 Hard coal

The bounds for hard coal imports are not changed (see Figure 23).

Figure 23: Bounds for the import of hard coal



Source:	IEF-STE 2010

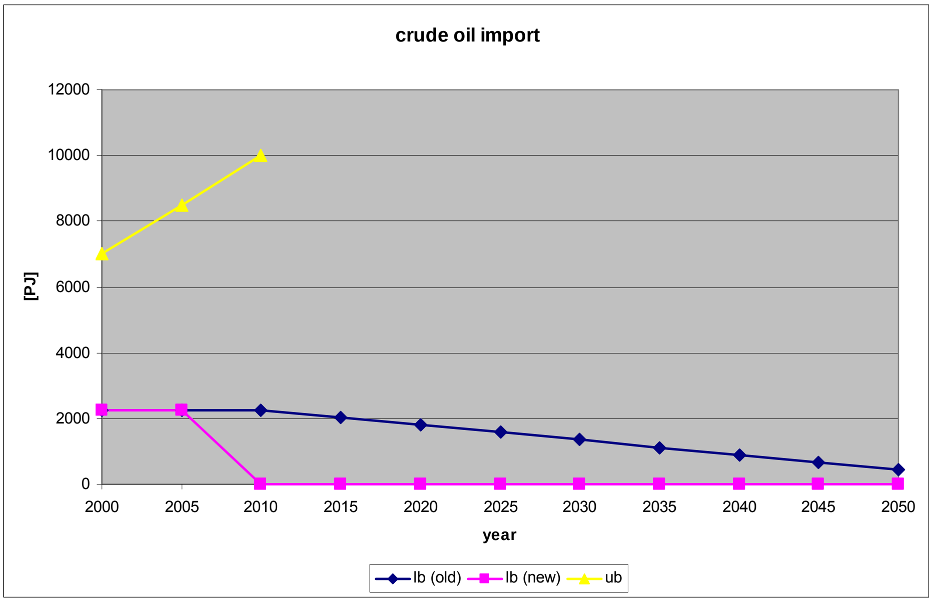
V.2.2 Natural gas

Natural gas of type A has no bounds. Natural gas of type B has bounds, however they are unimportant, because natural gas of type B is more expensive than natural gas A and, thus, will not be chosen by the model. Therefore, the bounds of natural gas imports are not changed.

V.2.3 Crude oil

The crude oil import was limited downwards. In order to let the model decide about the use of crude oil, from the year 2010 on the lower bound for crude oil import is set to zero (see Figure 24).

Figure 24: Bounds for the import of crude oil



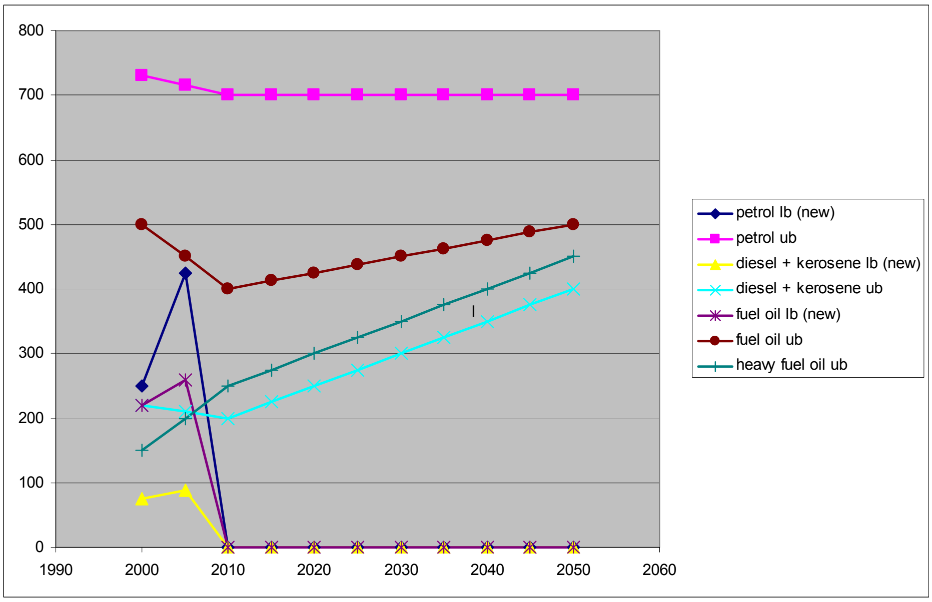
Source:	IEF-STE 2010

V.2.4 Petrol, diesel, kerosine and fuel oils

Petrol, diesel, kerosene and fuel oil had lower import bounds whereas heavy fuel oil has not had a lower bound. In order to enable the fully domestic production of these fuels, from the year 2010 their lower bounds are set to zero (see Figure 25).

Note: The import restrictions of secondary energy carriers come from the former IKARUS project. Actually, it would be more reasonable either to suppress the import of secondary energy carriers at all (i.e. to produce these energy carriers at home) or to define a specific amount of imports for each energy carrier.

Figure 25: Bounds for the import of petrol, diesel, kerosene, fuel oil and heavy fuel oil



Source:	IEF-STE 2010

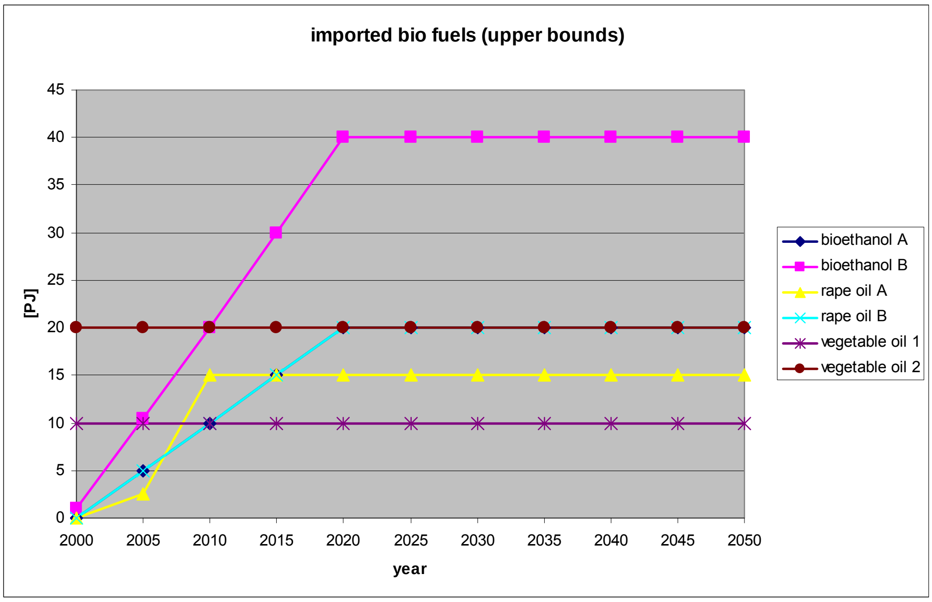
V.2.5 Electricity and hydrogen

Electricity imports are suppressed to avoid pro forma CO_2 reduction by dislocation of power plants. An exception is solar electricity (see Section V.2.7). For the same reason import of hydrogen is suppressed. Therefore, the upper bounds of "conventional" electricity imports and of hydrogen imports are set to zero.

V.2.6 Biofuels

The bounds for biofuel imports were reasonably set in a separate project [Funk, 2008] and have not been changed due to lack of new findings (see Figure 26).

Figure 26: Bounds for the import of biofuels



Source: IEF-STE 2010

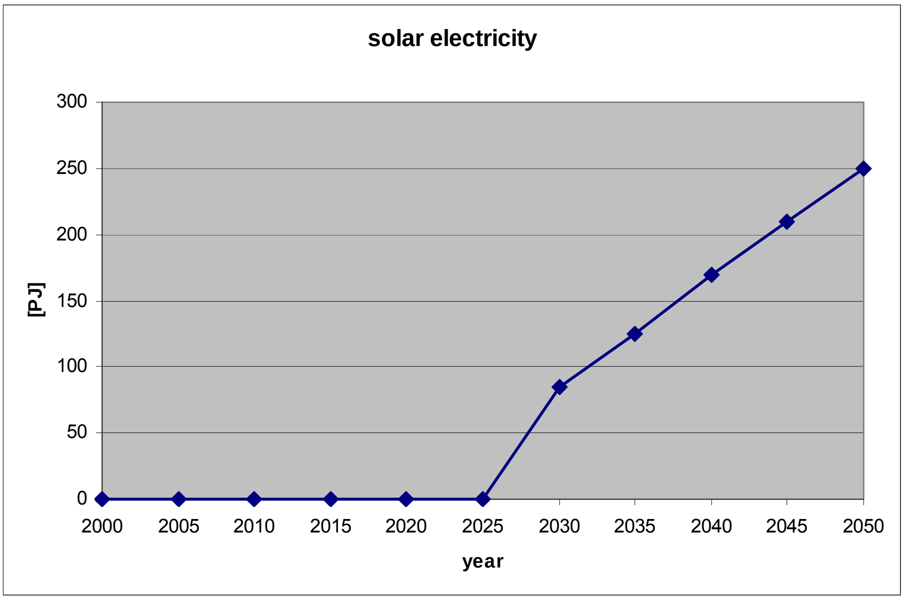
V.2.7 Solar electricity

It is assumed that from 2030 the import of solar electricity generated by solar thermal power plants in the deserts of North Africa is possible. Upper bounds and import prices are based on information from DESERTEC [DESERTEC Foundation, 2009a, DESERTEC Foundation, 2009b].

> *"In 2050, twenty to forty power lines with 2500 - 5000 MW capacity each could provide about 15 % of the European electricity …" ([DESERTEC Foundation, 2009a], p. 36)*

In the year 2005 the German electricity consumption was about 1864 PJ or 517.8 TWh [Bundesministerium für Wirtschaft und Technologie (BMWi), 2010]. A share of 15 % of the 2005 value equals 279.6 PJ or 77.7 TWh. Therefore the upper limit for solar electricity imports in 2050 is estimated conservatively at 250 PJ or 69.4 TWh. Before, the amount of imported solar electricity is rising linearly starting in 2030.

Figure 27: Upper bounds for the import of solar electricity



Source:	IEF-STE 2010

V.3 Exports of Energy Carriers

The export of any energy carrier is suppressed. Therefore, from the year 2010 on the upper bound for brown coal dust is set to zero.

Technical note: The change was made for the base case BASIS, because it was not possible to change it via the GUI due to some problems.

V.4 Power Plant Capacities

V.4.1 Nuclear power plants

In order to let the decision about utilization of nuclear power to the model according to the sustainability targets, the capacity bounds for nuclear power have been changed as follows (see Section IV.3.11):

- No pre-set phase-out of nuclear energy.
- The operational life of nuclear power plants is extended to 60 years.
- No limit for the new building of nuclear power plants.
- Shutdown of nuclear power plants is possible.

Technical notes:

- The IKARUS database table ST_RESID0 was changed to enable operational life extension to 60 years.
- The upper bound for the capacity of existing nuclear power plants was set to the residual capacity curve (as described by database table ST_RESID0). This measure disables the new building of power plants of the "current type" (without investment cost).

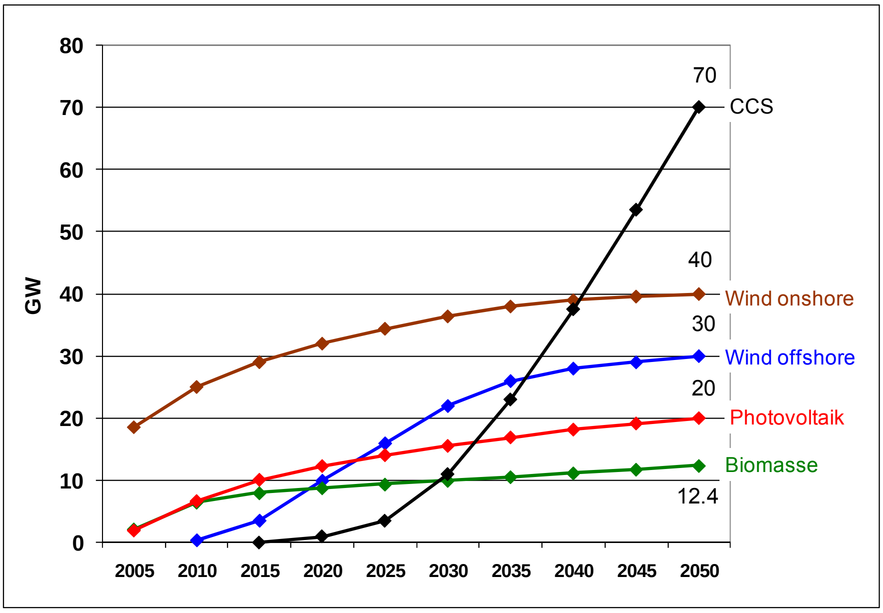
- Nuclear power plants of the “new building” type (in the model EHE$KH) do not have an upper capacity bound.
- Capacity equation signs were changed and user equations were inserted in order to enable the shut-down of nuclear power plants while the remaining plants operate in base load.

V.4.2 Other power plants

No bounds are changed.

- As the potential for hydro power is exhausted in Germany, the upper limit of hydro power plant capacity is set to the 2005 level.
- Lignite power plants have to run in base load, however, entire plants can be shut down.
- For CCS power plants and for power plants which utilize renewable energy carriers upper bounds are set according to technological plausibility. Figure 28 shows the maximal possible extension of these power plant types in terms of installed net capacity until the year 2050.

Figure 28: Upper bounds of net installed power plant capacity



Quelle:	[Hake et al., 2009]

VI Miscellaneous

VI.1 CO_2 Adjustment in Recent IKARUS Versions

For 330 variables in the industrial sector the specific CO_2 emission factors were adjusted in order to calculate the total CO_2 emissions according to the currently official statistics (see Table 7).

Table 7: CO_2 emission values calculated by IKARUS and from official statistics

Period	CO_2 emissions	Remark
1990	971 Mt	Statistical average from 1989-1992, temperature adjusted
2000	837.0 Mt	IKARUS result (calibrated)
2005	798.0 Mt	IKARUS result (not calibrated)
2010	773.5 Mt	Optimization result from [Martinsen et al., 2010]

Source: IEF-STE 2010

VI.2 Investment Cost of Nuclear Power Plants

In the VDI study [Hake et al., 2009] the investment cost of EPR type nuclear power plants was set to 1565 €/kW on behalf of the European technical association for power and heat generation "VGB Power Tech e. V." According to an information from the IAEA the investment cost of the EPR currently built in Finland is 4031 US$/kW which, i.e. 3023 €/kW (at an exchange rate of 0.75 €/US$). This is similar to the figure reported by the Financial Times, which estimates the total cost of the Finnish EPR at about 5.3 billion € or 3313 €/kW [Hollinger, 2009]. Therefore, the investment cost of nuclear power plants in IKARUS was altered to 3500 €/kW.

VI.3 Relaxation Priorities of Fuzzy Constraints

In IKARUS-FLP the system cost objective function $c^T x$ is replaced by the system cost fuzzy constraint $c^T x \left(\tilde{\leq}!\right) \tilde{z}$ [Weber & Martinsen, 2009]. This constraint is considered equally to the sustainability constraints. In principle, the fuzzy set

$$\tilde{z} = \left(\underline{z}, \overline{z}, \underline{\varsigma}, \overline{\varsigma}\right)_{LR} = \left(0, \overline{z}, 0, \overline{\varsigma}\right)_{LR}$$

is calculated as follows:

- $\overline{z}$ is the system cost if any sustainability indicator takes its worst case value (see Section IV.1.1). As the worst case value of any sustainability indicator is the IKARUS value in the period 2005, the related optimization problem is feasible and an optimal solution can be computed.
- $\overline{z} + \overline{\varsigma}$ is the system cost if any sustainability indicator takes its ideal case value. For the problem described in this document, this cost is higher than $\overline{z}$ and thus $\overline{\varsigma} \geq 0$. In general, the ideal cases of the various sustainability indicators cannot be obtained simultaneously and, thus, the optimization problem is infeasible. In this case, the equations of the problem related to sustainability targets are relaxed until the problem becomes feasible and $\overline{\varsigma}$ is derived from this problem. The relaxation is performed automatically by the optimization solver CPLEX [IBM]. It is

steered by priorities attached to the equations (see Table 8). Equations with high priority are relaxed before equations with lower priority. Therefore, if the optimization problem becomes feasible after some relaxations, then any other equation with the same priority or with lower priorities is not relaxed at all. The priorities in Table 8 follow the principle:

- First, relax equations related to fuel share and import share indicators (less important than other indicators).
- Second, relax equations related to energy intensity indicators.
- Third, relax equations related to waste indicators.
- Fourth, relax equations related to CO_2 emission indicators (more important than other indicators).

Table 8: Relaxation priorities of the sustainability indicators in IKARUS-FLP

Indicator	Priority
ECO 1	3
ECO 2	3
ECO 6	3
ECO 9	3
ECO 10-1	3
ECO 10-2	3
ECO 11-1	4
ECO 11-2	4
ECO 11-3	4
ECO 11-4	4
ECO 11-5	4
ECO 12	4
ECO 13	4
ECO 15-1	4
ECO 15-2	4
ENV 1-1	1
ENV 1-2	1
ENV 9	2

Indicator	Priority
ENV 11	2

Source: IEF-STE 2010

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Systems Analysis and Technology Evaluation at the Research Centre Jülich

Many of the issues at the centre of public attention can only be dealt with by an interdisciplinary energy systems analysis. Technical, economic and ecological subsystems which interact with each other often have to be investigated simultaneously. The group Systems Analysis and Technology Evaluation (STE) takes up this challenge focusing on the long-term supply- and demand-side characteristics of energy systems. It follows, in particular, the idea of a holistic, interdisciplinary approach taking an inter-linkage of technical systems with economics, environment and society into account and thus looking at the security of supply, economic efficiency and environmental protection. This triple strategy is oriented here to societal / political guiding principles such as sustainable development. In these fields, STE analyses the consequences of technical developments and provides scientific aids to decision making for politics and industry. This work is based on the further methodological development of systems analysis tools and their application as well as cooperation between scientists from different institutions.

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